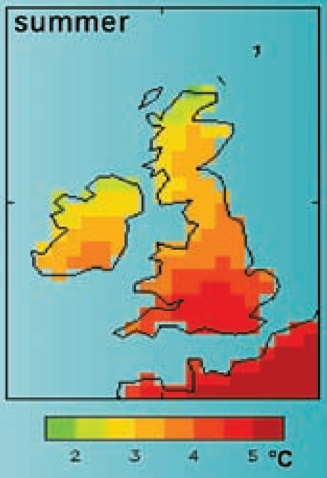
AIR QUALITY EXPERT GROUP

Air Quality and Climate Change: A UK Perspective



Published for:
Department for Environment, Food and Rural Affairs;
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This is the third report produced by the Air Quality Expert Group

Further copies of the publication are available from:
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This document is also available on the AQEG website at:
http://www.defra.gov.uk/environment/airquality/aqeg

Published by the Department for the Environment, Food and Rural Affairs. Printed in March 2007 on material that contains a minimum of 100% recycled fibre for uncoated paper and 75% recycled fibre for coated paper.

Department for the Environment, Food and Rural Affairs
Nobel House
17 Smith Square
London SW1P 3JR
Telephone: 020 7238 6000

Product code PB12489 ISBN 0-85521-172-5

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TELETEXT	page 156
Internet	http://www.airquality.co.uk http://www.defra.gov.uk/environment/airquality/

Terms of Reference

The Air Quality Expert Group (AQEG) was set-up in 2001, to provide independent scientific advice on air quality, in particular the air pollutants contained in the Air Quality Strategy (AQS) for England, Scotland, Wales and Northern Ireland and those covered by the EU Directive on ambient air quality assessment and management (the Air Quality Framework Directive). AQEG replaces the Airborne Particles Expert Group, who published their report on 'Source apportionment of airborne particulate matter in the UK' in January 1999.

AQEG reports to the Secretary of State for Environment, Food and Rural Affairs, Scottish Ministers, the National Assembly for Wales and the Department of the Environment in Northern Ireland (the Government and Devolved Administrations). AQEG is an advisory non-departmental public body in England, Wales and Northern Ireland. In terms of the Scotland Act 1998, the Group is a jointly established body.

AQEG's main functions are:

- to give advice to ministers on levels, sources and characteristics of air pollutants in the UK
- to assess the extent of exceedences of Air Quality Strategy objectives and proposed objectives, EU limit values and proposed or possible objectives and limit values, where monitoring data is not available
- to analyse trends in pollutant concentrations
- to assess current and future ambient concentrations of air pollutants in the UK
- to suggest potential priority areas for future research aimed at providing a better understanding of the issues that need to be addressed in setting air quality objectives.

The Group will not give approval for products or equipment.

Further information on AQEG can be found on the Group's website at: http://www.defra.gov.uk/environment/airquality/aqeg. Information on these pages includes the dates, agendas, and minutes of meetings as they become available, a list of the members, the Register of Interests, and draft and final reports as they become available.

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Acknowledgments

The Group would like to acknowledge the following individuals and organisations for their help in the preparation of this report.

Dr Steven Utembe (Imperial College London) for contributions to the TORCH trajectory modelling calculations reported in Chapter 4.

Professor Alastair Lewis and co-workers (University of York) for provision of the TORCH isoprene and temperature data reported in Chapter 4.

Yvonne Li at AEA Energy & Environment for her contribution to Chapter 5 in areas focusing on emissions.

Taru Jusilla for her help in compiling the consultation document.

Kate Sugden for her help in preparing both the main report and the summary for publication.

Dr Marcus Amann (IIASA), Professor Øystein Hov (Norwegian Meteorological Institute) and Professor Keith Shine (Reading University) for their helpful comments on the draft version of this report.

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Executive summary

1. Background

Defra and the Devolved Administrations asked the Air Quality Expert group (AQEG) to examine linkages between climate change and air quality pollutants and their potential mitigation policies. AQEG was asked to examine the scientific background to these interactions and to identify synergies, where measures to improve air quality can help to ameliorate climate change, and trade-offs where policy measures in the two areas act in opposition. Six specific questions were asked and these are shown in Box A. AQEG was asked to focus on the next 10 – 15 years and also to comment on the decades starting 2030 and 2050. The focus was on the UK and Europe and on likely rather than catastrophic future events.

The Earth's long-term, globally-averaged equilibrium temperature depends on the balance between the incoming solar energy and the outgoing radiation, which has been reflected or emitted from the atmosphere and the surface of the Earth. Any perturbation to this balance is termed radiative forcing. The radiative forcings of the greenhouse gases of relevance to this report, carbon dioxide, methane, nitrous oxide and ozone, are all positive (they lead to warming). These forcings are generally assessed for a current or future year relative to 1750 and are globally integrated quantities. Aerosols (particulate matter) show more complex behaviour. Black carbon (black smoke) aerosols absorb incoming solar radiation and so have a positive radiative forcing. Other aerosol components, such as sulphate, reflect solar radiation and have a negative radiative forcing effect (they lead to cooling). Aerosols also affect cloud formation and clouds affect the radiation balance.

Climate change resulting from changes in radiative forcing is a long term process and the impact of emissions depends on the atmospheric lifetime of the emitted species. The effect of a greenhouse gas or aerosol is assessed through its global warming potential, which provides a measure of its impact on global climate, relative to that for carbon dioxide on a given time frame, for example 100 years. Compared to greenhouse gases, many substances that affect air quality have quite short atmospheric lifetimes. Aerosols for example have a substantial impact on the radiation balance, but are short-lived and reductions in emissions affect the radiation balance rapidly, in contrast to any reductions in, for example, carbon dioxide. Other pollutants, such as nitrogen oxides, have an indirect effect through their influence on the concentrations of the greenhouse gases methane and ozone.

Predictions of future temperatures using global models are subject to substantial uncertainties. The most uncertain contribution is that from aerosols, because of the complex and various ways in which they interact with radiation. In addition, unlike long-lived greenhouse gases such as carbon dioxide, their atmospheric distribution is quite inhomogeneous and they can affect the regional as well as the global climate. As a result, it is difficult to draw firm conclusions about the effects on climate change of air quality mitigation measures for particulate matter.

2. Impact of air quality on climate change

Nitrogen oxides, sulphur dioxide, ammonia and volatile organic compounds are all precursors of secondary aerosols. These aerosols are reflective so that they scatter solar radiation back to space and have a negative (cooling) radiative forcing of climate. They also influence the radiative properties of clouds. Thus, reductions in the precursors of secondary aerosols are likely to lead to *increases* in temperatures and there is evidence that the cooling effects of sulphate aerosol may have partly masked the warming effects of greenhouse gases.

Black carbon is a product of incomplete combustion, and in the UK is emitted especially from diesel vehicles. In an air quality context, it is measured as black smoke. Black carbon absorbs solar radiation and black carbon aerosols, or mixtures of aerosols containing a relatively large fraction of black carbon, exert a positive (warming) radiative forcing. Their effect is especially marked when the black carbon aerosol is located above reflective surfaces such as clouds or snow and ice. While black carbon emissions have decreased significantly in the UK over recent years, substantially increased emissions have been observed from China and India.

Aerosols also act indirectly by modifying the radiative properties of clouds. They act as cloud condensation nuclei, increasing the droplet number concentrations and decreasing the average droplet size in clouds. This process affects the ability of the clouds to scatter radiation. The precipitation efficiency from the clouds is also reduced, so that their lifetime is increased. Overall the aerosol indirect effect is cooling; its magnitude is highly uncertain.

Tropospheric ozone is one of the largest single components of the current radiative forcing of climate, after the well-mixed greenhouse gasses carbon dioxide and methane. Nitrogen oxides, volatile organic compounds, carbon monoxide and hydrogen are precursors of ozone and so have indirect effects on climate. These impacts should be considered alongside measures designed to control ozone and nitrogen dioxide as air quality pollutants. Interactions between these effects are complicated by the fact that air quality management is concerned with ground-level ozone, whilst radiative forcing of climate is more influenced by ozone at higher altitude.

The climate effect of methane, carbon monoxide, hydrogen and some volatile organic compound species via ozone production is reinforced by their impact on the lifetime of methane. For nitrogen oxides emissions however, the time-integrated ozone production and methane lifetime effects on climate are approximately equal in magnitude but opposite in sign, with a high degree of uncertainty in both. The net climate effect of nitrogen oxides emissions on ozone and methane may be slightly negative for ground-based sources and slightly positive for aviation. In general, combustion sources with a typical ratio of nitrogen oxides to carbon dioxide emissions have a net radiative forcing due to nitrogen oxides which is a hundred times smaller than that due to the co-emitted carbon dioxide.

Air pollutants may also have significant effects on concentrations of carbon dioxide and methane through their impacts on ecosystem sources and sinks. These include effects of nitrogen deposition in increasing plant growth and thus carbon uptake, effects of sulphate deposition in reducing methane emissions from major natural sources, and effects of ozone in reducing plant growth and carbon uptake.

Greenhouse gases are most effective high in the troposphere, where temperatures are lower and radiative impact greatest. The effect of aerosols also depends on their altitude. The concentration of pollutants at the surface is the most important issue in air quality.

Furthermore, the distribution of air quality pollutants is highly inhomogeneous and most are short-lived. The use of metrics such as radiative forcing and global warming potential, which are globally-integrated quantities, to describe the impact of air quality pollutants, such as aerosols, on climate change is problematic. The relationship between the effects on regional radiation of pollutants and the regional temperature response is far from clear, especially for pollutants that are not evenly distributed.

3. Impact of climate change on air quality

Increases in temperature as the climate changes will lead to changes in the chemistry associated with ozone formation. The greatest effect will be on the concentration of water vapour, which will lead to decreases in ozone in the background troposphere but increases in more polluted regions where there are higher nitrogen oxides concentrations. There could also be an increase in the flux of ozone from the stratosphere to the troposphere.

Hot summers like 2003, when there was a substantial photochemical smog episode in Europe, including SE England, are likely to become 'typical' by the 2040s, leading to a higher frequency of summer pollution episodes. There was evidence that emissions of volatile organic compounds from vegetation played a role in the 2003 episode; increases in temperature lead to increases in emissions of biogenic compounds such as isoprene. Since emissions vary between tree species, tree planting schemes aimed at energy production or carbon sequestration should take account of the potential for increased emission of volatile organic compounds and their impact on the formation of ozone and of secondary organic aerosol. In addition, hot, dry summers reduce the uptake of ozone through the stomata of plants. This decreases the damage to the plant but increases the concentration of ground-level ozone. Episodes of winter smog, by contrast, are likely to be less prevalent because of a likely decrease in the frequency of winter stagnation events, where low wind speeds and atmospheric stability hinder the dispersal of pollutants.

It is difficult to use output from current climate models to investigate the effects of climate change on regional air quality. Improvements in the temporal resolution are needed to examine processes with daily variations, and seasonal changes in emissions from natural sources; shorter timescales (for example to 2020 – 2030) are also needed. Both surface temperature and soil dryness are keys to understanding the likely severity of future summer pollution episodes.

4. Mitigation measures for air pollution and climate change

Air quality pollutant emissions in the UK have fallen considerably over recent years and further decreases are forecast for the period up to 2020 (for example nitrogen oxides 45%, sulphur dioxide 64%, volatile organic compounds 26%, particulate matter (PM_{10}) 19%, for a 2002 base year). These decreases have and will be driven by legislation and by technology changes. Little or no consideration has been given in these legislative and technological developments to the impact of the measures on climate change. Much smaller decreases are forecast over the same period for carbon dioxide (4%), which is on top of a 7.5% decrease between 1990 and 2002. UK projections show that future emissions of air quality pollutants will be spread over a much larger number of sectors, because of improvements in control of the previously dominant emitters. Further reductions beyond 2020, and assessments of the impact on greenhouse gas emissions, will require measures across a much larger number of sectors than was the case in 2002.

Since the projected UK decreases in carbon dioxide are small, even small carbon dioxide increases from air quality abatement technologies are significant. Many 'end-of-pipe' technologies for air quality controls result in small increases in carbon dioxide emissions. For example, flue gas desulphurisation on power stations leads to a 2% increase in carbon dioxide, whilst some forms of abatement or road vehicle exhaust emissions result in up to a 5% increase in carbon dioxide. The production of sulphur free (<10 parts per million sulphur) petrol and diesel in order to meet new fuel sulphur limits leads to increased emissions of carbon dioxide from refineries of 5 – 20%. These emissions could be offset by improved technologies in petrol engines. Without the introduction of limits on carbon dioxide emissions from diesel vehicles, emissions from future diesel vehicles are expected to rise on a 2010 – 2015 timeframe relative to current levels for Euro IV vehicles. These changes derive from the application of new pollution control technologies such as four-way catalysts, lean nitrogen oxides traps and particulate filters. Emissions of nitrous oxide, which is a much more powerful greenhouse gas than carbon dioxide, are also important for climate change. The use of selective catalytic reduction to reduce nitrogen oxides emissions from road vehicles could lead to increased emissions of nitrous oxide. These emissions may more than offset the global warming mitigation of reduced carbon dioxide emissions resulting from the higher engine efficiency.

Fuel and life-cycle analyses must be applied to all power generation and vehicular technologies when considering policies at a national level. For example:

- The analysis for the use of energy crops and biofuels should include fuel production and distribution, as well as end-use emissions. In addition, the management systems used to produce these crops, including the application rates of fertilisers and the land use they replace, will influence the extent to which increased production of such crops may lead to changed emissions of both air quality and greenhouse gas pollutants, for example ammonia, nitrous oxide and biogenic volatile organic compounds. National policies to increase forest planting to increase the UK carbon sink may also lead to increases in emissions of volatile organic compounds, precursors of ozone, depending on the species selected, increase rates of pollutant deposition. This is not to say that production of biofuels and more tree planting should be discouraged in the UK – they are important elements of national strategies to improve the national carbon budget - but rather that appropriate assessments of the implications for both local and national air quality, as well as climate change, should be made.

- Diesel fuel is generally considered to have greenhouse gas benefits over petrol. This is mostly because diesel emits lower quantities of carbon dioxide than petrol. However, the overall benefits of diesel in this respect are less apparent when other factors are accounted for. For example, diesel cars tend to have larger engines than equivalent petrol cars, thus reducing their carbon dioxide benefits. Furthermore, the refinery processes used to produce diesel are increasing in energy intensity to meet increased diesel fuel demand and fuel compositional requirements. Some emerging emissions control technologies for diesel vehicles can also result in increased fuel penalties, which would reduce their carbon dioxide benefit compared with petrol. Finally, recent modelling work indicates that black carbon emissions associated with diesel vehicles contribute to warming effects, although the magnitude of these effects is uncertain. These issues suggest that it is important to consider emissions and effects beyond those associated with tailpipe emissions, and this applies equally to other fuel cycles.

- The full fuel-cycle environmental implications of non-fossil fuel means of electricity generation (wind, tidal, nuclear, biomass etc) should be evaluated, as part of the development of future energy supply policies.

Some fuel-cycle analyses have been undertaken, but not necessarily on a consistent basis and always with a high level of uncertainty compared with estimates of emissions at the point-of-use of a fuel (for example vehicle tailpipe). At present, lack of information makes such assessments difficult and potentially incomplete.

The measures that most clearly benefit climate change and air quality are those which result in the reduction in the demand for a product or service or those that enable the same activity to be carried out more efficiently. For these measures there is generally a commensurate percentage reduction in both climate-active and air quality emissions. These reductions can be brought about in several ways including demand management and improvements in technology. These types of measures exist across the different sectors such as transport, energy and agriculture. Examples include energy conservation measures (for example insulation and more energy efficient appliances) and the reduction in road traffic by demand management. Mode-switching, for example from car to train and from air to train can also produce substantial benefits. Overall, behavioural change through incentives or legislation lies at the heart of such measures.

An integrated approach to processes that occur in and that affect the atmosphere is essential if progress is to be made in limiting the impact of human activity on climate change and air quality. This progress is currently limited by the availability of data for, for example fuel-cycle analyses. A further problem is the lack of common metrics that can be used to assess both air quality and climate change impacts. A number of specific measures that could correct some of the deficiencies are discussed in the main report.

The main recommendations from the report are reproduced in Box B. A more detailed discussion of the recommendations can be found in Chapter 6 of the main report.

Box A: Questions on air quality/climate change interactions set by Defra and the Devolved Administrations

Impact of air quality on climate change

Question 1: What are the links between the sources of emissions responsible for climate change and air quality? What are the main scientific issues associated with the interactions of greenhouse gases and air pollutants in the atmosphere and their impacts on climate change and air quality?

Question 2: What do future trends in UK air pollutant emissions tell us about the potential impact on climate for the UK and Europe? Given that some air pollutants cause air quality concerns on a regional scale, over what scale will their impact on climate be felt?

Impact of climate change on air quality

Question 3: How could the likely impact of climate change on the general weather patterns and emissions of air pollutants and their precursors affect atmospheric dispersion and chemistry processes in general, and UK air quality in particular? For example, might an increase in heatwaves affect air pollution episodes? Might the frequency and intensity of winter inversions decrease? If so, how will this affect air quality?

Impacts of climate change policies on air quality and vice versa

Question 4: What current or potential air pollution mitigation measures are likely to be detrimental/beneficial to UK climate change and vice versa? In particular, which mitigation techniques are likely to produce win/win for both air quality and climate change and which will result in unavoidable trade-offs? Priority should be given to considering the energy, transport, and agricultural sectors along with any others deemed to be appropriate.

Question 5: In the case of road transport, for different potential mitigation options (e.g. low-emission vehicles) and fuels (e.g. water diesel emulsion, biofuels, diesel fitted with particle traps, hydrogen etc) what are the main trade-off and synergies with regard to emissions that impact on climate change and local and regional air quality for the UK? It would be helpful to consider the effect of coupling the technical measure with different traffic management procedures (such as Low Emission Zones or Congestion Charging Zones etc).

Future research requirements

Question 6: What are the current gaps in our knowledge? Where should future research focus to provide appropriate scientific information to inform decisions about the comparative benefits of air quality and climate change mitigation measures? Are the currently available scientific tools sufficient to answer these gaps in our knowledge, and if not, what further developments are required?

Box B: Recommendations

These recommendations are taken from Chapter 6 of the report and a more detailed rationale for them may be found there.

1. Impact analysis of policies or specific developments, whether for industry, transport, housing etc., should take account of the interlinkages of emissions of air quality and climate change pollutants. In particular, measures at the national level designed to improve local air quality or to abate greenhouse warming should not be implemented without prior consideration of all types of impact on the atmosphere and other environmental media.
2. Detailed consideration should be given to appropriate policy drivers and legislation that could be introduced to ensure that the reduction of greenhouse gas emissions is properly incorporated into regional and local government planning decisions.
3. Detailed consideration should be given to developing better means of expressing the influence of air quality pollutants on climate, and for inter-comparing the benefits of abatement strategies in respect of air quality and of climate change.
4. The relationship between local radiative forcing and local temperature response has not been sufficiently investigated. This may be particularly important for spatially inhomogeneous radiative forcing agents such as aerosol (direct and indirect effects) and tropospheric ozone and needs further research.
5. Research is needed on the extent to which policies for large-scale tree planting within the United Kingdom and elsewhere within Europe would influence air quality in high temperature summer pollution episodes. Wider impacts of land use change upon both air quality and global pollutants also need to be considered.
6. Consideration should be given to promoting measures which result in benefits both for air quality and climate. These might include incentives for domestic energy conservation, improved industrial process efficiency and measures designed to modify the behaviour of individuals so as to reduce the impact of their activities on the atmosphere. Given the significant influence of transport emissions, measures which reduced the use of road vehicles, shipping and aircraft would be highly beneficial.
7. A comprehensive life cycle analysis should be conducted comparing the environmental implications of electric and hybrid vehicles with each other and with conventionally-fuelled vehicles, to inform policy on incentivising their use. A detailed fuel cycle analysis is required to consider the air quality and greenhouse gas emission implications for the production, supply and consumption of biofuels for transport.
8. The full fuel cycle environmental implications of non-fossil fuel means of electricity generation (i.e. wind, tidal, nuclear, etc.) should be evaluated, as part of the development of future energy supply policies. This should include the implications of large-scale biofuel and bioenergy production for land-surface exchange of both air pollutants and greenhouse gases.

Box B: Recommendations (continued)

9. The development of well informed European policy on ozone precursors would benefit greatly from a more global view of emissions, trends and abatement issues.
10. Future climate change policy should consider extending the basket of radiative forcing agents included in the development of climate change policies.

Chapter 1

Introduction

1.1 Background

1. Climate change (CC) and air quality (AQ) are two key environmental concerns for the Government. Both concerns can be addressed using a combination of technological improvements and behavioural change. Although CC and AQ both impact on the well being of people and the environment, their policies have tended to develop independently. The same could be said of scientific research. Annex 1 gives a brief overview of the main AQ and CC legislative agreements.

2. Like the science, CC policy has developed from a global perspective to more regional scales. In contrast, AQ policy has grown from the national- to the regional- or European-scale. The pollutants they address often share similar sources and drivers. Recently, research in both areas has recognised that CC and AQ are linked through atmospheric chemical, radiative and dynamic processes that operate at multiple scales. Consequently there has been a growing awareness of the need to combine both scientific research and subsequent policy thinking regarding CC and AQ.

3. A potential risk of keeping research and policy on CC and AQ separate is that abatement strategies may not recognise the synergies or trade-offs that may exist. For example, where emission sources of both CC and AQ related pollutants are the same, emission reductions of some greenhouse gases (GHGs) will yield additional benefits for AQ and health. Although the full benefits of GHG reduction in terms of improved climate is a long-term issue, the ancillary benefits regarding the 'knock-on' effects will be realised in a much shorter timeframe, offsetting the initial costs of mitigation.

4. It is with these potential benefits in mind that Defra and the Devolved Administrations requested this report from the Air Quality Expert Group (AQEG). Their findings will be used to inform the most appropriate way to adopt a more holistic approach to AQ and CC policy development.

5. From the environmental science perspective, to address these issues properly requires the widest possible consideration of the environmental impacts of the different pollutants and their interactions. So the scientific questions raised are those of the adequacy and completeness of current understanding of environmental systems. From the policy perspective, the links between AQ and CC provide support for a holistic approach to local, regional and global pollution problems. The policy issues include assessment of the widest range of environmental benefits from any emission reduction policy in cost-benefit analyses.

6. From the policy stand-point, there are two immediate issues to be resolved that are raised by the links between AQ and CC:

   - **Policy issue 1**: Could the steps taken to reduce local and regional air pollution problems make CC goals more or less achievable?
   - **Policy issue 2**: Could the steps taken for CC mitigation make local and regional AQ goals appear more or less achievable?

7. Emissions of nitrogen oxides (NO_X) and volatile organic compounds (VOCs) lead to the formation of tropospheric ozone (O_3), a regional atmospheric pollutant. Ozone is also an important GHG, so that reductions in emissions of these O_3 precursors on AQ grounds would also help us achieve CC goals. Nitrogen oxides, though, also affect the concentration of methane (CH_4) and of nitrate aerosols, so their impact on CC is complex. Energy efficiency is an example of a CC mitigation measure that would bring considerable benefits for local and regional AQ through reducing the consumption of fossil fuels. These examples illustrate the interaction between processes occurring on local, regional and global scales and the types of consideration that are central to this report.

1.2 Requirements and scope of this report

8. Measures to limit CC are aimed at the long-term while mitigation polices for AQ have much shorter time horizons of 10 – 15 years. The importance of the linkages between these two policy areas is increasingly recognised. Are there *synergies*, where measures to improve AQ can help to ameliorate CC? Are there *trade-offs* where policy measures in the two areas act in opposition?

9. Defra and the Devolved Administrations asked AQEG to review this general area and to collect scientific evidence that will inform policy in the following areas:

   - **The likely impacts of predicted levels of CC on air pollutant concentrations**. To assess the relationships between CC and AQ pollutants following publication of the 2002 UK Climate Impacts Programme (UKCIP02) scenarios. Such analysis is informing the current review of the Air Quality Strategy.
   - **Synergies and trade-offs between CC and AQ**. An improved understanding of the scientific synergy and trade-off issues between CC and AQ will help ensure that policy measures implemented to improve one problem will not adversely impact on the other; or if it does, at least the consequences will have been identified and considered.
   - **Decisions about the ancillary effects of CC policy**. Policies that encourage the reduction of carbon dioxide (CO_2) will not only mitigate global warming but may also benefit local and regional AQ, through their impact on emissions of AQ pollutants, such as NO_X from combustion, resulting in potential health benefits. Although it is accepted that the benefits of GHG mitigation may only be realised by future generations, the ancillary benefits of GHG mitigation often benefit the current generation through improvements in AQ. Policy strategies aimed at reducing GHG emissions may, through improvements in AQ, bring about additional environmental benefits that help to offset the immediate mitigation costs.

10. This report aims to inform the ultimate aim of Defra and the Devolved Administrations; to develop a more holistic assessment for CC and AQ policy. Four key policy-related technical topic areas were identified and six specific questions posed (see Box 1.1). Chapters 3 – 6 address each of these topic areas in turn.

11. The following additional suggestions were made by Defra and the Devolved Administrations:

    - The most useful timescale from an AQ perspective is 10 – 15 years. It may, however, prove difficult to discern impacts from climate models on such a timescale. While this timescale should provide the focus if at all possible, the group should also consider impacts for the decades starting 2030 and 2050.
    - While the global context is important, and provides the focus for most modelling of CC, impacts on Europe and the UK are of prime interest. Results from regional climate model runs, where available, should be used together with an assessment of their uncertainties. The European context is important from a policy perspective, but impacts on the UK should form the focus whenever possible.
    - Changes in weather patterns are critical to AQ. AQEG was asked to concentrate on high probability, low level changes, such as changes in the frequency of summer O_3 episodes, rather than low probability, catastrophic events such as much colder winters in the UK resulting from the collapse of the thermohaline circulation.
    - The report should include an assessment of the likely future changes in both natural and anthropogenic emissions. The former should be limited to a consideration of natural emissions where reliable information already exists, such as the increase in isoprene emissions that occurs with increasing temperature, but should not include a detailed assessment of the mechanism of formation of such emissions and the impact of a changed climate on them.

Box 1.1: Topic area and specific questions identified by Defra and the Devolved Administrations

Impact of air quality on climate change (Chapter 3)

As with some environmental processes it is conceivable that changes to AQ may, through feedback mechanisms, result in impacts on CC. An example of this might be the climate-cooling effect of aerosol pollutants released to the atmosphere.

Question 1: What are the links between the sources of emissions responsible for CC and AQ? What are the main scientific issues associated with the interactions of GHGs and air pollutants in the atmosphere and their impacts on CC and AQ?

Question 2: What do future trends in UK air pollutant emissions tell us about the potential impact on climate for the UK and Europe? Given that some air pollutants cause AQ concerns on a regional scale, over what scale will their impact on climate be felt?

Impact of climate change on air quality (Chapter 4)

Question 3: How could the likely impact of CC on the general weather patterns and emissions of air pollutants and their precursors affect atmospheric dispersion and chemistry processes in general, and UK AQ in particular? For example, might an increase in heatwaves affect air pollution episodes? Might the frequency and intensity of winter inversions decrease? If so, how will this affect AQ?

Changes in AQ are governed by changes in pollutant emissions and the weather. It seems likely that CC will result in an impact on the general weather patterns, in particular, wind climatology, temperature, sunshine hours and rainfall patterns. This in turn may result in a change in the processes that govern chemical transformations in the atmosphere. For example, a potential decrease in the temperature differential between the Tropics and Polar Regions may result in an increase in areas of stagnant or stationary air masses. Where these are located may have a bearing on the intensity of future O_3 episodes.

In addition to the changes in the general weather patterns, it is likely that CC will alter the emissions of certain GHGs and pollutants that impact on AQ. These emissions may be from 'natural' sources (e.g. increased isoprene emissions from vegetation due to rising ambient temperatures – resulting in increased O_3 generation) or due to changing human activity (e.g. reduced energy requirement for spatial heating but more for air conditioning due to rising ambient temperatures).

Impacts of climate change policies on air quality and vice versa (Chapter 5)

Question 4: What current or potential air pollution mitigation measures are likely to be detrimental/beneficial to UK CC and vice versa? In particular, which mitigation techniques are likely to produce win-win for both AQ and CC and which will result in unavoidable trade-offs? Priority should be given to considering the energy, transport, and agricultural sectors along with any others deemed to be appropriate.

Question 5: In the case of road transport, for different potential mitigation options (e.g. low-emission vehicles) and fuels (e.g. water diesel emulsion, biofuels, diesel fitted with particle traps, hydrogen etc.) what are the main trade-offs and synergies with regard to emissions that impact on CC and local and regional AQ for the UK? It would be helpful to consider the effect of coupling the technical measure with different traffic management procedures (such as Low Emission Zones or Congestion Charging Zones etc.).

Generally, the main GHGs are well mixed throughout the global atmosphere. As a result the effects of CC will impact at a global level, although the magnitude of the resulting impacts may vary from region to region. Currently CC and AQ strategy have different legal frameworks, reporting requirements and approaches. Policies aimed at mitigating the effects of GHG concentrations are implemented in the knowledge that the benefits will be long-term and globally effective. There is a risk that these policies will address the long-term global needs of CC at the expense of short-term regional or local AQ.

Future research requirements (Chapter 6)

Question 6: What are the current gaps in our knowledge? Where should future research focus to provide appropriate scientific information to inform decisions about the comparative benefits of AQ and CC mitigation measures? Are the currently available scientific tools sufficient to answer these gaps in our knowledge, and if not, what further developments are required?

Defra and the Devolved Administrations are committed to developing their policies on the basis of sound science. Decisions therefore have to be periodically reviewed as new scientific evidence emerges. The issues controlling both CC and AQ are complex and varied. The tools that are currently available to answer policy-related questions in both of these areas (economic, global circulation and dispersion models, AQ networks, met data etc.) have been developed with specific policy questions in mind. However, a more holistic approach that investigates synergies and trade-offs between these two issues may require a new set of scientific tools, or further development of the existing ones mentioned above, but operating at local and regional scales.

1.3 Air quality and climate change

12. Human activities emit a wide range of substances into the atmosphere; these substances have different behaviour and effects. Localised peaks of higher concentration may occur close to the origin of emissions, of importance e.g. in urban areas for AQ and possible health effects of human exposure. Chemical reactions occur in the atmosphere that transform some pollutants as they disperse leading to secondary pollutants with additional consequences. Examples include gases such as O_3 and fine particulate matter (PM) comprising sulphates and nitrates. Pollutants may also be removed from the atmosphere by deposition back to the surface, either directly from surface air, or following absorption into and precipitation in rain. Chemical reactions can occur on a time scale of days and pollutants may travel a few thousand kilometres, so that problems such as acid deposition or eutrophication (excess nitrogen in sensitive ecosystems) are transboundary/continental in scale. Unreactive gases however may persist for years or even hundreds of years, mixing globally and penetrating the whole troposphere. This leads to accumulation and globally increased concentrations with a slow response to reduction of emissions. Both gases and PM (aerosols) can contribute to CC, through their effect on the balance of incoming and outgoing radiation to and from the Earth and its atmosphere. This effect can be either direct, as is the case for long-lived gases such as CO_2 and CH_4, or indirect, through their influence on the concentration of GHGs through their chemistry. Aerosols act both directly and indirectly. This range of behaviour is illustrated for some common pollutants in Table 1.1.

13. While effects on human health drive many of the measures and policies developed to improve AQ, they are not specifically addressed in this report. The Department of Health recognises the importance of this agenda and is currently updating its 2001 report on Health Effects of Climate Change in the UK (DH, 2001).

1.4 Structure of the report

14. Chapters 3 – 5 examine the three main topic areas. They provide an analysis of available information and answers to the five questions posed in Box 1.1. Chapter 2 provides the appropriate scientific background needed to understand the issues that are raised in Chapters 3 – 5. It introduces:

- radiative properties of both gases and aerosols
- models, and particularly models used to predict CC on both global and regional scales
- emissions scenarios and emission inventories used for CC and for AQ assessments
- feedbacks in the climate system
- tropospheric chemistry
- the links between CC and AQ through a number of examples.

Chapter 6 assembles the main conclusions of the report and makes a number of recommendations as requested in Question 6 in Box 1.1.

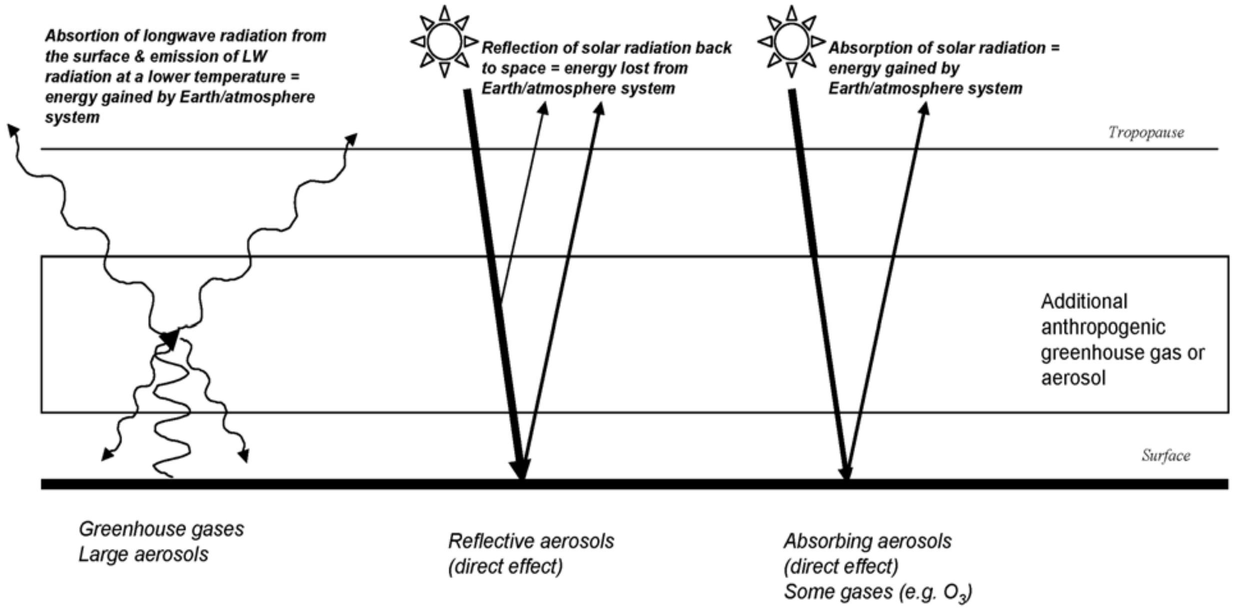
Table 1.1: Contrasting characteristics of some common pullutants

Pollutant [a]	Main anthropogenic sources	Lifetime in the atmosphere	Potential effects:				
			AQ/health effects	Acid deposition/ Eutrophication	Tropospheric O_3 [b]	Radiative forcing /climate	Oxidising capacity of atmosphere
SO_2 ($\rightarrow SO_4^{2-}$)	Fossil fuel combustion	~ days	SO_2 & SO_4^{2-} aerosol	Acid deposition		SO_4^{2-} short-term cooling	
NO_x ($NO+NO_2$) ($\rightarrow NO_3^-$)	Stationary combustion and transport	~ days	NO_2 & NO_3^- aerosol	Acid depostion and eutrophication	✓	NO_x indirect effect on CH_4 and O_3 NO_3^- short-term cooling	✓
NH_3 ($\rightarrow NH_4^+$)	Agriculture	~ days	(NH_4^+ aerosol)	Acid depostion and eutrophication		NH_4^+ short-term cooling	
N_2O	Soils, biomass	>100 years				Warming	
CO_2	Combustion	50 – 200 years				Warming	
CH_4	Fossil fuel, agriculture, landfills	12 years (adjustment time)			✓	Warming	✓
CO	Traffic	~1 month	Yes		✓	Indirect effect on CH_4 and O_3	✓
VOCs	Fuel combustion, solvents, traffic	Varies by compound	Some species		✓	Indirect effect on CH_4 and O_3	✓
Primary particles $PM_{10}/PM_{2.5}$	Combustion, traffic and grinding/dusty process	~ days	Yes in combination with secondary PM: SO_4^{2-}, NO_3^-, organic, etc.			Short-term warming and cooling	

[a] Sulphur dioxide (SO_2), sulphate (SO_4^{2-}), nitrogen oxides (NO_x), nitric oxide (NO), nitrogen dioxide (NO_2), nitrate (NO_3^-), ammonia (NH_3), ammonium (NH_4^+), nitrous oxide (N^2O), carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO) and Volatile Organic Compounds (VOCs).

[b] Ozone (O_3) is a secondary pollutant. It affects human health, vegetation and crops: it is also important as a GHG, and in atmospheric chemistry and cleansing (or oxidising) capacity of the atmosphere.

Figure 2.1: Schematic diagram showing the mechanisms of the radiative forcing due to greenhouse gases and of the direct radiative forcings due to aerosols



17. Many of the gases, particulate matter (PM, aerosols) and PM precursors emitted by human activity that are traditionally associated with AQ also interact with solar or terrestrial radiation and therefore exert a significant radiative forcing. The most important GHG, in terms of its radiative effect on the atmosphere, is water vapour, but its concentration and distribution in the troposphere is influenced mainly by physical processes, such as evaporation, and is not significantly affected by anthropogenic activity. Figure 2.2 shows the main contributors to radiative forcing, based on changes since 1750 (IPCC, 2001a). The natural contribution arising from changes in solar radiation is also shown for comparison.

18. Gases such as carbon dioxide (CO_2), O_3 and methane (CH_4) absorb terrestrial radiation emitted by the surface and lower regions of the atmosphere and emit radiation at a lower temperature. Some of the emitted radiation is transmitted back towards the Earth's surface via the well-known greenhouse effect. The magnitude of the greenhouse effect of a specified gaseous component is dependent on its absorption wavelength and on the temperature difference between the surface/lower regions of the atmosphere and the radiation emission temperature. The altitude of the absorbing/emitting gaseous species is therefore important because the species is generally at a lower temperature at a higher altitude. Therefore a molecule of a particular GHG will generally exert a stronger radiative forcing at higher altitudes than if the molecule were at lower altitudes.

19. The distribution of gaseous components in the atmosphere depends on the homogeneity of their emissions and on the lifetime of the pollutant. Thus long lived compounds such as CO_2, CH_4, nitrous oxide (N_2O) and many halocarbons are homogeneously mixed, even though they are not evenly emitted. Ozone, on the other hand, is much shorter-lived and its distribution is inhomogeneous. Since it is a secondary pollutant, its distribution also depends on where its precursors are emitted and on the timescale of its formation, as well as on its lifetime.

20. Aerosols can scatter and absorb solar and terrestrial radiation, therefore perturbing the energy balance of the Earth/atmosphere system (*direct* radiative forcing, Figure 2.1). Scattering aerosols reflect a proportion of incident solar radiation back to space causing a net loss of energy from the Earth/atmosphere system and are associated with a negative radiative forcing and a cooling of the atmosphere. Absorbing aerosols cause a net gain in energy for the Earth/atmosphere system and are associated with a positive radiative forcing and a warming of the atmosphere. The aerosol *indirect* radiative forcing arises because aerosols act as cloud condensation nuclei and can therefore modify the microphysics, radiative properties, precipitation efficiency, and lifetime of clouds (Figure 2.3). The aerosol *semi-direct effect* is the mechanism whereby absorption of solar radiation by aerosols modifies the atmospheric temperature and humidity structure thereby reducing the cloud amount.

Figure 2.2: Global-average relative forcing (RF) estimates and ranges in 2005 (relative to 1750) for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU), (IPCC, 2007)

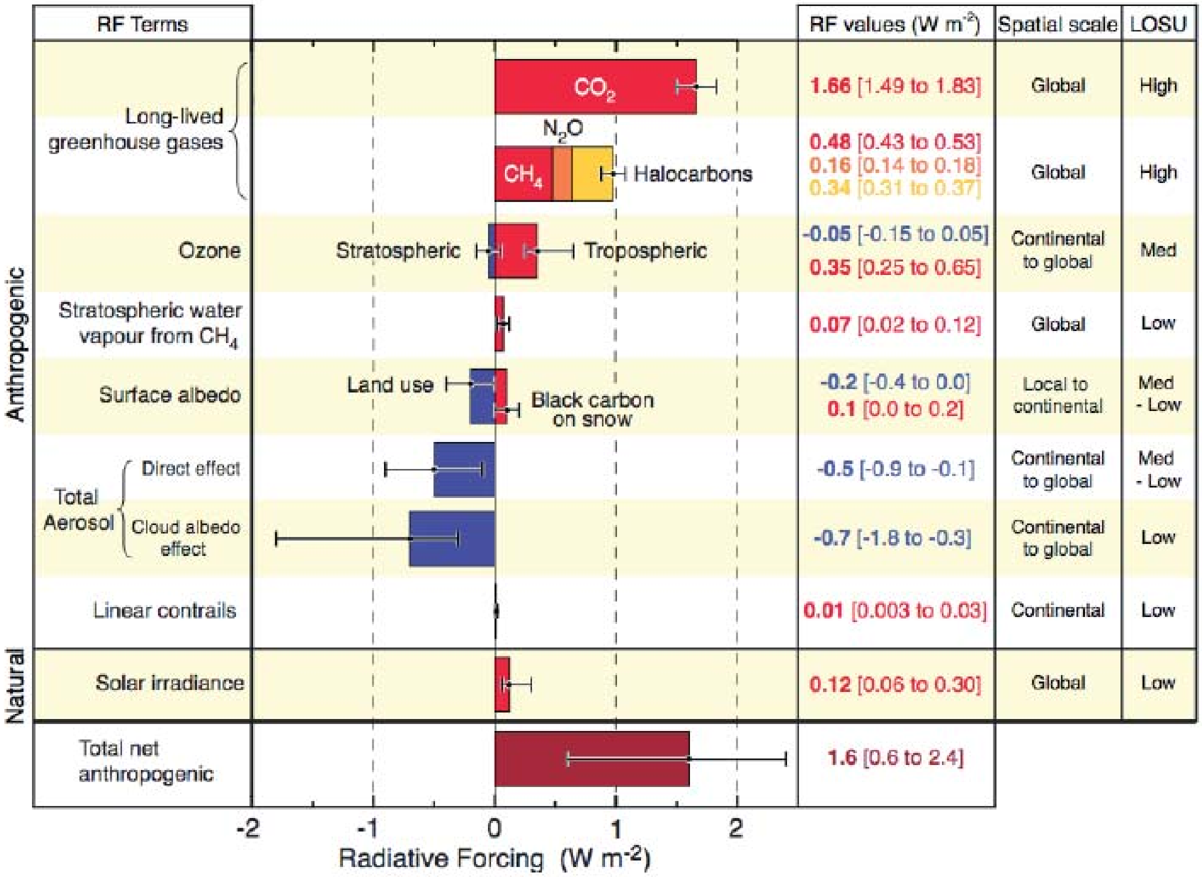
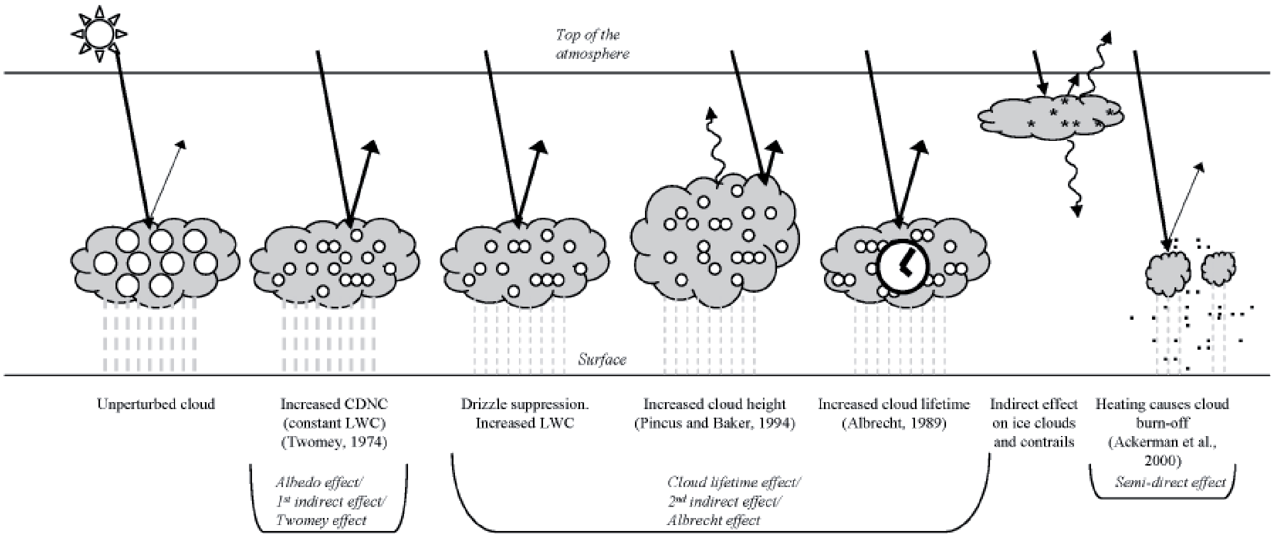


Figure 2.3: Schematic diagram showing the mechanisms associated with the indirect effects. Modified from Haywood and Boucher (2000). (CDNC = Cloud Droplet Number Concentration; LWC = Liquid Water Content (of cloud))



2.2.2 Quantification of radiative forcing and Global Warming Potentials

21. The utility of radiative forcing as a measure of potential CC comes from many early studies using energy balance, and slab ocean-atmosphere global models (e.g. WMO, 1986). These studies showed that the global equilibrium surface temperature change, dT_{global}, could be related to the radiative forcing, dF_{global}, by the climate sensitivity parameter, λ (units of $K/(W\ m^{-2})$), by the following relationship:

$$dT_{global} = \lambda\ dF_{global}$$

22. These early studies suggested that, provided the stratosphere was allowed to adjust to a new radiative equilibrium, the climate sensitivity was essentially independent of the forcing mechanism. Thus, while the climate sensitivity may differ from model to model, the relative importance of a particular anthropogenic perturbation to the climate system may be assessed in any of these models by calculation of the radiative forcing. The radiative forcing concept is therefore also valuable as it removes the need for full general circulation model simulations as the global mean temperature may be deduced solely from λ, and dF_{global}. However, more recent studies using models with improved representation of physical processes have shown that the constant climate sensitivity assumption for each individual forcing mechanism may not hold for some mechanisms such as that due to black carbon (BC) aerosol (e.g. Roberts and Jones, 2004; Hansen *et al.*, 2002). This realisation has led to the concept of climate efficacy, ε, which is the ratio of the climate sensitivity for the particular forcing mechanism to that for CO_2:

$$\varepsilon = \frac{\lambda_{forcing}}{\lambda_{CO2}}$$

23. Forcing mechanisms with a high ε will produce a higher global temperature change per unit radiative forcing than those with low ε. The global temperature change, dT_{global} is then defined as:

$$dT_{global} = \lambda_{CO_2}\, \varepsilon\, dF_{global}$$

24. It is important to realise that radiative forcing has always been essentially a *globally integrated* quantity. Therefore the relationship between local radiative forcing and local climate response cannot be deduced from this relationship.

25. The climate sensitivity, λ_{CO_2}, differs between climate models because the strength of feedbacks differs between models. Feedback mechanisms may be thought of as specific responses inherent within the models. For example, anthropogenic CO_2 exerts a positive radiative forcing which warms the atmosphere; a warmer atmosphere can hold more water vapour which is itself a GHG and therefore the warming will be enhanced. A climate feedback process that acts to enhance the original effect is known as a *positive feedback*. A climate feedback process that acts to reduce the original effect is known as a *negative feedback*. Several feedback mechanisms such as those involving water vapour, cloud and snow/ice albedo have been identified as being important within climate models.

26. The GWP provides a measure of the relative potential impact of emissions of a particular substance upon global climate. Global Warming Potentials are defined as the ratio of the time integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that for a reference gas, normally CO_2 (Ramaswamy *et al*., 2001). Global Warming Potentials are calculated for different time horizons, to provide a measure of the effect of the lifetime of a particular gas. When the lifetime of a particular gas is similar to that of CO_2, the GWP is relatively insensitive to the choice of time horizon, but when the atmospheric lifetime differs considerably, then the choice of time horizon becomes important. Ramaswamy *et al*. (2001) chose time-horizons of 20, 100, and 500 years when presenting the GWPs to emphasise this point in considering the potential impact of emissions of a particular substance upon global climate. The 100 year version has been accepted for use in the Kyoto protocol.

27. Global Warming Potentials are defined by the equation:

$$GWP = \frac{\int_0^{TH} a_x [x(t)] dt}{\int_0^{TH} a_{CO_2} [CO_2(t)] dt}$$

where TH represents the time horizon, ax the radiative efficiency due to a unit increase in the atmospheric abundance of a substance (in W m^{-2} kg^{-1}), and [x(t)] is the time-dependent decay of the atmospheric abundance following instantaneous release of that substance.

28. Table 2.1 shows GWPs on a 100 year horizon for some well-mixed GHGs and also includes their GWP-weighted emissions, showing that, when emissions are taken into account, CO_2 has a greater impact on radiative forcing than CH_4, despite its smaller GWP. The effect of the time horizon on GWPs can be gauged by reference to CH_4, the shortest-lived compound in Table 2.1, which has a 20 year GWP of 62 and a 500 year GWP of 7 and to the longer-lived compound CFC-115, which has a 20 year GWP of 4900 and a 500 year GWP of 9900.

Table 2.1: Examples of Global Warming Potential for various well-mixed Greenhouse gases. Adapted from Ramaswamy *et al*. (2001)

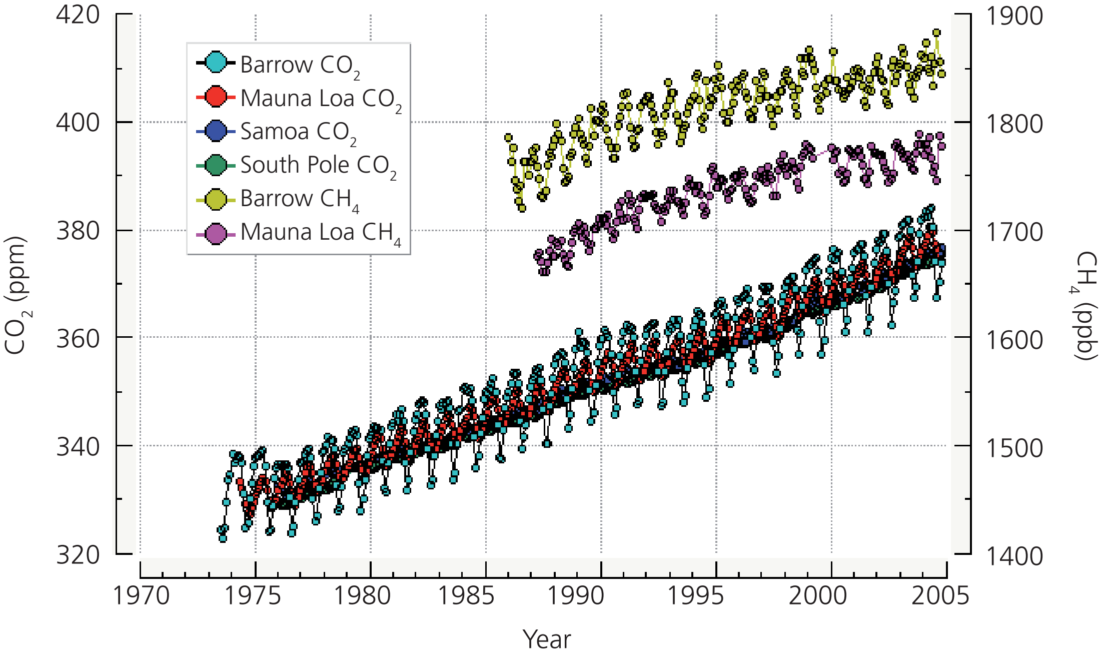
Gas		Radiative efficiency ($W\ m^{-2}\ ppb^{-1}$)	Lifetime (years)	GWP (100 year horizon)	GWP-weighted emissions (10^9 tonne y^{-1})
Carbon dioxide	CO_2	1.5×10^{-5}	150	1	24
Methane	CH_4	3.7×10^{-4}	12[a]	23	14
Nitrous oxide	N_2O	3.1×10^{-3}	114[a]	296	8
CFC-115	CF_3CClF_2	0.18	1700	7200	0.01
HCFC-142b	CH_3CClF_2	0.20	19	2400	0.07
HFC-23	CHF_3	0.16	260	12000	0.08

[a] The timescales for CH_4 and N_2O are their *adjustment* timescales and not the lifetimes, since the former is a better measure of the persistence of an emission pulse of these gases

2.2.2.1 Carbon dioxide

29. Before 1750, the mixing ratio of atmospheric CO_2 was approximately 280 ± 10 ppm ($512 \pm 18\ mg\ m^{-3}$), but has risen steadily since then to a concentration of around 380 ppm ($695\ mg\ m^{-3}$) in 2005 due to direct anthropogenic emissions (Figure 2.4). Around 75% of these emissions are from anthropogenic fossil-fuel burning with the remainder being due to land use change including biomass burning. Because CO_2 concentrations are relatively well-mixed the radiative forcing that is exerted is relatively homogeneously distributed across the globe, although it is slightly larger in the tropics and slightly smaller at high latitudes. From Figure 2.2 it can be seen that the radiative forcing in 2005 (i.e. the change owing to the increase in the CO_2 concentration since 1750) is estimated to be $1.66\ W\ m^{-2}$, which is an increase of $0.2\ W\ m^{-2}$ on its value for the year 2000 reported by Ramaswamy *et al*. (2001), an increase that is mainly due to the continued rise in atmospheric CO_2 concentrations in the intervening time period. The GWP of CO_2 is necessarily 1 whatever the timescale given, because it is the reference trace gas.

Figure 2.4: Carbon dioxide and methane mixing ratios versus time from a number of monitoring stations. (NOAA Climate Monitoring and Diagnostics Laboratory http://www.cmdl.noaa.gov/ccgg/insitu.html)



2.2.2.2 *Methane*

30. The mixing ratio of CH_4 (1778 ppb (1191 µg m^{-3}) in 2004 according to a global network of measurements performed by NOAA Climate Monitoring and Diagnostics Laboratory (CMDL)) is also increasing, although the rate has slowed in recent years (Figure 2.4). Methane has a range of sources, both natural and anthropogenic. The change from the pre-industrial concentration of 715 ppb (479 µg m^{-3}) to the 2004 value of 1778 ppb (1191 µg m^{-3}) gives a radiative forcing of 0.48 W m^{-2}. The GWP is stronger than that for CO_2 owing to the stronger radiative efficiency, but the GWP decreases as longer time horizons are considered because its atmospheric residence time is shorter than that of CO_2 (Table 2.1). Methane has a shorter atmospheric lifetime than CO_2 and, although still quite well-mixed, its concentration shows greater variation between monitoring sites (Figure 2.4).

31. Methane is removed from the atmosphere mainly by reaction with the hydroxyl radical (OH), whose concentration is affected by emissions of VOCs and NO_X. Thus, in addition to direct emissions of CH_4, anthropogenic emissions of VOCs and NO_X can respectively increase and decrease the atmospheric CH_4 burden. Positive and negative indirect GWPs can therefore be ascribed to VOCs and NO_X (Derwent *et al.*, 2001; Collins *et al.*, 2002) (see Chapter 3). Similarly CH_4 itself has an indirect GWP through its effect on its own removal rate and on tropospheric O_3 production.

2.2.2.3 Nitrous oxide

32. Estimates of N_2O mixing ratios show an increase from a pre-industrial value of around 270 ppb (494 µg m^{-3}) (Prather *et al*., 2001) to 318 – 319 ppb (582 – 584 µg m^{-3}) in early 2004; recent increases of 0.2 to 0.3% per year have been measured. The primary mechanism for the increase in N_2O concentrations is thought to be enhanced microbiological production in expanding and fertilising agricultural lands (Prather *et al*., 2001). The radiative forcing due to N_2O in 2005 was reported to be 0.16 W m^{-2} (IPCC, 2007), which is similar to the 0.15 W m^{-2} reported for 2000 by Ramaswamy *et al*. (2001). The GWP is larger than for CO_2 no matter what time horizon is considered because the radiative efficiency is higher and the atmospheric lifetime longer than those for CO_2 (Table 2.1).

2.2.2.4 Halocarbons

33. Halocarbons consist of several different types of compounds such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), which are emitted entirely by anthropogenic activities. CFC-11, CFC-12, CFC-13, HCFC-22, and CCl_4 are of particular importance because the increase in their concentrations from a pre-industrial value of zero to 268 ppt, 533 ppt, 4 ppt, 132 ppt, and 102 ppt respectively (1998 concentrations) leads to radiative forcings of 0.07 W m^{-2}, 0.17 W m^{-2}, 0.03 W m^{-2}, 0.03 W m^{-2} and 0.01 W m^{-2} respectively (Ramaswamy *et al*., 2001). All other halocarbons have been estimated to exert radiative forcings of <0.01 W m^{-2} (e.g. CFC-115, 7 ppt, 0.001 W m^{-2}; HFC-23; 14 ppt, 0.002 W m^{-2}) although when summed together they may exert a radiative forcing of a few tenths of a W m^{-2}. As shown in Figure 2.2, IPCC (2007) reported the direct radiative forcing due to changes in halocarbons since 1750 to be 0.34 W m^{-2}. As noted in Table 2.1, the GWPs of halocarbons tend to be extremely high because of their low background concentrations and their inherent infra-red absorbing properties coupled with the long lifetimes of these molecules.

2.2.2.5 Tropospheric ozone

34. Tropospheric O_3 is a GHG; however it is not directly emitted from anthropogenic activities. This means that it cannot itself be assigned a GWP. Ozone is formed in the troposphere by photochemical reactions involving NO_X (Nitric oxide (NO) and Nitrogen dioxide (NO_2)) and VOCs. These precursor species have direct anthropogenic emissions to the atmosphere and therefore indirectly contribute to global warming through the O_3 they produce. Calculating the effect of NO_X and VOC emissions on tropospheric O_3 levels is a complex problem requiring sophisticated 3-dimensional chemistry transport models. The assessment of these indirect effects is discussed in section 3.2.1.2.

35. Early measurements of O_3 were made at the surface in the 19th Century (e.g. Volz and Kley, 1988). These show an approximate doubling of concentrations between the pre-industrial and present day. Unfortunately it is not possible to use surface data to reconstruct the O_3 concentrations throughout the troposphere. Ozone is most effective as a GHG in the upper troposphere (Lacis *et al*., 1990) so to determine the present day radiative forcing of O_3 due to anthropogenic emissions of precursors, chemical transport models must again be used. From a comparison

of ten chemistry transport models, Gauss *et al*. (2006) calculated a radiative forcing due to O_3 since pre-industrial times of 0.36 ± 0.07 W m^{-2}. IPCC (2007) estimated that in 2005, tropospheric O_3 changes due to emissions of O_3-forming chemicals contributed to a radiative forcing of 0.35 W m^{-2}, whilst stratospheric O_3 resulted in a radiative forcing of -0.05 W m^{-2} (Figure 2.2).

2.2.2.6 Aerosol

36. The aerosol direct radiative effect has been approximately quantified for sulphate aerosol, biomass burning aerosol, fossil-fuel organic and fossil-fuel BC aerosols, and mineral dust (Penner *et al*., 2001). In addition, the radiative forcing due to nitrate aerosol has recently been quantified, as has the effect of BC deposition onto snow surfaces. However, considerable uncertainty still exists with regard to the magnitude (and even sometimes the sign) of the radiative forcing due to aerosols. The Aerosol Comparison Project (AEROCOM) was set up to address these uncertainties and provide a comprehensive assessment of the inter-model variability of the aerosol optical depths and direct radiative forcing due to various aerosol components (Kinne *et al*., 2005). IPCC (2007) reported that anthropogenic contributions to aerosols (primarily sulphate, organic carbon, black carbon, nitrate and dust) together produced a cooling effect, with total direct radiative forcing of -0.5 W m^{-2} and an indirect cloud albedo forcing of -0.7 W m^{-2} (Figure 2.2).

2.3 Climate modelling

2.3.1 Climate models

37. We can determine the effects of past CC by analysing direct temperature measurements and temperatures inferred from proxy data. However, the climate system (Figure 2.5) includes many different components and is therefore too complicated to allow simple extrapolations into the future using past observational data. One way to predict how the climate might change in the future is to construct mathematical models of the climate system that represent as many of the known relevant physical processes as possible. The most sophisticated of these climate models incorporate three-dimensional general circulation models (3D GCMs) of the atmosphere and oceans.

38. General Circulation Models are constructed by dividing the atmosphere into hundreds of thousands of boxes (Figure 2.6) usually on a regular rectangular grid. The physical equations that govern the evolution of such quantities as temperature, moisture and momentum are solved for each of these grid boxes in turn and are updated on timescales of typically 30 minutes. The size of the grid spacing is determined by a compromise between resolving the finer-scale processes in the atmosphere and the length of time taken for the computer to run the model. The atmospheric parts of climate models have a very similar construction to the models used for weather forecasting. However, because the climate models need to be run for hundreds of years rather than a few days, the grid resolution needs to be much coarser than that used, e.g. for weather forecasts. A typical climate model has a horizontal resolution of around 150 km.

This is sufficient to resolve large-scale weather systems, but not to resolve smaller-scale features such as clouds. The vertical resolution of climate GCMs usually varies with height from a few tens of metres near the surface to a few kilometres in the upper atmosphere. Clouds, turbulence, convection and other small-scale features which are too small to be resolved explicitly are parameterised. This means that the model includes equations accounting for their average effects on the large-scale dynamics rather than explicitly simulating the physics of the features themselves.

Figure 2.5: A schematic view of the climate system. The numerous components that comprise the system introduce a large degree of complexity

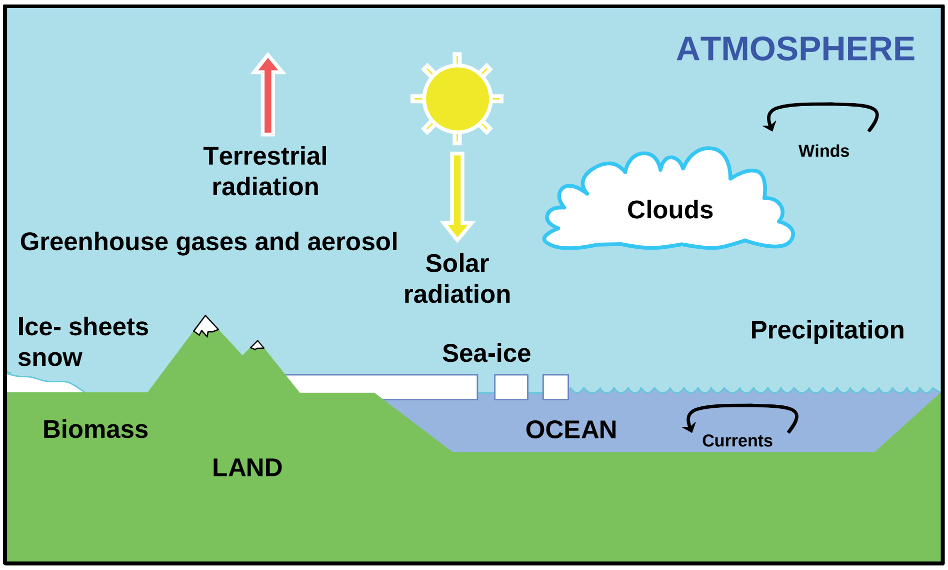
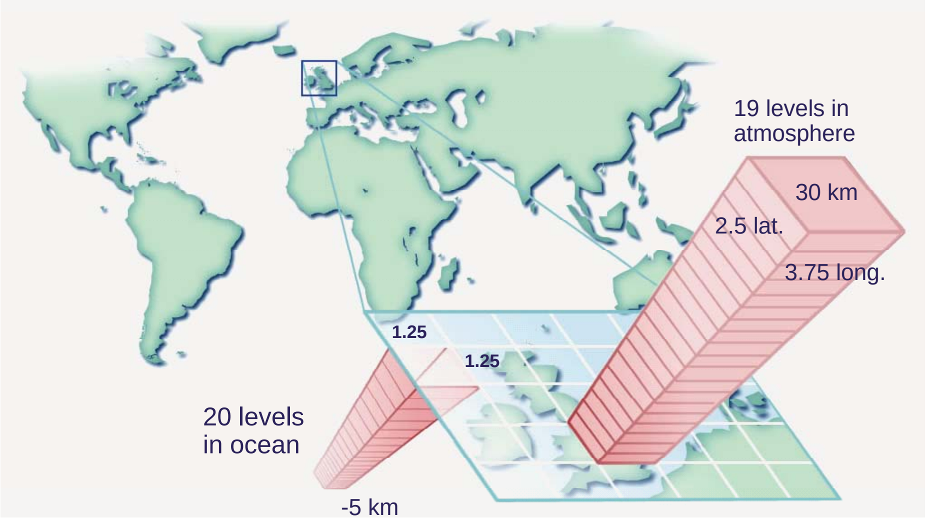


Figure 2.6: Schematic depiction of an atmosphere-ocean General Circulation Model. The details refer to the Hadley Centre model HadCM3 that was used for the IPCC Third Assessment Report



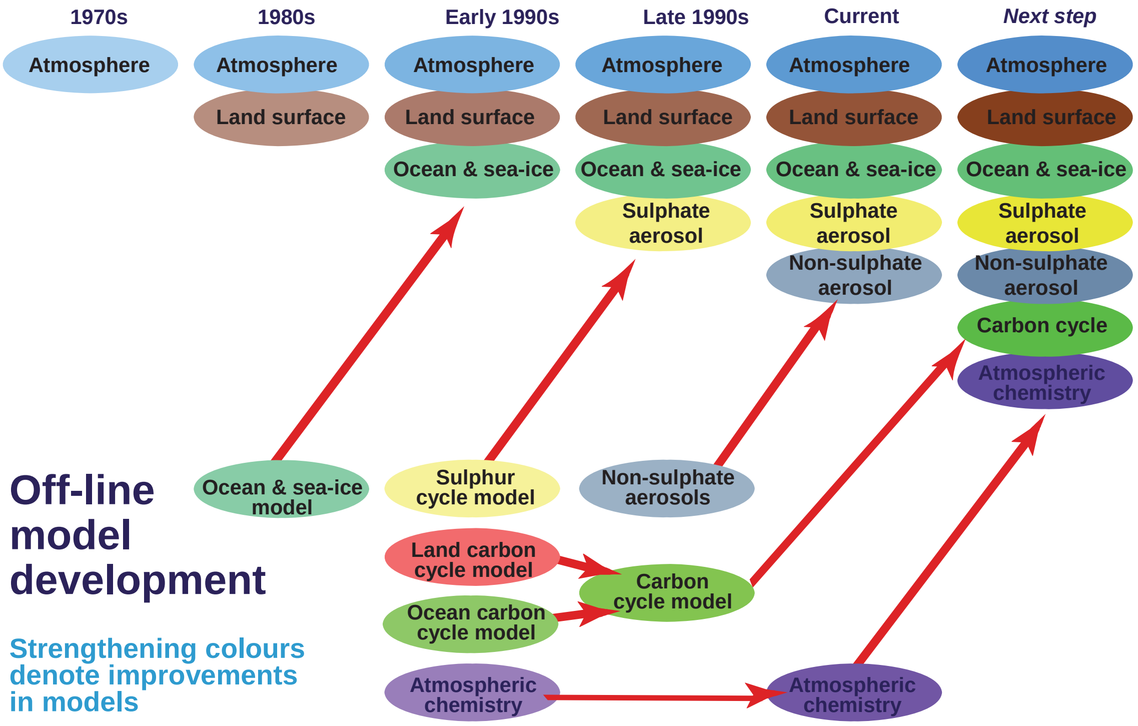
39. The effect of GHGs and aerosols on the atmosphere is simulated by the climate model's radiation scheme. This scheme divides up the spectrum of radiation from the sun into a few small wavelength bands that cover the range from the ultra-violet through the visible to the infra-red. The absorption, scattering and emission of this radiation lead to heating and cooling of the model's atmosphere and surface.

40. Where climate models differ most noticeably from weather forecasting models is that they need to include components of the climate system that are practically unchanging over the few days of a forecast, but change considerably over the hundreds of years of a CC experiment. The most important of these is the ocean. The ocean exchanges heat, water and CO_2 with the atmosphere and because of its large mass and heat capacity, it slows the response of the climate system to changes in forcing. The ocean is also the main driver of climate variability on timescales of decades to centuries. Ocean models are constructed in a similar way to the atmospheric GCMs. The resolution of ocean models tends to be higher than that of atmospheric models since the spatial scale of dynamical features is smaller in the ocean. Typical ocean model resolutions are around 100 km horizontally and 100 m vertically. The atmosphere and ocean models are coupled together as sub-models of the overall climate model, sometimes called an atmosphere-ocean GCM (AOGCM) to allow the exchange of information on heat, momentum and other variables. The coupling timescale is usually the same as the atmospheric timestep, about 30 minutes.

41. As climate models become more sophisticated (Figure 2.7), they now include modules to enhance their representation of the real world. For example land and ocean ice modules permit the extent of the ice cover to vary dynamically with the climate; carbon-cycle modules interactively represent the exchange of CO_2 between the atmosphere, ocean, vegetation and marine organisms; and dynamic vegetation modules allow the vegetation cover and type to evolve in response to a changing climate.

42. Of particular relevance to this report is the inclusion of modules to simulate the atmospheric composition of aerosols and GHGs that are chemically reactive. Nearly all climate models include an interactive sulphur cycle in which anthropogenic and natural emissions of SO_2 and dimethyl sulphide (DMS) are oxidised to sulphate aerosol. Other aerosol components are now being included in climate models such as anthropogenic BC and natural mineral dust. These aerosol schemes are necessarily highly simplified to reduce the computing time needed for long climate simulation. They thus lag a long way behind the sophisticated aerosol models used as research tools.

Figure 2.7: The increasing sophistication of climate models. The modules are usually developed offline before being coupled fully into the climate model. The timeline is only approximate and refers to the times when sub-models were (or will be) incorporated into a climate centre's standard climate prediction runs, rather than simply being coupled for research purposes



43. Apart from simplified schemes to generate sulphate aerosol, reactive chemistry schemes have not yet been implemented in operational climate models. Instead, the concentrations of reactive radiatively active gases are read in from data files generated by separate chemistry models. These gases include CH_4, N_2O, O_3 and HCFCs. By failing to simulate the chemicals interactively, the models are, firstly, not accounting for correlations between the chemical species and the meteorology in the model, and secondly, not allowing the changing climate to affect the chemical concentrations. Sophisticated chemistry models have been developed. These models tend to be designed to simulate the chemistry of either the stratosphere or the troposphere. There are few models that can simulate comprehensively the chemistry of both regions simultaneously. The stratospheric chemistry models are more advanced in that they are already run in a coupled mode, with the concentrations of the radiatively active gases interacting with the climate model's radiation scheme. Tropospheric chemistry models are usually run with one-way coupling: the meteorology affects the chemistry, but the chemical concentrations do not affect the radiation schemes. Both types of model are only run for short periods (up to a few decades) for research purposes. The major climate centres are currently trying to incorporate chemistry schemes into their operational climate models, but the computational expense of calculating all the chemical reaction rates means that some way of simplifying the chemistry is needed.

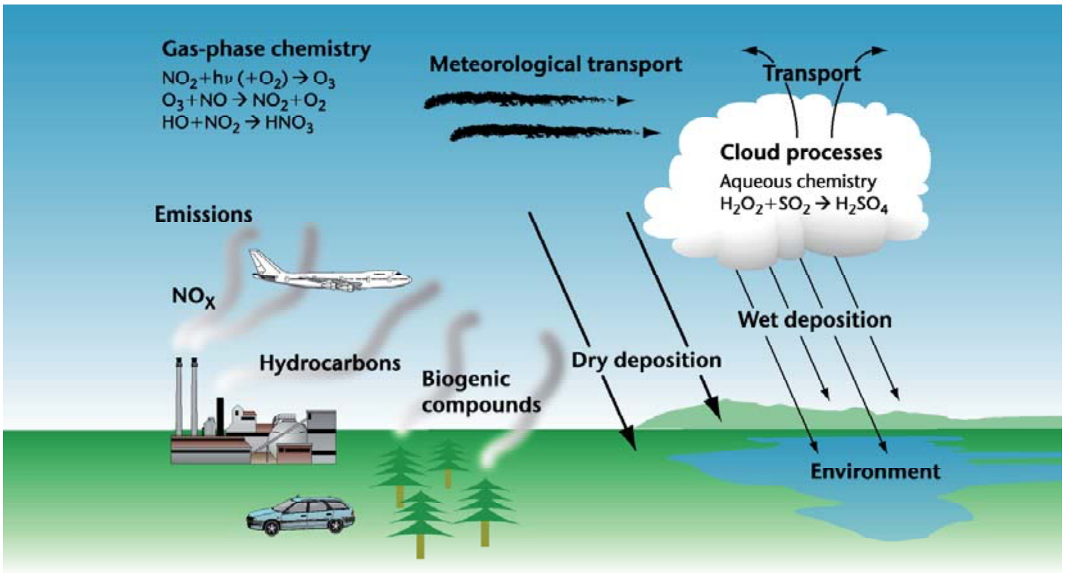
44. There are considerable uncertainties involved in modelling the climate. The most obvious is the limited spatial resolution. Climate models typically have a horizontal resolution of approximately 150 km compared to approximately 12 km resolution of the models used to forecast the UK weather. This means that important meteorological features such as frontal systems are poorly represented. These features can impact on the large-scale dynamics such as storm tracks and monsoon patterns. Similarly in the ocean, most current climate models cannot resolve the ocean eddies that, together with the atmospheric circulation, are responsible for the poleward transport of heat. Each 2-fold increase in resolution requires an 8-fold increase in computing power (since the timestep needs to be halved as well). Hence it will be many years before the amount of computing power available to climate modellers will allow them to model at sufficient resolution to capture these important processes. As mentioned earlier in this section, climate models try to represent processes they can not resolve by parameterisations. These can only be approximate representations, but are often tested against very high resolution large-eddy simulations or cloud-resolving models to quantify the effect of the approximation. There are other processes, such as the nucleation of ice particles by aerosols that are not represented at all in climate models because the underlying science is poorly understood. It is highly likely that there are processes not yet discovered that may be important in the Earth-Climate system.

2.3.2 Atmospheric chemistry models

45. To study the effects of atmospheric chemistry on climate and vice-versa, chemistry transport models are often used. These usually have a similar format to the climate models, in that the atmosphere is divided up into grid points and the calculations that predict the evolution of the chemical species are carried out for each grid point in turn every timestep. These calculations involve the transport (advection) of chemical species, emission of species, their chemical reactions and their removal at the surface via the processes of dry deposition wet deposition (precipitation) (see Figure 2.8).

46. The simplest chemistry models only include the chemistry of the NO_X, O_3, CH_4 and carbon monoxide (CO) – a total of about 20 species. Complex chemistry models, such as used for simulating urban pollution, may need to treat over 100 species. For global tropospheric chemistry-climate modelling, typically about 50 or 60 species are treated including higher hydrocarbons such as isoprene and its degradation products, and organic nitrogen compounds such as peroxyacetyl nitrate (PAN). Some include chemistry to form secondary aerosols from sulphur compounds and ammonia (NH_3) (around another 15 species), and from terpenes (around another 10 species). None of these models can represent all the important chemical species found in the atmosphere.

Figure 2.8: Schematic representation of the processes represented in an atmospheric chemistry model



47. The chemical schemes include both thermal and photolytic reactions (and aqueous reactions for the sulphur/ammonia chemistry). The photolysis rates are calculated using radiative transfer codes. These can either be pre-calculated and supplied as look-up tables to the model, or calculated interactively each timestep within the chemistry model.

48. The emissions from natural sources such as vegetation or lightning can be specified as fluxes from data files, but chemistry models are becoming more sophisticated in modelling these fluxes interactively based on the changing properties of the vegetation or convective clouds. Similarly, interactive schemes are being added to models whereby the rate of deposition of chemical species to the Earth's surface depends on the changing vegetation and soil properties.

49. Atmospheric chemistry models can either be run online or offline. In online models, the chemistry code is run within the climate model. This has the advantage that all the climate variables used in the climate model are accessible to the chemistry model, and that the radiatively active chemical species can feedback on the climate. The disadvantages are that the resolution of the chemistry model usually has to the be the same as the climate model, and the extra expense of running the climate model every time means longer computing times. Offline chemistry models (sometimes called chemistry transport models – CTMs) are run completely separately from the climate models. They get their climate information by reading in archived data files. This makes them quicker to run and allows them to be run at any desired resolution. However they require archiving of appropriate climate variables in the preceding climate model run, and hence need large amounts of data storage. It is rarely feasible to store these at the 30 minute resolution of the climate model, so the data are usually averaged over

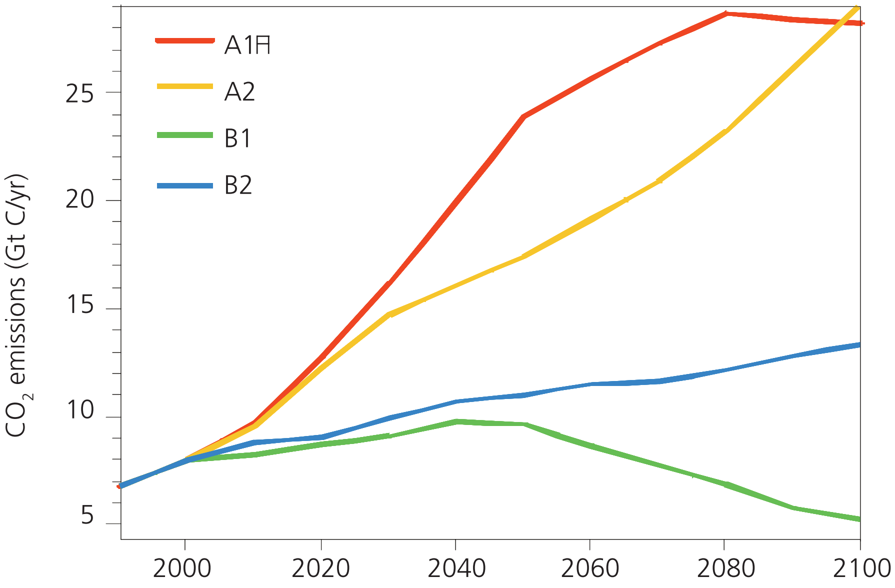
3 or 6 hours – losing information in the process. Detailed climate information such as convective transport is often not archived by the climate model. In this case the information has to be recreated inside the CTM by replicating the convective parameterisation code used by the climate model, but based on time-average driving data. Offline chemistry modelling is becoming less common as the sophistication of the chemistry models grows.

2.3.3 Emissions scenarios

50. Emission inventories are a fundamental part of most AQ and climate modelling, forecasting and policy assessments. They quantify the mass of a primary pollutant emitted from different sources over a period of time. Inventories are the means by which the relative importance of different sources to emissions of a given pollutant can be expressed and therefore allow an appreciation of how measures brought in to control one pollutant (e.g. an AQ pollutant) might affect another (e.g. a GHG).

51. However, inventories can vary in spatial scale and coverage (regional, national or local), in time and in sector allocation, depending on the purpose for which it was constructed. Many countries develop their own national emission inventories and these are generally constructed in a consistent manner. There are international obligations for countries to report emissions annually to bodies like the UN Framework Convention on Climate Change (UNFCCC), the UN Economic Commission for Europe (UNECE) and the EU following strict reporting guidelines in terms of definitions of emission sources. This offers the advantage that these countries' inventories are comparable and updated on a regular and consistent basis. However, the focus of these inventories is on national responsibility, so emissions from certain sectors that cross national boundaries such as international aviation and shipping are excluded, as are emissions from many natural sources. Separate, more global or regionally-based emission inventories are usually reported for these specific sectors by bodies looking beyond the national frame, but these are produced periodically and may not be updated on a regular basis. The future GHG emissions are commonly taken from the IPCC Special Report on Emission Scenarios (SRES). They are based on a variety of different assumptions about population, economic and technological growth. The variety in the assumptions leads to a large range of predicted future emissions. Predictions of CO_2 emissions from the four scenarios most commonly used by climate models are shown in Figure 2.9.

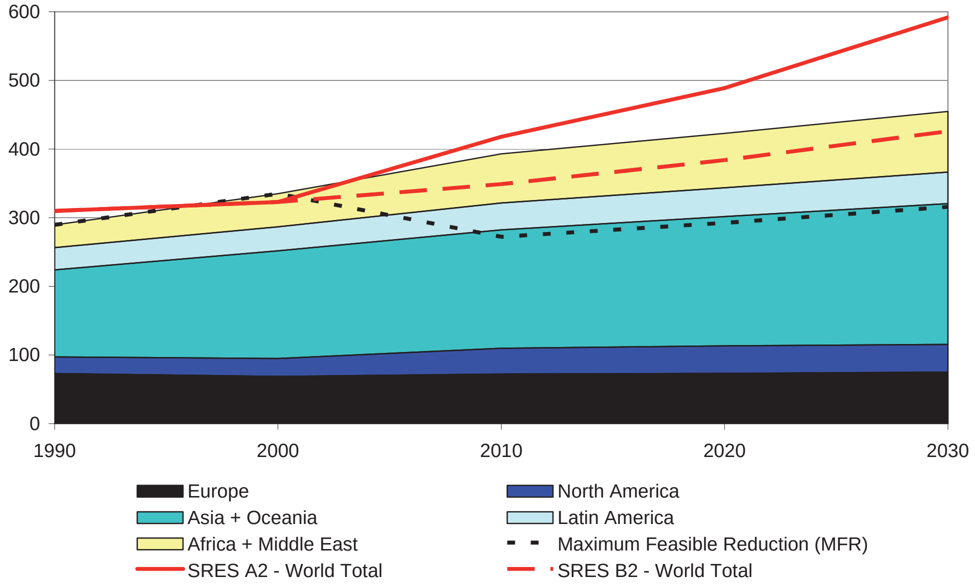
Figure 2.9: Predictions of future carbon dioxide emissions according to the four most commonly used SRES scenarios

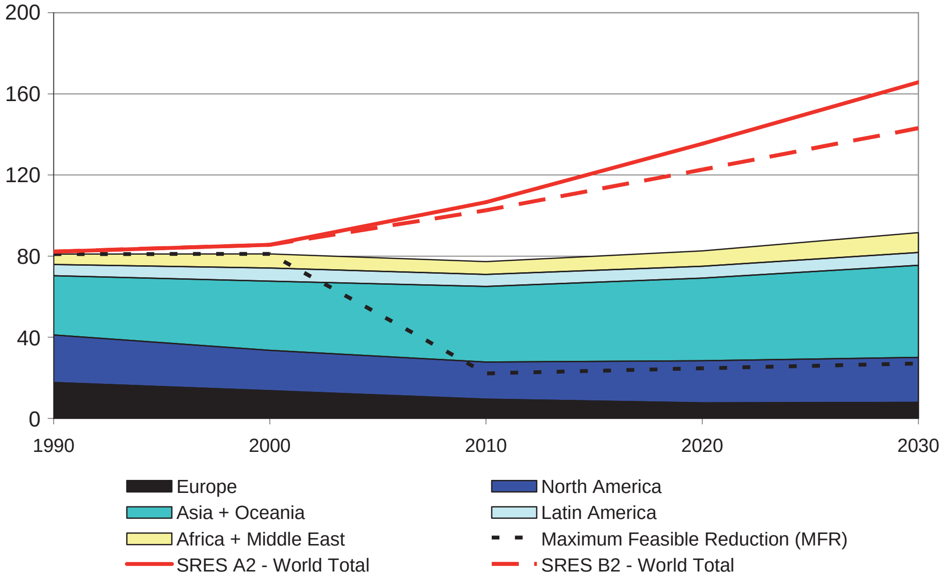


52. Climate models use emission inventories and projection scenarios that are a composite of both national inventories and these more sector-specific inventories (e.g. aviation, shipping), e.g. the SRES projections. Air quality models generally use national inventories. Inventories and projections developed by the International Institute for Applied Systems Analysis (IIASA) covering different regions (e.g. Europe, Asia, North America) are used in both AQ and climate models.

53. The SRES scenarios specifically do not assume that any action will be taken to limit emissions under international treaties such as the Kyoto protocol. They do, however, allow for expected controls on emissions in order to improve AQ. This concept is taken further by a new set of predictions of reactive gas emissions by IIASA, which has generated two scenarios for emissions to 2030 (described in Dentener *et al*., 2005; Dentener *et al*., 2006) called 'current legislation' (CLE) and 'maximum feasible reduction' (MFR). The CLE scenario assumes that current national legislation to control pollutant emissions will be enacted and adhered to. This legislation includes that of many developing countries and particularly limits emissions from transport sources. The CLE scenario is put forward as the most realistic estimate. The MFR scenario explores the consequences if the most advanced technologies currently available were applied to control pollutant emissions. Application of these technologies will involve some cost, so the MFR scenario is not expected to be the most realistic; rather it is an example of what could be achieved. The population and economic growths assumed by IIASA are similar to those assumed by SRES. Examples of the predicted CH_4 and NO_X emissions by IIASA and SRES are shown in Figure 2.10.

Figure 2.10: Global annual emissions of methane (upper plot) in Tg (CH_4) yr^{1} and nitrogen oxides (lower plot) in Tg (NO_2) yr^{1}. The coloured areas depict the IIASA CLE (current legislation) emission scenario, the dotted black line IIASA MFR (maximum feasible reduction) and the red solid and dotted lines SRES A2 and B2. Taken from Dentener *et al*. (2005)





54. In the UK, AQ models generally use emissions data taken from the National Atmospheric Emissions Inventory (NAEI). The NAEI provides a historic time-series in UK emissions for AQ pollutants (including O_3 and secondary aerosol precursor emissions) and GHGs from different sectors. The NAEI also provides projections of AQ pollutant emissions to 2020. The NAEI UK emission projections are tied to Department for Trade and Industry (Dti) energy forecasts which are periodically updated, traffic forecasts from the Department for Transport and various sources for agriculture. The Dti provides the UK's projections for CO_2 emissions from its UK Energy Model and includes impacts of policy measures included in the Climate Change Programme. There are also UK projections of non-CO_2 GHG emissions produced on a consistent basis on behalf of Defra.

55. Details of the methods and assumptions used for compiling emission inventories and emission projections in the UK for the AQ pollutants were given in detail in previous AQEG reports (AQEG, 2004; 2005).

56. This report explores numerous linkages between emissions of the pollutants contributing to AQ and CC. Emission inventories, principally, but not solely, from the NAEI are used to provide the quantitative information required to assess these interactions and for identifying trade-offs and synergies between mitigation measures for AQ and CC. There are various stages in the report where, in answer to the specific questions posed by Defra and the Devolved Administrations, reference is made to emission inventory information at a sector level, but it is in Chapter 5 covering policy issues in relation to Questions 4 and 5 on mitigation measures where the contribution of different sources to AQ pollutants and GHG emissions are discussed in detail. Chapter 5 considers from a policy context measures that produce win-win outcomes, i.e. reducing both AQ pollutant emissions and GHGs, and those which lead to a trade-off of one group of pollutants against another. Classic examples are measures brought in to reduce NO_X and primary particulate matter (PM) emissions and how they affect emissions of CO_2, e.g. through fuel switching (coal to gas or petrol to diesel) and through introducing end-of-pipe abatement.

57. To an extent, the quantitative conclusions are based on the UK emission projections from the NAEI. Reference is made to a number of potential transport and non-transport measures being examined by Defra in the current review of the Air Quality Strategy through analysis of the projected emission changes and ensuing impacts on concentrations of NO_2 and PM_{10} against AQ targets and the effects on CO_2. However, Chapter 5 highlights where there is a need to look beyond "end-of-pipe" emissions, as presented by inventories, to consideration of impacts over a whole life cycle or fuel cycle, covering emissions at various stages from generation and supply of a fuel through to its final use. This is particularly crucial to understanding the impacts on CO_2 emissions, where the point of release is unimportant, compared with those on AQ pollutant emissions, where the point of release is critical. This is relevant to mitigation measures based on switch to biofuels and hydrogen as fuels, for which emissions associated with growth and supply may become more important than those associated with point of use. The fact that natural emissions, and uptake, of both AQ pollutants and GHGs are not considered in current inventories, means that the net impact of changes in land use on emissions inventories needs to be assessed with care.

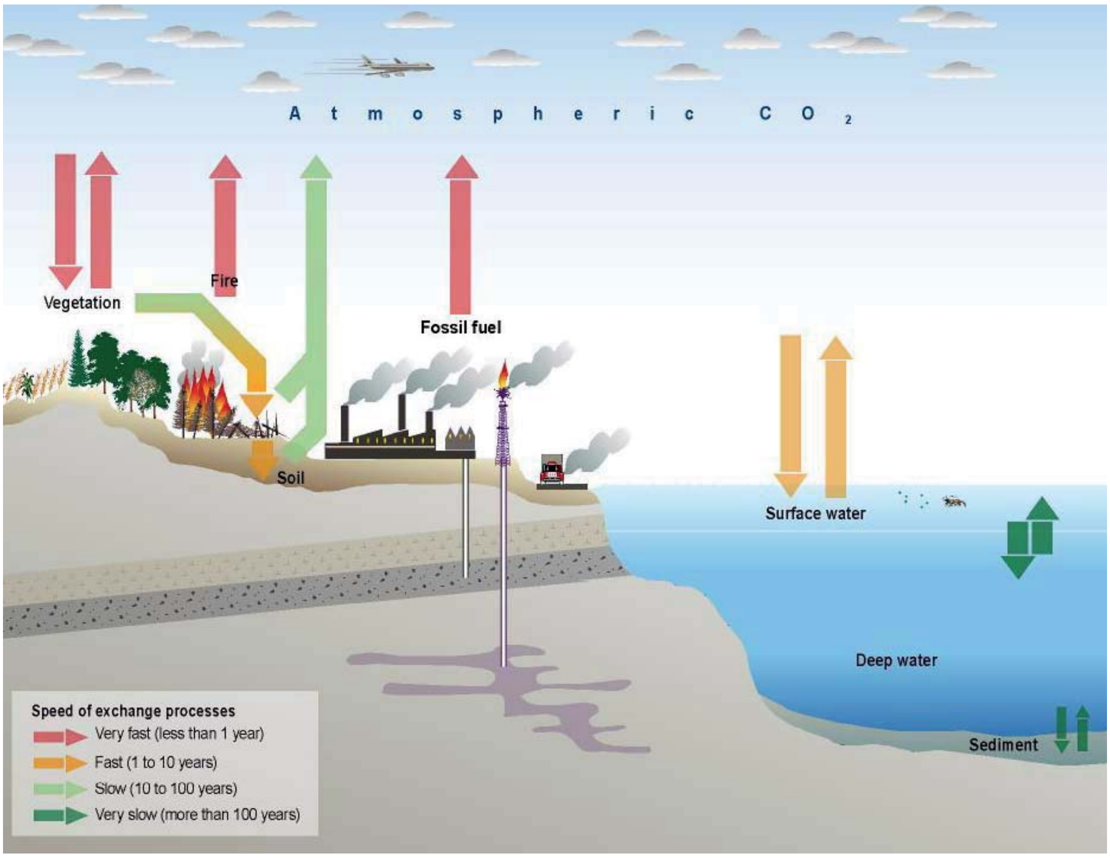
2.3.4 Feedbacks

58. It is possible to calculate the direct change in the Earth's radiation balance caused by the introduction of GHGs without using a complex 3D climate model. If the meteorology of the Earth (other than the temperature) was unchanged then radiation changes could easily be converted into a global temperature change. However, in a warmer climate other aspects of the climate system will change too, leading to climate feedbacks, either enhancing (positive) or dampening (negative) the CC. The most important of these is the water vapour feedback. Climate

models predict that the *relative* humidity of the atmosphere will remain largely constant in a warmer atmosphere but since warmer air can hold more moisture, the absolute amount of water vapour will increase. Since water vapour is a GHG this will increase CC further in a positive feedback. Another example of positive feedback is through changes in snow and ice cover. As the surface of the Earth warms, the ice and snow cover will decrease. Since the land and sea are darker than ice and snow, more solar radiation will be absorbed by the Earth, causing more warming. A more complicated example is the effects of clouds. Clouds can reflect and absorb solar radiation, thus cooling the Earth's surface. But they can also absorb and emit the long-wave radiation emanating from the surface, thus warming the Earth. Whether the net effect is a warming or a cooling depends on the height and characteristics of the clouds. Climate scientists have not yet reached a consensus on whether clouds induce a positive or negative feedback on CC.

59. Further important feedbacks relate to climate effects on the carbon cycle. This is illustrated in Figure 2.11, which emphasises the large bidirectional fluxes between the atmosphere and the biosphere, soils and the surface ocean. The size of these fluxes means that the perturbation of the underlying processes by changes in climate can lead to significant changes in net carbon uptake or release. For example, Cox *et al*. (2000) explored the effect of CC on the natural terrestrial carbon cycle, and found that by 2100 increasing temperature decreased the amount of CO_2 taken up by plants, and increased the amount of CO_2 released by decaying matter in soils, causing a positive feedback on the rate of increase of atmospheric CO_2 concentrations.

Figure 2.11: The carbon cycle (from IPCC, 2001b)



60. There are both positive and negative feedbacks involving atmospheric chemistry. Warmer conditions may cause circulation changes that lead to a redistribution in lightning and to lower concentrations of CH_4 and O_3 in the troposphere – a negative feedback (e.g. Stevenson *et al*. 2005; Grewe, 2005) while a positive feedback has been shown to occur through an increase in O_3 transferred to the troposphere from the stratosphere (Collins *et al*., 2003; Sudo *et al*., 2003; Zeng and Pyle, 2003). The faster chemical reactions in a warmer atmosphere with more water vapour will decrease the concentrations of CH_4 and O_3 (e.g. Johnson *et al*., 2001) – a negative feedback on climate. Changes in cloud cover and precipitation will affect the rates of photolytic reactions and the rate of removal of soluble species. It is not clear how these will be affected by CC.

61. The following are two important examples of known feedbacks associated with the coupling between climate and chemistry via ecosystem responses. Firstly, warmer temperatures are likely to increase the natural emissions of reactive gases, such as CH_4 from wetlands and tundra (e.g. Gedney *et al*., 2004; Gauci *et al*., 2004a) and VOCs from vegetation (e.g. Sanderson *et al*., 2003; Guenther *et al*., 1995), while drier and warmer conditions may increase emissions of various gases from wildfires. Secondly, in a climate with higher CO_2, the uptake of O_3 by plant stomata will decrease, thus increasing O_3 concentrations in the atmosphere, but decreasing O_3 damage to vegetation. This latter effect may offset to some extent the impact of higher O_3 levels in reducing the uptake of CO_2 and hence in increasing CO_2 concentrations. It is not yet known whether the overall impact of atmospheric chemistry on CC is a net positive or negative feedback.

62. Further examples of climate feedbacks involve aerosols. In the so-called CLAW hypothesis, Charlson *et al*. (1987) postulated that increasing sea temperatures would increase the emissions of DMS from phytoplankton which would generate more sulphate aerosol, thus cooling the climate. Some modelling studies (e.g. Woodward *et al*., 2005) show that mineral dust aerosol will increase in future due to changes in winds, aridity and vegetation cover; others (e.g. Mahowald and Luo, 2003) suggest that increases in vegetation cover in a CO_2-rich atmosphere will cause decreases in dust. Mineral dust is also an agent in a climate feedback loop involving marine phytoplankton; increasing dust deposition to the oceans provides iron which increases phytoplankton growth and hence absorption of CO_2 from the atmosphere.

63. Feedbacks could lead to sudden changes in climate. One example is the release of CH_4 hydrates from the deep ocean which would cause a sudden warming. Another is the Atlantic Ocean's thermohaline circulation (of which the Gulf Stream is a part). If this were to shut down, it would cause a cooling of Western Europe. However, while current climate models suggest that this circulation might weaken, it is very unlikely to shut down during the 21st Century.

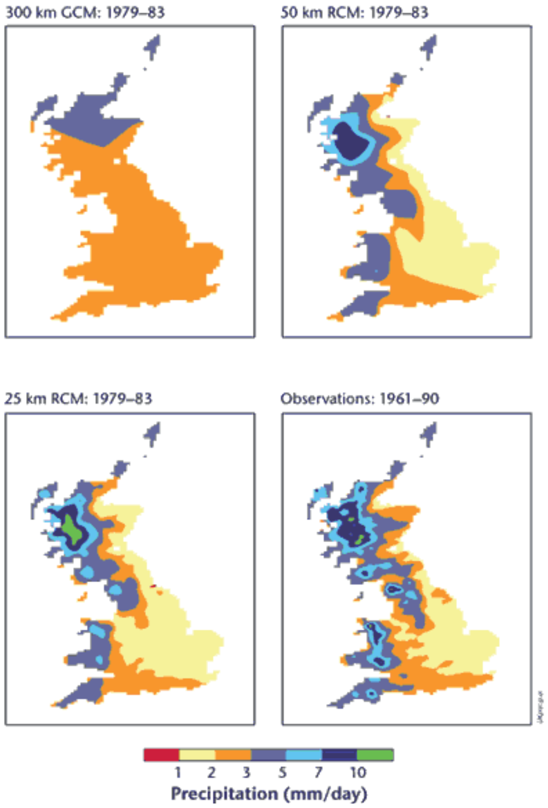
2.3.5 Regional modelling

64. Global coupled climate models that are computationally expensive are required to simulate the climate over many centuries. This limits the spatial resolution that can be afforded to approximately 100 – 200 km. However, the local climate is often determined by features smaller than this, such as the surface topography. Small mountain ranges such as the Pennines cannot be resolved by global models,

but can cause very different climates on either side of them. One solution to this problem is to use a regional climate model (RCM) embedded within the global model. RCMs can be configured to simulate the climate for a small sector of the planet at finer resolution, enabling the representation of important topography and processes otherwise not presented. The RCM can be supplied with meteorological data on its boundaries at 6-hourly intervals from an AOGCM. Sea surface temperatures and sea ice can be provided on a monthly basis, again from an AOGCM.

65. The large-scale CC signal in the RCM is therefore driven by the global AOGCM. The main way the RCM adds detail to the large-scale signal is through the use of higher resolution land surface data. The predicted changes in surface temperature due to CC will vary according to land surface type. For instance the amplitude of the CC signal is generally larger over areas with little vegetation, and smaller over areas with dense vegetation. For example, by resolving different land surface types over the UK, the RCM is able to give more accurate predictions of surface temperature changes over a particular UK location, rather than an average for the UK as a whole. Predicted precipitation changes are very sensitive to the small-scale orography (height of land). Figure 2.12 shows simulations of UK precipitation from an AOGCM (HadCM3) with a 300 km resolution compared to an RCM (HadRM3) run at 50 km and 25 km resolutions. The physical formulation is the same for all models, and the 300 km global model is used to provide the boundary conditions for the regional model. It is obvious that a regional model is needed to represent UK precipitation patterns, although lower resolution models may be able to simulate the broad-scale changes.

Figure 2.12: Simulated annually-averaged precipitation rates from the HadCM3 family of models with different resolutions, and observed data



66. A use to which RCMs would be well-suited, but are not currently applied, is the effect of regional air pollution (particularly aerosols) on regional climate. Aerosol concentrations vary widely across the UK, so measures to control them will have different climatic implications at a regional level.

67. Although the large-scale simulated changes generated by RCMs are broadly comparable with those modelled by GCMs, there can be a tendency for some RCMs to overestimate the variability of some small-scale processes. For example there is more scope for unrealistic positive feedbacks to occur, e.g. between precipitation and soil moisture. In this case, a higher frequency of extremes, such as heavy precipitation, may be predicted than is realistic. This has implications for predictions of changes in frequencies of extreme pollution events. Moreover, if there are biases in the driving data from the global model, such as excessive summertime drying, then the regional model is unlikely to correct this and may even amplify it.

68. Another way of making use of more detailed surface-type data is through tiling. Typically a global resolution grid square will contain several surface types such as water, bare soil, urban and vegetation. The surface characteristics for that square will be assigned an average of the different types weighted by the fraction of the grid square each occupies. In tiling, the surface exchange scheme, which calculates the interaction between the surface and the atmosphere, is run for each surface type ('tile') separately, and it is the net effect on the atmosphere that is averaged over the grid square, rather than the original surface types. This means that the model calculates a set of different surface temperatures for each surface type within the grid square. Thus, although one model grid square may cover much of SE England, it is possible to distinguish the different expected CC effects on surface temperature over urban areas from those over grassland or forests.

2.3.6 Current predictions

Figure 2.13: Predicted global surface temperature rise for four different emission scenarios

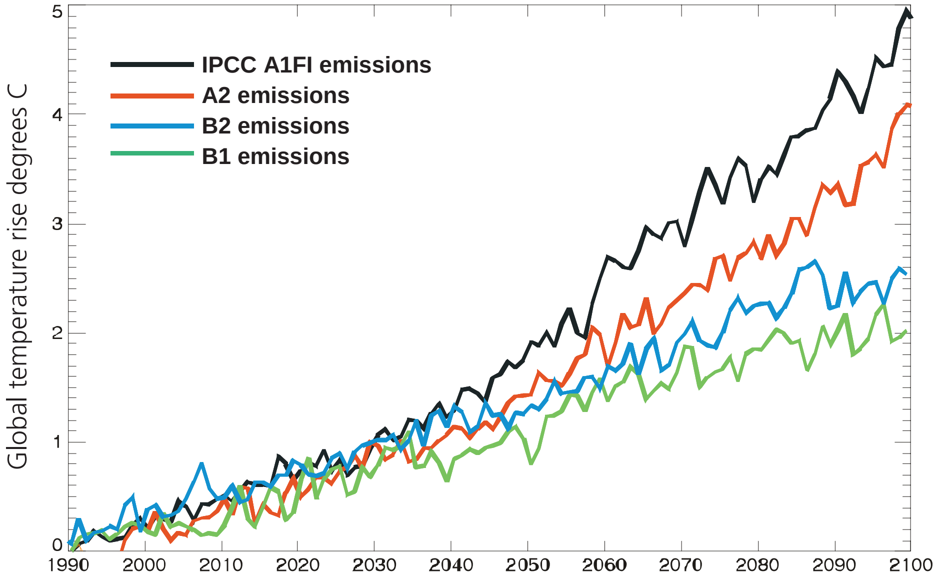
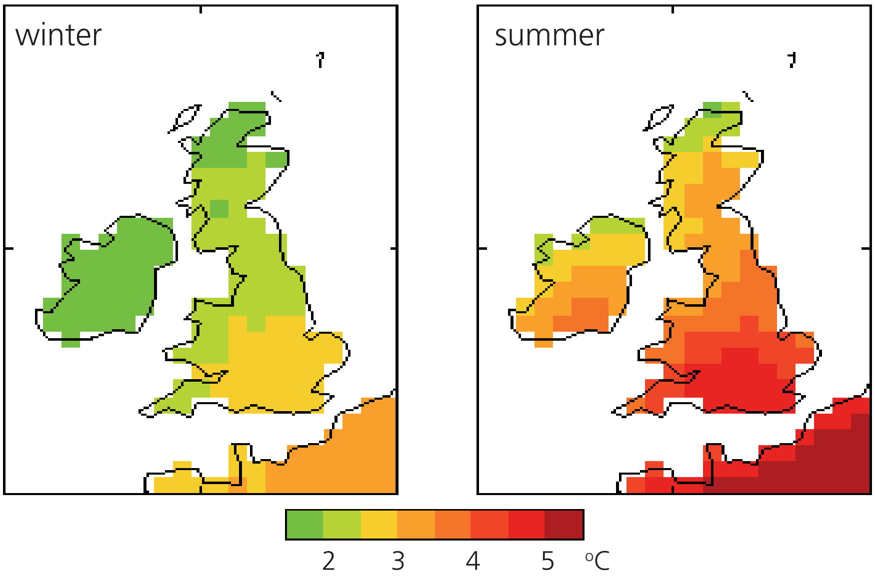


Figure 2.14: Changes in surface temperature by 2080s predicted by a regional climate model. The emission scenario corresponds to SRES A2



69. Some current predictions for global surface temperature rises, for four different emissions scenarios, are shown in Figure 2.13. These do not include the carbon cycle feedbacks found in Cox *et al*. (2000). They show that changes in emissions scenarios do not lead to significant changes in global surface temperature until about 2040. An example of the predicted future temperature changes from a regional model is shown in Figure 2.14.

2.4 Tropospheric chemistry

2.4.1 Impact of tropospheric chemistry on greenhouse gases

70. Both CH_4 and O_3 are important GHGs. Their atmospheric concentrations and their radiative forcing depend on the chemistry occurring in the troposphere. Methane is emitted directly to the atmosphere, and is removed mainly by chemical reaction; its concentration depends on the balance between these two processes.
As discussed above, O_3 is produced by chemical reaction in the atmosphere and is thus a secondary pollutant. Its precursors are VOCs and NO_X. Volatile organic compounds include compounds such as butane and benzene that are emitted from a range of anthropogenic sources (e.g. fuels and solvents), as well as compounds such as isoprene that are emitted by vegetation. These compounds are not significant direct GHGs, because of their short atmospheric lifetimes. Their impact on CC occurs mainly though their effects on O_3 formation and on CH_4 removal. Nitric oxide is emitted from combustion and from soils and is also formed higher in the troposphere by lightning.

71. The chemical reactions occurring in the troposphere are discussed in Box 2.1 (and are described in more detail in Section 2.4.2 below). A key concept is the oxidising capacity of the atmosphere, which refers to its ability to remove chemical compounds, such as CH_4 and VOCs. These compounds are removed by oxidation, through complex sequences of chemical reactions that convert them to CO_2 and water.

72. The oxidation sequence, e.g. of CH_4, is initiated by reaction with the hydroxyl radical (OH). The atmospheric lifetime of CH_4 is, to a good approximation, equal to $1/(k_{CH4}[OH]_{av})$, where k_{CH4} is the rate coefficient for the reaction of OH with CH_4 – a measure of how fast this reaction is. The square brackets around OH signify its concentration, which refers, in this instance to its average throughout the atmosphere. The lifetime of CH_4 is about eight years, which is sufficiently long for it to be distributed throughout the troposphere – its concentration varies little with latitude, longitude and altitude. The atmospheric burden of CH_4 is approximately equal to its rate of emission multiplied by its atmospheric lifetime. Thus $[OH]_{av}$ influences radiative forcing through its effect on the atmospheric CH_4 concentration; future changes in atmospheric chemistry resulting from CC can lead to feedbacks through their influence on $[OH]_{av}$.

73. Ozone plays a role in both AQ, through its influence on human health and on plant growth, and in CC. It is formed in the atmosphere by the photolysis of NO_2. The complex chemistry involved in the oxidation of CH_4 and of VOCs converts NO into NO_2 and hence leads to the formation of O_3. While other compounds are also important (see below), OH is a key species in initiating this oxidation chemistry. The hydroxyl radical is formed by the photolysis of O_3, in the presence of water vapour. The efficiency of O_3 formation following reaction of OH with a VOC depends on the local concentration of NO_X ($NO + NO_2$). Near the surface, where the VOC concentrations are highest, NO_X concentrations are greater close to anthropogenic emission sources, which are primarily located in the continental northern hemisphere. At low NO_X, the oxidation can lead to destruction of O_3.

74. Volatile organic compounds have shorter atmospheric lifetimes than CH_4, because their rate constants for reaction with oxidants, such as OH, are larger. The lifetime for butane, for example, is about five days, while that for isoprene is about three hours. As a result, they are not so widely distributed throughout the atmosphere, but have higher concentrations closer to their sources. While they absorb infra-red radiation, they do not act directly as GHGs because their concentrations are low in the upper troposphere. They act indirectly, however, through their impact on the oxidising capacity of the atmosphere, e.g. on OH concentration, and through their influence on O_3 formation.

75. Atmospheric oxidation leads to the formation of secondary aerosol. Sulphate aerosol is formed from the oxidation of sulphur dioxide (SO_2) to produce sulphuric acid. Emissions from the combustion of sulphur containing fuels are the major source of SO_2. Secondary sulphate aerosol is also formed from the oxidation of DMS, which derives from plankton. The importance of this process for CC was briefly discussed in Section 2.3.4. Nitrate contributes to secondary aerosol via the formation of nitric acid (HNO_3) from NO_2 (reaction 9 in Box 2.1). The oxidation of VOCs leads to oxygenated intermediates, some of which have very low volatility, so that they condense onto existing aerosol and contribute to their growth and to their radiative properties. The main VOCs that contribute to Secondary Organic Aerosols are aromatics and terpenes.

2.4.2 Chemical mechanisms in the troposphere

76. Box 2.1 outlines the chemistry involved in the oxidation of CH_4, as a result of its reaction with OH in the presence of NO_X. Carbon monoxide is also oxidised following reaction with OH, and a similar mechanism to that shown in Box 2.1 applies to the oxidation of other VOCs. Ozone can also initiate the oxidation of certain VOCs, as can nitrate (NO_3), which is the main oxidant at night. Hydroxyl relies primarily on sunlight for its formation and its concentration is very small at night. In assessing the relationship between AQ and CC in this and the following chapter, several features of the chemistry outlined in Box 2.1 are important:

- Nitric oxide is primarily emitted from the combustion of fossil fuels, although lightning, soils and biomass burning are significant sources. Both NO and NO_2 are short-lived in the atmosphere and are found primarily close to their sources; a mechanism for long range transport of NO_X is discussed below.
- The formation of OH from O_3 photolysis leads to loss of O_3, which depends on the competition between the reactions 2 and 3. The excited oxygen atom, O^1D, can either be converted to ground state oxygen atoms, O^3P, on collision with nitrogen (N_2) and oxygen (O_2), which leads to regeneration of O_3, or can react with water to form OH, which leads to net loss of O_3. Increasing the concentration of water vapour, through increases in the global temperature, leads to an increase in the rate of destruction of O_3 through photolysis.
- The net production of O_3 in the reaction sequence shown in Box 2.1 depends on the concentration of NO:
  - At low concentrations of NO, the peroxy radicals (CH_3O_2, HO_2) react primarily via reactions 10 and 11 and their oxidation does not generate NO_2, the precursor of O_3. These conditions apply in the background troposphere. The loss of O_3 from O_3 photolysis, coupled with low rate of formation via NO reactions leads to an overall consumption of O_3.
  - At high concentrations of NO, the peroxy radicals react mainly with NO (reactions 6 and 8), generating NO_2 and hence O_3 by NO_2 photolysis.
- These observations suggest that O_3 is not formed in regions that are far from NO_X sources, where many biogenic emissions occur. It is possible to transport NO_X into such regions via so-called reservoir species such as PAN (Box 2.1). This compound is produced from the reaction of the peroxyacetyl radical, formed in the oxidation of a wide range of VOCs, with NO_2 (reaction 14). Peroxyacetyl nitrate dissociates quite rapidly at the earth's surface, but much more slowly at the lower temperatures found at higher altitudes. Once it has been lifted to such altitudes, PAN can be transported considerable distances before it subsides to lower altitudes. The resulting higher temperatures lead to dissociation (the reverse of reaction 14) to form NO_2. This process provides a mechanism for transport of NO_X into regions not directly subjected to anthropogenic emissions, and for the formation of O_3 from the oxidation of biogenic emissions. Increases in the global temperature will lead to a more rapid rate of dissociation of PAN and hence to a reduction in the efficiency of transport of NO_X to less polluted regions. Thus the impact of short-lived biogenic VOCs on CC, through O_3 production, may be reduced.

Box 2.1 Oxidation of methane in the atmosphere and the formation of ozone

1. The major route for forming the hydroxyl radical (OH) in the atmosphere is through ozone photolysis. The reaction produces an excited oxygen atom, labelled O^1D:

$$O_3 + \text{light} \rightarrow O^1D + O_2 \qquad \text{(R1)}$$

which can either react with water to form OH, or lose energy to form unexcited oxygen atoms, O^3P, on collision with nitrogen (N_2) or oxygen (O_2) molecules.

$$O^1D + H_2O \rightarrow 2OH \qquad \text{(R2)}$$

$$O^1D + N_2, O_2 \rightarrow O^3P + N_2, O_2 \qquad \text{(R3)}$$

The unexcited oxygen atom combines with an oxygen molecule to form ozone:

$$O^3P + O_2 \rightarrow O_3 \qquad \text{(R4)}$$

2. The OH react with CH_4, CO and VOCs. The mechanism for CH_4 is given here to illustrate the reactions involved. The OH takes a hydrogen atom from the CH_4 to form water and CH_3 which in turn reacts with oxygen to form a peroxy radical CH_3O_2:

$$OH + CH_4\ (+O_2) \rightarrow CH_3O_2 + H_2O \qquad \text{(R5)}$$

A key reaction follows in which CH_3O_2 reacts with NO to form NO_2:

$$CH_3O_2 + NO \rightarrow NO_2 + CH_3O \qquad \text{(R6)}$$

A sequence of reactions then occurs which generates a hydroperoxyl radical, HO_2, which also reacts with NO to form NO_2 and to regenerate OH, which can start this reaction sequence again by reacting with a VOC:

$$CH_3O + O_2 \rightarrow HO_2 + HCHO \qquad \text{(R7)}$$

$$HO_2 + NO \rightarrow OH + NO_2 \qquad \text{(R8)}$$

3. This reaction sequence would go on and on indefinitely, but it is limited by reactions that remove radicals. The reactions involved depend on the concentrations of NO_X:

At high NO_X, OH reacts with NO_2 to form nitric acid,

$$OH + NO_2 \rightarrow HNO_3 \qquad \text{(R9)}$$

At low NO_X, hydroperoxyl radicals react with other hydroperoxyl radicals

$$HO_2 + HO_2 \rightarrow H_2O_2 \qquad \text{(R10)}$$

$$CH_3O_2 + H/RO_2 \rightarrow \text{Products} \qquad \text{(R11)}$$

Reactions 10 and 11 compete with reactions 6 and 8. At low NO_X, 10 and 11 win, so that the oxidation of the VOC does not lead to NO_2 formation.

Box 2.1 Oxidation of methane in the atmosphere and the formation of ozone

4. The NO_2 formed in reactions 6 and 7 can be photolysed to form unexcited oxygen atoms:

$$NO_2 + \text{light} \rightarrow NO + O^3P \qquad \text{(R12)}$$

which then form O_3 via reaction 4. From the perspective of both regional air pollution and CC, this step – the formation of O_3 – is a key one. The importance of NO in promoting O_3 formation arises from the competition outlined above.

5. Formaldehyde (or methanal), HCHO, formed in reaction 7 is an example of an aldehyde. Ethanal, CH_3CHO, formed in the oxidation of ethane, C_2H_6, provides a further example. Ethanal reacts with OH in the same way as CH_4 above, to form the radical CH_3CO, which reacts rapidly with O_2 to form the peroxyacetyl radical, CH_3CO_3.

$$CH_3CHO + OH\ (+O_2) \rightarrow CH_3CO_3 + {}_{H2}O \qquad \text{(R13)}$$

CH_3CO_3 reacts with NO_2 to form peroxyacetyl nitrate (PAN):

$$CH_3CO_3 + NO_2 \rightleftharpoons CH_3CO_3NO_2 \qquad \text{(R14)}$$

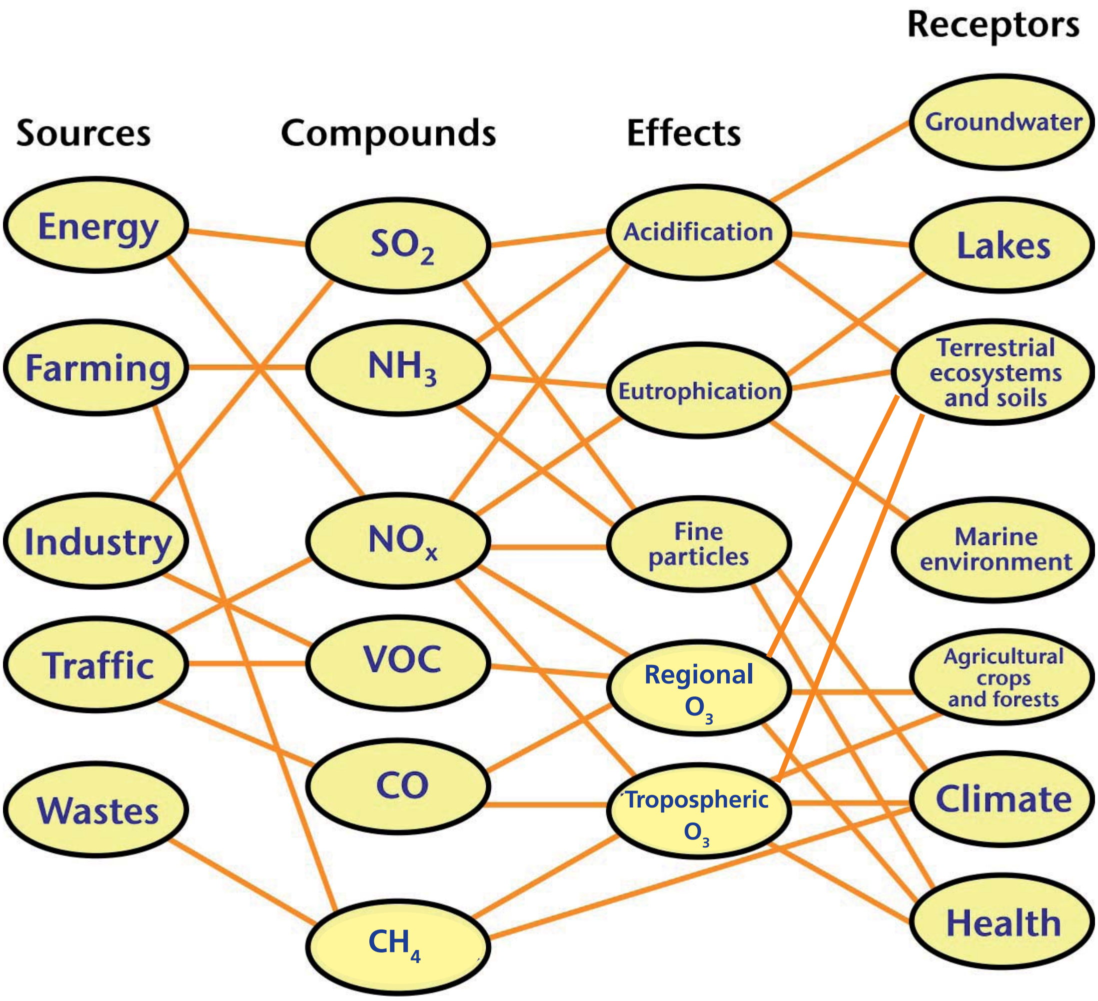
The reaction is reversible, so that PAN can dissociate to regenerate $CH_3CO_3 + NO_2$. This reaction occurs rapidly at the higher temperatures found near the surface, but if the PAN is lifted up to higher altitudes and lower temperatures, then its lifetime increases considerably and it can be transported large distances. As it subsides to lower altitudes, it dissociates and provides a source of NO_X in locations that may be well removed from direct anthropogenic pollution.

2.5 Air quality issues and links to climate change

2.5.1 Local and regional pollution controls and their ramifications for climate change

77. In principle, any pollutant that contributes to both local and regional pollution problems and also acts as a radiative forcing agent or changes the distributions of radiative forcing agents, may potentially produce a linkage between AQ and CC issues. Figure 2.15 shows some of the potential linkages.

Figure 2.15: Examples of some of the potential linkages between regional air quality and climate changes issues (after Grennfelt *et al*. (1994))



78. Black carbon and black smoke (BS) are local and urban scale pollutants and radiative forcing agents. Black smoke is a product of incomplete combustion and contributes to health effects in urban and industrial centres. Black carbon has been identified as a global warming agent because it absorbs solar radiation (Haywood and Shine, 1997; Chylek *et al*., 1996). Actions taken to reduce emissions of BS on the urban and regional scales will therefore reduce global warming and make CC goals more achievable. Furthermore, because of the short atmospheric lifetime of BC, the impact of emission reductions on radiative forcing is more or less instantaneous.

79. The linkages between BS and AQ and BC and the positive forcing of CC are important issues in the context of the environmental consequences of petrol versus diesel car usage. The CC consequences of CO_2 emissions are only one aspect that needs to be taken into account in evaluating these competitive vehicle technologies. A further CC issue is the radiative forcing from the BC emissions (Jacobson, 2002).

80. The linkages between BS, AQ and climate forcing are also relevant in the discussion of AQ problems in Asia. The use of biomass as a fuel for cooking and space heating in Asia has important consequences for indoor AQ and human health (Smith *et al*., 2002). There is also the concern that BC emissions, from this

and other sources, perturb the passage of solar radiation through the atmosphere and that, in addition to radiative forcing at the top of the atmosphere, there are also changes in surface radiation, evaporation and precipitation patterns. This is the Atmospheric (Asian) Brown Cloud phenomenon. Again, actions taken to reduce BC emissions because of indoor and local AQ concerns should make global CC goals appear more achievable.

81. Sulphur dioxide emissions in Europe have caused widespread acidification of sensitive soil and freshwater ecosystems in areas such as Scandinavia and upland Britain. Sulphur dioxide is oxidised in the atmosphere and in cloud droplets to form particulate sulphate. Sulphate aerosol contributes a major anthropogenic cooling term in the climate system. Ammonium sulphate is an efficient scatterer of atmospheric radiation and drives visibility reduction and climate cooling. Without treating the formation of particulate sulphate from the burning of fossil fuels, particularly since the 1940s, it would be difficult for the global climate models to reproduce the global temperature records during the 20th century. Action to control SO_2 emissions to reduce regional scale acidification will necessarily lead to a reduction in this climate cooling term. Hence, action to control regional acidification will make CC goals appear less achievable (Charlson *et al.* 1992)).

82. Emissions of NO_X and NH_3 contribute to regional scale acidification and eutrophication across Europe. These emissions drive the deposition of oxidised and reduced N_2 compounds and increase plant growth and microbial activity particularly in N_2-limited ecosystems. The increased N_2 deposition may increase the growth rate of forests in N_2-limited ecosystems, and this is thought to have led to the increasing uptake of atmospheric CO_2 in northern hemisphere boreal forest ecosystems (Schimel, 1995). This increased sink for CO_2 is an important part of the global carbon cycle and is thought to account for a significant fraction of current man-made CO_2 emissions. However, in the longer-term, increased N_2 deposition may have negative effects on forest growth because of nutrient imbalances and decreased stress tolerance. Hence, measures to reduce European NO_X and NH_3 emissions, because of concerns about regional scale eutrophication and acidification, need to be carefully evaluated in terms of their long-term effects on the strength of the boreal forest sink for CO_2.

83. The enhanced regional scale deposition of oxidised and reduced N_2 compounds may also stimulate production of N_2O through nitrification-denitrification processes in soils. Nitrous oxide is an exceedingly long-lived trace constituent of the atmosphere that is also an important radiatively active trace gas with a GWP that is about 300 times that of CO_2. Actions taken on the regional scale to halt eutrophication may therefore reduce emissions of N_2O and hence may make CC goals more achievable.

84. Background O_3 concentrations are rising and are influenced by global man-made CH_4 emissions. Methane emission controls would help meet both CC and AQ goals everywhere in the northern hemisphere (Fiore *et al*., 2002).

85. There is much current action within Europe, North America and Asia to control the emissions of the major urban and regional scale O_3 precursors, VOCs and NO_X. These precursors, in addition to CH_4 and CO, also take part in tropospheric chemistry on the global scale. This chemistry establishes the tropospheric distribution of OH, which provides the main removal process for CH_4 (the second most important GHG after CO_2). Actions taken to control urban and regional O_3 formation will necessarily influence the global distribution of OH. If this action leads to reductions in man-made NO_X emissions that are not supplemented by significant reductions in man-made emissions of CO, CH_4 and VOCs, then tropospheric OH levels may decrease exacerbating the build-up in global CH_4 burdens and hence making CC goals less achievable.

86. The capacity of the global tropospheric chemistry system to produce tropospheric O_3 is immense and is controlled by the combined source strength of the man-made and natural sources of CH_4, CO and VOCs. Only a small fraction of this huge capacity is currently harnessed and this small fraction is controlled by the combined emissions of NO_X from man-made and natural sources (Crutzen, 1973). Since tropospheric O_3 makes the third most important contribution to GHG radiative forcing, after CO_2 and CH_4, regional NO_X emissions have important global consequences that follow on from regional O_3 formation and its subsequent intercontinental transport (Li *et al*., 2002). Actions taken on the regional scale to control NO_X emissions also affect CC by decreasing global O_3 formation; this will also be the case for regional scale actions to reduce CO and VOC emissions. Changes in NO_X emissions have other effects on CC, e.g. through the formation of nitrate aerosol. The net effect of NO_X on CC is difficult to assess; attempts to do so are discussed in section 3.2.1.2.

2.5.2 Climate change and its ramifications for local and regional air quality

87. In principle, any CC outcome that influences local and regional pollution problems may potentially produce a linkage between CC and AQ issues.

88. The global climate system responds to the radiative forcing introduced by the increasing burdens of the radiatively-active trace gases. This global system response will be experienced through changes in surface and atmospheric temperatures, changes in winds and the global circulation, clouds and precipitation, ice cover and ocean currents. The climate of the UK will change as a result of all of the myriad of responses within the global climate system. Confidence in our ability to describe and predict these responses is very limited.

89. It is highly unlikely that the frequency of wintertime pollution events in the UK will remain unchanged as a result of CC. Such pollution events brought the Great Smog of 1952 and the major pollution episode in London during December 1991. These events were associated with stable, calm and cold conditions, conditions that are anticipated to become less frequent in the UK as a result of global warming. It is likely that episodes of poor, wintertime AQ will become less frequent in the future and so CC may well make local and regional NO_2 and PM AQ goals become more achievable in the future (Anderson *et al*., 2001).

90. By the same arguments, it is highly unlikely that the frequency of summertime pollution events in Europe will also remain unchanged as a result of CC. The intense O_3 episodes in the UK during 1976 and in France and Switzerland during 2003 were brought on by sustained high temperature and drought conditions. Such conditions favour O_3 production and minimise O_3 destruction through the uptake by vegetation at the earth's surface. These conditions are anticipated to become more frequent as a result of global warming. Climate change may well make local and regional O_3 AQ goals become more difficult to achieve in the future (Anderson *et al*., 2001).

91. Regional acidification will also be influenced by CC (Alcarno *et al*., 2002). Climate change will bring about changes in the major weather systems that influence the patterns and intensity of rainfall. There will be impacts on the scavenging of the acidic pollutants that will drive changes in the acidic pollution loads (Langner *et al*., 2005). As precipitation patterns change, there will also be impacts on the deposition of base cations from wind-blown dusts. Sensitive catchments will also be impacted by changes in run-off and evaporation, and the frequency of drought events. Hence there will be CC impacts, not only on the rates of acidic deposition, but also on the capacity of ecosystems to buffer the incoming acidity. Changes in soil temperature and moisture content will also influence the N_2 cycle and may increase leaching of nitrate from soils (Posch, 2002). It is too early to tell, however, what the overall impact of CC will be on the soil and water acidification and eutrophication across Europe in response to decreased emissions of sulphate, nitrate and ammonium.

92. The climate of the Arctic is already being strongly influenced by man-made CC. A wide range of toxic and persistent substances, including PCBs and mercury, have been steadily accumulating in cold, wet Arctic ecosystems as a result of decades of human activities at lower latitudes. As the Arctic climate changes, there may be potentially a change in the behaviour of the persistent organic pollutants (POPs) and mercury which could change the global circulation of these substances.

93. As the global climate system responds to increased radiative forcing, atmospheric temperatures will inevitably rise and with them there will be increases in humidity and water vapour mixing ratios. Increases in water vapour mixing ratios will lead to an increases in the photolytic source of OH from O_3. In turn, this will increase the oxidising capacity of the troposphere, decrease the build-up in the global CH_4 burden and hence provide a negative feedback on CC. In regions close to NO_X emissions, this increase in the photolytic source of OH will stimulate O_3 production and exacerbate regional O_3 AQ problems. In remote regions, such as over the oceans, the increase in the photolytic source of OH will lead to increased O_3 destruction, lower global burdens of tropospheric O_3 and a negative feedback on CC.

94. What are more difficult to assess are the ecosystem responses to CC. The physical changes in terms of atmospheric CO_2 concentration, surface and atmospheric temperatures, rainfall amounts and radiation will induce biological responses in terms of changed growth, pests and competition with other species, and soil microbial activity that ultimately will drive ecosystem responses. The ecosystem responses will drive changes in the natural biogenic emissions of trace gases such as isoprene and the terpenes, and these may impact upon the oxidising capacity of the troposphere and the distribution of tropospheric O_3. Because of the efficient intercontinental and interhemispheric transport of O_3, there may be impacts on regional AQ as a results of this ecosystem feedback on CC.

95. In addition, CC mitigation measures may have local and regional AQ consequences. For example, the hydrogen economy may ultimately displace fossil fuel combustion and lead to significant improvements in local and regional AQ. However, increasing reliance on biofuels and biomass may result in increasing soil emissions linked to the fertiliser applications required for high production rates, and increasing biogenic emissions, depending on which species and cropping systems that are used. These emissions may have impacts on eutrophication and O_3 formation.

Chapter 2

Scientific background

2.1 Introduction

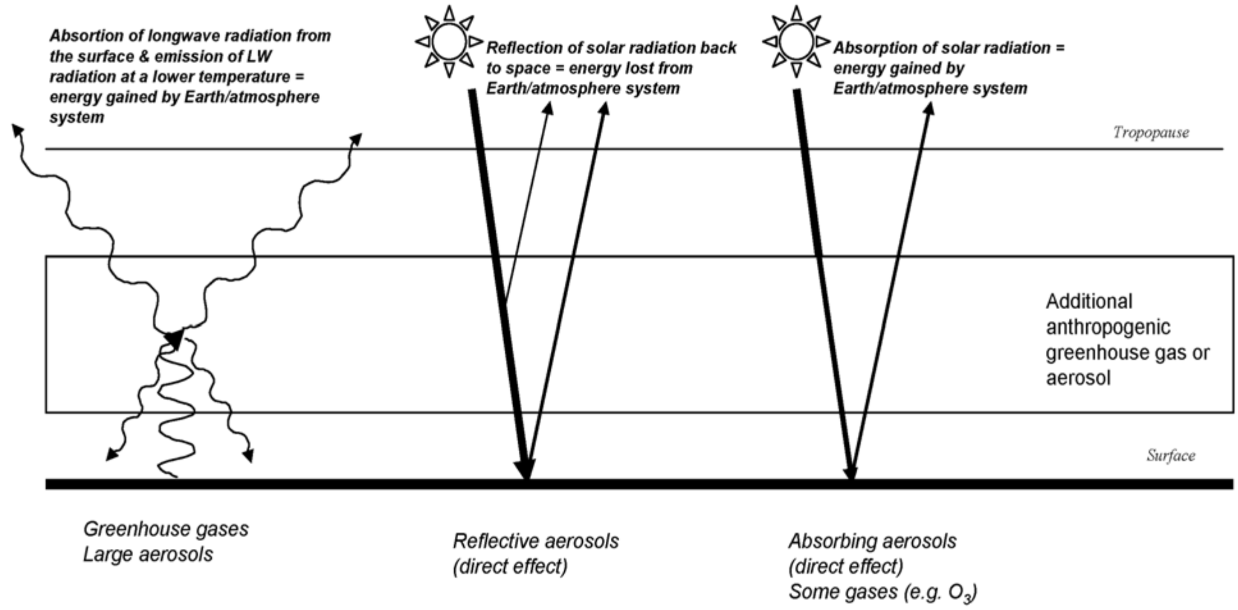
15. The aim of Chapter 2 is to provide an overview of the scientific background necessary for an appreciation of the issues discussed in the main body of the report. The subsequent chapters provide answers to the questions raised in Chapter 1. Section 2.2 addresses climate change (CC) itself, by introducing the concepts of radiative forcing and global warming potential (GWP); a brief overview of contributions of the main greenhouse gases (GHGs) and of aerosols is also given. Section 2.3 discusses climate models, including their basis, methodology and evolution. Important aspects of such models are the chemistry and emissions components. For this report, the relationships between emissions scenarios used for climate modelling and the inventories used for air quality (AQ) purposes are particularly relevant and are briefly introduced here and amplified in Chapter 5. One of the key functions of global climate models is the quantification of feedbacks, and a brief outline is given; the issue of the prediction of regional CC, while difficult, is central to the concerns of this report. Section 2.4 outlines the chemistry occurring in the troposphere that is relevant to CC; the section emphasises the links between CC and AQ considerations, particularly through the formation of ozone (O_3) from volatile organic compounds (VOCs) and nitrogen oxides (NO_X). The final section examines the general issues linking AQ and CC, introduces the ideas behind impacts in both directions – of local and regional pollution controls on CC and of CC on local and regional AQ – and provides a number of examples. Annex 2 gives a brief summary of the main units of gaseous concentration used in this report.

2.2 Climate change

2.2.1 Radiative forcing

16. The temperature of the Earth's atmosphere is determined by the balance of the radiation absorbed by the atmosphere and the surface against the radiation emitted (Figure 2.1). Radiative forcing is defined as the change in the net radiation balance at the tropopause caused by a particular external factor in the absence of any climate feedbacks. These forcing mechanisms can be caused by a change in the atmospheric constituents such as the increase in GHGs or aerosols due to anthropogenic activity, or by changes in other components of the Earth/atmosphere system such as changes in the surface albedo (the fraction of incoming radiation that is reflected). Albedo changes are caused, e.g., by changes in vegetation (e.g. burn scars or agriculture).

Figure 2.1: Schematic diagram showing the mechanisms of the radiative forcing due to greenhouse gases and of the direct radiative forcings due to aerosols



17. Many of the gases, particulate matter (PM, aerosols) and PM precursors emitted by human activity that are traditionally associated with AQ also interact with solar or terrestrial radiation and therefore exert a significant radiative forcing. The most important GHG, in terms of its radiative effect on the atmosphere, is water vapour, but its concentration and distribution in the troposphere is influenced mainly by physical processes, such as evaporation, and is not significantly affected by anthropogenic activity. Figure 2.2 shows the main contributors to radiative forcing, based on changes since 1750 (IPCC, 2001a). The natural contribution arising from changes in solar radiation is also shown for comparison.

18. Gases such as carbon dioxide (CO_2), O_3 and methane (CH_4) absorb terrestrial radiation emitted by the surface and lower regions of the atmosphere and emit radiation at a lower temperature. Some of the emitted radiation is transmitted back towards the Earth's surface via the well-known greenhouse effect. The magnitude of the greenhouse effect of a specified gaseous component is dependent on its absorption wavelength and on the temperature difference between the surface/lower regions of the atmosphere and the radiation emission temperature. The altitude of the absorbing/emitting gaseous species is therefore important because the species is generally at a lower temperature at a higher altitude. Therefore a molecule of a particular GHG will generally exert a stronger radiative forcing at higher altitudes than if the molecule were at lower altitudes.

19. The distribution of gaseous components in the atmosphere depends on the homogeneity of their emissions and on the lifetime of the pollutant. Thus long lived compounds such as CO_2, CH_4, nitrous oxide (N_2O) and many halocarbons are homogeneously mixed, even though they are not evenly emitted. Ozone, on the other hand, is much shorter-lived and its distribution is inhomogeneous. Since it is a secondary pollutant, its distribution also depends on where its precursors are emitted and on the timescale of its formation, as well as on its lifetime.

20. Aerosols can scatter and absorb solar and terrestrial radiation, therefore perturbing the energy balance of the Earth/atmosphere system (*direct* radiative forcing, Figure 2.1). Scattering aerosols reflect a proportion of incident solar radiation back to space causing a net loss of energy from the Earth/atmosphere system and are associated with a negative radiative forcing and a cooling of the atmosphere. Absorbing aerosols cause a net gain in energy for the Earth/atmosphere system and are associated with a positive radiative forcing and a warming of the atmosphere. The aerosol *indirect* radiative forcing arises because aerosols act as cloud condensation nuclei and can therefore modify the microphysics, radiative properties, precipitation efficiency, and lifetime of clouds (Figure 2.3). The aerosol *semi-direct effect* is the mechanism whereby absorption of solar radiation by aerosols modifies the atmospheric temperature and humidity structure thereby reducing the cloud amount.

Figure 2.2: Global-average relative forcing (RF) estimates and ranges in 2005 (relative to 1750) for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other important agents and mechanisms, together with the typical geographical extent (spatial scale) of the forcing and the assessed level of scientific understanding (LOSU), (IPCC, 2007)

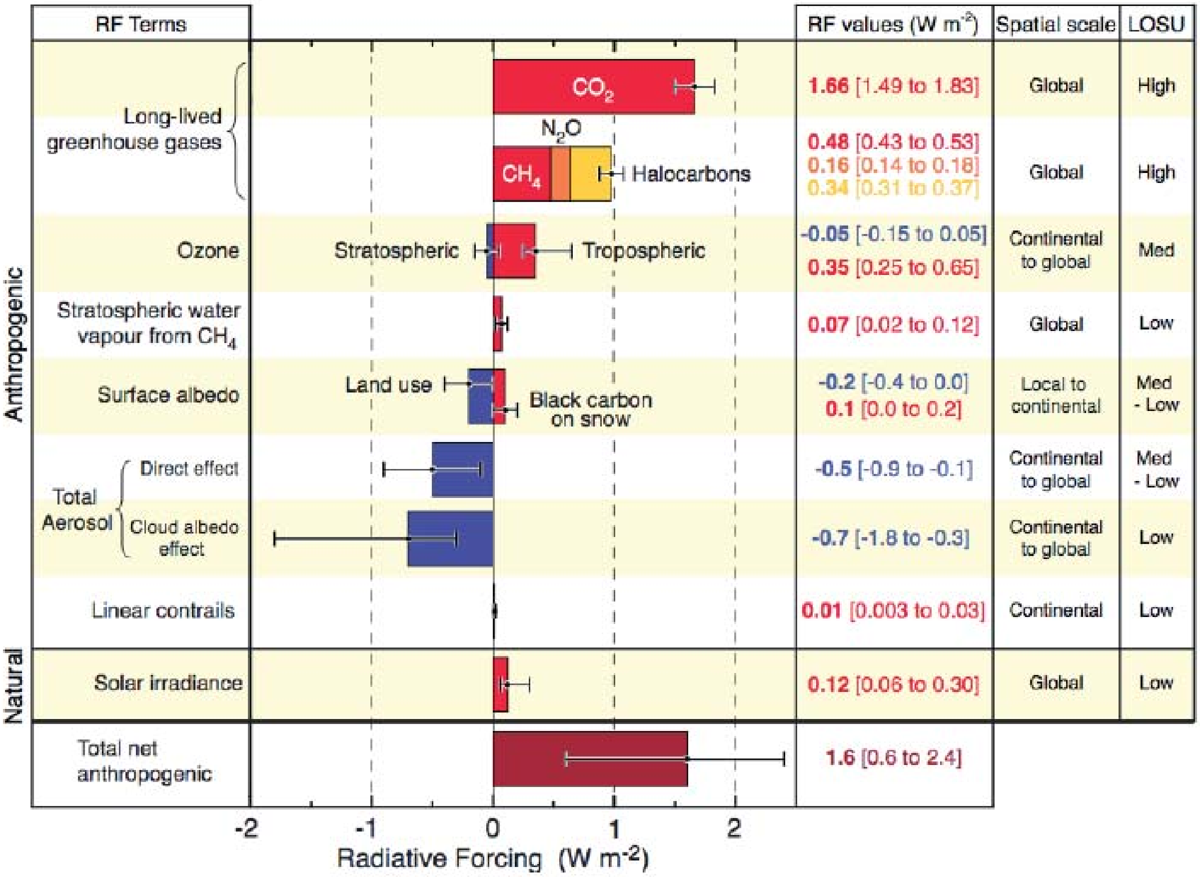
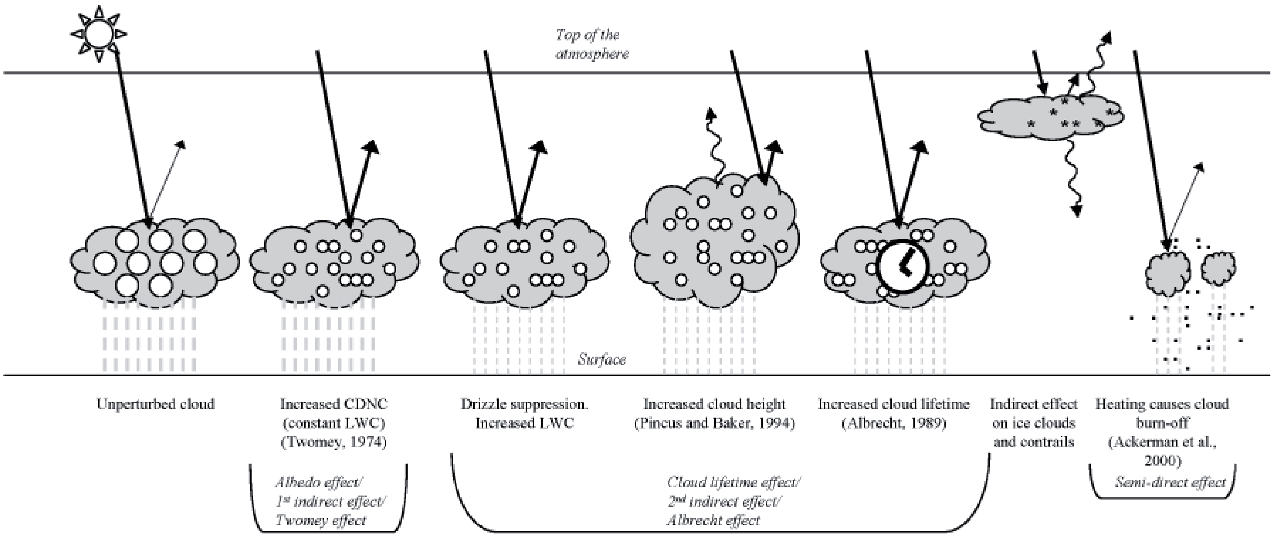


Figure 2.3: Schematic diagram showing the mechanisms associated with the indirect effects. Modified from Haywood and Boucher (2000). (CDNC = Cloud Droplet Number Concentration; LWC = Liquid Water Content (of cloud))



2.2.2 Quantification of radiative forcing and Global Warming Potentials

21. The utility of radiative forcing as a measure of potential CC comes from many early studies using energy balance, and slab ocean-atmosphere global models (e.g. WMO, 1986). These studies showed that the global equilibrium surface temperature change, dT_{global}, could be related to the radiative forcing, dF_{global}, by the climate sensitivity parameter, λ (units of K/(W m^{-2})), by the following relationship:

$$dT_{global} = \lambda \, dF_{global}$$

22. These early studies suggested that, provided the stratosphere was allowed to adjust to a new radiative equilibrium, the climate sensitivity was essentially independent of the forcing mechanism. Thus, while the climate sensitivity may differ from model to model, the relative importance of a particular anthropogenic perturbation to the climate system may be assessed in any of these models by calculation of the radiative forcing. The radiative forcing concept is therefore also valuable as it removes the need for full general circulation model simulations as the global mean temperature may be deduced solely from λ, and dF_{global}. However, more recent studies using models with improved representation of physical processes have shown that the constant climate sensitivity assumption for each individual forcing mechanism may not hold for some mechanisms such as that due to black carbon (BC) aerosol (e.g. Roberts and Jones, 2004; Hansen *et al.*, 2002). This realisation has led to the concept of climate efficacy, ε, which is the ratio of the climate sensitivity for the particular forcing mechanism to that for CO_2:

$$\varepsilon = \frac{\lambda_{forcing}}{\lambda_{CO2}}$$

23. Forcing mechanisms with a high ε will produce a higher global temperature change per unit radiative forcing than those with low ε. The global temperature change, dT_{global} is then defined as:

$$dT_{global} = \lambda_{CO_2} \varepsilon \, dF_{global}$$

24. It is important to realise that radiative forcing has always been essentially a *globally integrated* quantity. Therefore the relationship between local radiative forcing and local climate response cannot be deduced from this relationship.

25. The climate sensitivity, λ_{CO_2}, differs between climate models because the strength of feedbacks differs between models. Feedback mechanisms may be thought of as specific responses inherent within the models. For example, anthropogenic CO_2 exerts a positive radiative forcing which warms the atmosphere; a warmer atmosphere can hold more water vapour which is itself a GHG and therefore the warming will be enhanced. A climate feedback process that acts to enhance the original effect is known as a *positive feedback*. A climate feedback process that acts to reduce the original effect is known as a *negative feedback*. Several feedback mechanisms such as those involving water vapour, cloud and snow/ice albedo have been identified as being important within climate models.

26. The GWP provides a measure of the relative potential impact of emissions of a particular substance upon global climate. Global Warming Potentials are defined as the ratio of the time integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that for a reference gas, normally CO_2 (Ramaswamy *et al*., 2001). Global Warming Potentials are calculated for different time horizons, to provide a measure of the effect of the lifetime of a particular gas. When the lifetime of a particular gas is similar to that of CO_2, the GWP is relatively insensitive to the choice of time horizon, but when the atmospheric lifetime differs considerably, then the choice of time horizon becomes important. Ramaswamy *et al*. (2001) chose time-horizons of 20, 100, and 500 years when presenting the GWPs to emphasise this point in considering the potential impact of emissions of a particular substance upon global climate. The 100 year version has been accepted for use in the Kyoto protocol.

27. Global Warming Potentials are defined by the equation:

$$GWP = \frac{\int_0^{TH} a_x [x(t)] dt}{\int_0^{TH} a_{CO_2} [CO_2(t)] dt}$$

where TH represents the time horizon, ax the radiative efficiency due to a unit increase in the atmospheric abundance of a substance (in W m^{-2} kg^{-1}), and [x(t)] is the time-dependent decay of the atmospheric abundance following instantaneous release of that substance.

28. Table 2.1 shows GWPs on a 100 year horizon for some well-mixed GHGs and also includes their GWP-weighted emissions, showing that, when emissions are taken into account, CO_2 has a greater impact on radiative forcing than CH_4, despite its smaller GWP. The effect of the time horizon on GWPs can be gauged by reference to CH_4, the shortest-lived compound in Table 2.1, which has a 20 year GWP of 62 and a 500 year GWP of 7 and to the longer-lived compound CFC-115, which has a 20 year GWP of 4900 and a 500 year GWP of 9900.

Table 2.1: Examples of Global Warming Potential for various well-mixed Greenhouse gases. Adapted from Ramaswamy *et al*. (2001)

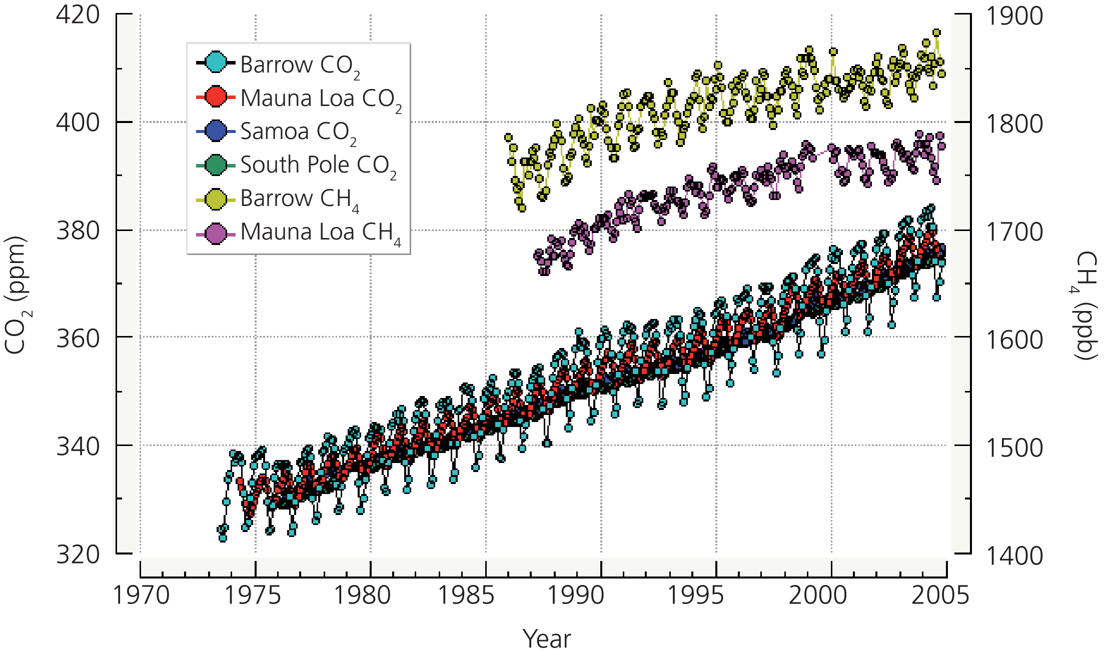
Gas		Radiative efficiency ($W\ m^{-2}\ ppb^{-1}$)	Lifetime (years)	GWP (100 year horizon)	GWP-weighted emissions (10^9 tonne y^{-1})
Carbon dioxide	CO_2	1.5×10^{-5}	150	1	24
Methane	CH_4	3.7×10^{-4}	12[a]	23	14
Nitrous oxide	N_2O	3.1×10^{-3}	114[a]	296	8
CFC-115	CF_3CClF_2	0.18	1700	7200	0.01
HCFC-142b	CH_3CClF_2	0.20	19	2400	0.07
HFC-23	CHF_3	0.16	260	12000	0.08

[a] The timescales for CH_4 and N_2O are their *adjustment* timescales and not the lifetimes, since the former is a better measure of the persistence of an emission pulse of these gases

2.2.2.1 Carbon dioxide

29. Before 1750, the mixing ratio of atmospheric CO_2 was approximately 280 ± 10 ppm ($512 \pm 18\ mg\ m^{-3}$), but has risen steadily since then to a concentration of around 380 ppm ($695\ mg\ m^{-3}$) in 2005 due to direct anthropogenic emissions (Figure 2.4). Around 75% of these emissions are from anthropogenic fossil-fuel burning with the remainder being due to land use change including biomass burning. Because CO_2 concentrations are relatively well-mixed the radiative forcing that is exerted is relatively homogeneously distributed across the globe, although it is slightly larger in the tropics and slightly smaller at high latitudes. From Figure 2.2 it can be seen that the radiative forcing in 2005 (i.e. the change owing to the increase in the CO_2 concentration since 1750) is estimated to be $1.66\ W\ m^{-2}$, which is an increase of $0.2\ W\ m^{-2}$ on its value for the year 2000 reported by Ramaswamy *et al*. (2001), an increase that is mainly due to the continued rise in atmospheric CO_2 concentrations in the intervening time period. The GWP of CO_2 is necessarily 1 whatever the timescale given, because it is the reference trace gas.

Figure 2.4: Carbon dioxide and methane mixing ratios versus time from a number of monitoring stations. (NOAA Climate Monitoring and Diagnostics Laboratory http://www.cmdl.noaa.gov/ccgg/insitu.html)



2.2.2.2 *Methane*

30. The mixing ratio of CH_4 (1778 ppb (1191 μg m^{-3}) in 2004 according to a global network of measurements performed by NOAA Climate Monitoring and Diagnostics Laboratory (CMDL)) is also increasing, although the rate has slowed in recent years (Figure 2.4). Methane has a range of sources, both natural and anthropogenic. The change from the pre-industrial concentration of 715 ppb (479 μg m^{-3}) to the 2004 value of 1778 ppb (1191 μg m^{-3}) gives a radiative forcing of 0.48 W m^{-2}. The GWP is stronger than that for CO_2 owing to the stronger radiative efficiency, but the GWP decreases as longer time horizons are considered because its atmospheric residence time is shorter than that of CO_2 (Table 2.1). Methane has a shorter atmospheric lifetime than CO_2 and, although still quite well-mixed, its concentration shows greater variation between monitoring sites (Figure 2.4).

31. Methane is removed from the atmosphere mainly by reaction with the hydroxyl radical (OH), whose concentration is affected by emissions of VOCs and NO_X. Thus, in addition to direct emissions of CH_4, anthropogenic emissions of VOCs and NO_X can respectively increase and decrease the atmospheric CH_4 burden. Positive and negative indirect GWPs can therefore be ascribed to VOCs and NO_X (Derwent *et al*., 2001; Collins *et al*., 2002) (see Chapter 3). Similarly CH_4 itself has an indirect GWP through its effect on its own removal rate and on tropospheric O_3 production.

2.2.2.3 Nitrous oxide

32. Estimates of N_2O mixing ratios show an increase from a pre-industrial value of around 270 ppb (494 µg m^{-3}) (Prather *et al.*, 2001) to 318 – 319 ppb (582 – 584 µg m^{-3}) in early 2004; recent increases of 0.2 to 0.3% per year have been measured. The primary mechanism for the increase in N_2O concentrations is thought to be enhanced microbiological production in expanding and fertilising agricultural lands (Prather *et al.*, 2001). The radiative forcing due to N_2O in 2005 was reported to be 0.16 W m^{-2} (IPCC, 2007), which is similar to the 0.15 W m^{-2} reported for 2000 by Ramaswamy *et al*. (2001). The GWP is larger than for CO_2 no matter what time horizon is considered because the radiative efficiency is higher and the atmospheric lifetime longer than those for CO_2 (Table 2.1).

2.2.2.4 Halocarbons

33. Halocarbons consist of several different types of compounds such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), which are emitted entirely by anthropogenic activities. CFC-11, CFC-12, CFC-13, HCFC-22, and CCl_4 are of particular importance because the increase in their concentrations from a pre-industrial value of zero to 268 ppt, 533 ppt, 4 ppt, 132 ppt, and 102 ppt respectively (1998 concentrations) leads to radiative forcings of 0.07 W m^{-2}, 0.17 W m^{-2}, 0.03 W m^{-2}, 0.03 W m^{-2} and 0.01 W m^{-2} respectively (Ramaswamy *et al.*, 2001). All other halocarbons have been estimated to exert radiative forcings of <0.01 W m^{-2} (e.g. CFC-115, 7 ppt, 0.001 W m^{-2}; HFC-23; 14 ppt, 0.002 W m^{-2}) although when summed together they may exert a radiative forcing of a few tenths of a W m^{-2}. As shown in Figure 2.2, IPCC (2007) reported the direct radiative forcing due to changes in halocarbons since 1750 to be 0.34 W m^{-2}. As noted in Table 2.1, the GWPs of halocarbons tend to be extremely high because of their low background concentrations and their inherent infra-red absorbing properties coupled with the long lifetimes of these molecules.

2.2.2.5 Tropospheric ozone

34. Tropospheric O_3 is a GHG; however it is not directly emitted from anthropogenic activities. This means that it cannot itself be assigned a GWP. Ozone is formed in the troposphere by photochemical reactions involving NO_X (Nitric oxide (NO) and Nitrogen dioxide (NO_2)) and VOCs. These precursor species have direct anthropogenic emissions to the atmosphere and therefore indirectly contribute to global warming through the O_3 they produce. Calculating the effect of NO_X and VOC emissions on tropospheric O_3 levels is a complex problem requiring sophisticated 3-dimensional chemistry transport models. The assessment of these indirect effects is discussed in section 3.2.1.2.

35. Early measurements of O_3 were made at the surface in the 19th Century (e.g. Volz and Kley, 1988). These show an approximate doubling of concentrations between the pre-industrial and present day. Unfortunately it is not possible to use surface data to reconstruct the O_3 concentrations throughout the troposphere. Ozone is most effective as a GHG in the upper troposphere (Lacis *et al.*, 1990) so to determine the present day radiative forcing of O_3 due to anthropogenic emissions of precursors, chemical transport models must again be used. From a comparison

of ten chemistry transport models, Gauss *et al*. (2006) calculated a radiative forcing due to O_3 since pre-industrial times of 0.36 ± 0.07 W m^{-2}. IPCC (2007) estimated that in 2005, tropospheric O_3 changes due to emissions of O_3-forming chemicals contributed to a radiative forcing of 0.35 W m^{-2}, whilst stratospheric O_3 resulted in a radiative forcing of -0.05 W m^{-2} (Figure 2.2).

2.2.2.6 Aerosol

36. The aerosol direct radiative effect has been approximately quantified for sulphate aerosol, biomass burning aerosol, fossil-fuel organic and fossil-fuel BC aerosols, and mineral dust (Penner *et al*., 2001). In addition, the radiative forcing due to nitrate aerosol has recently been quantified, as has the effect of BC deposition onto snow surfaces. However, considerable uncertainty still exists with regard to the magnitude (and even sometimes the sign) of the radiative forcing due to aerosols. The Aerosol Comparison Project (AEROCOM) was set up to address these uncertainties and provide a comprehensive assessment of the inter-model variability of the aerosol optical depths and direct radiative forcing due to various aerosol components (Kinne *et al*., 2005). IPCC (2007) reported that anthropogenic contributions to aerosols (primarily sulphate, organic carbon, black carbon, nitrate and dust) together produced a cooling effect, with total direct radiative forcing of -0.5 W m^{-2} and an indirect cloud albedo forcing of -0.7 W m^{-2} (Figure 2.2).

2.3 Climate modelling

2.3.1 Climate models

37. We can determine the effects of past CC by analysing direct temperature measurements and temperatures inferred from proxy data. However, the climate system (Figure 2.5) includes many different components and is therefore too complicated to allow simple extrapolations into the future using past observational data. One way to predict how the climate might change in the future is to construct mathematical models of the climate system that represent as many of the known relevant physical processes as possible. The most sophisticated of these climate models incorporate three-dimensional general circulation models (3D GCMs) of the atmosphere and oceans.

38. General Circulation Models are constructed by dividing the atmosphere into hundreds of thousands of boxes (Figure 2.6) usually on a regular rectangular grid. The physical equations that govern the evolution of such quantities as temperature, moisture and momentum are solved for each of these grid boxes in turn and are updated on timescales of typically 30 minutes. The size of the grid spacing is determined by a compromise between resolving the finer-scale processes in the atmosphere and the length of time taken for the computer to run the model. The atmospheric parts of climate models have a very similar construction to the models used for weather forecasting. However, because the climate models need to be run for hundreds of years rather than a few days, the grid resolution needs to be much coarser than that used, e.g. for weather forecasts. A typical climate model has a horizontal resolution of around 150 km.

This is sufficient to resolve large-scale weather systems, but not to resolve smaller-scale features such as clouds. The vertical resolution of climate GCMs usually varies with height from a few tens of metres near the surface to a few kilometres in the upper atmosphere. Clouds, turbulence, convection and other small-scale features which are too small to be resolved explicitly are parameterised. This means that the model includes equations accounting for their average effects on the large-scale dynamics rather than explicitly simulating the physics of the features themselves.

Figure 2.5: A schematic view of the climate system. The numerous components that comprise the system introduce a large degree of complexity

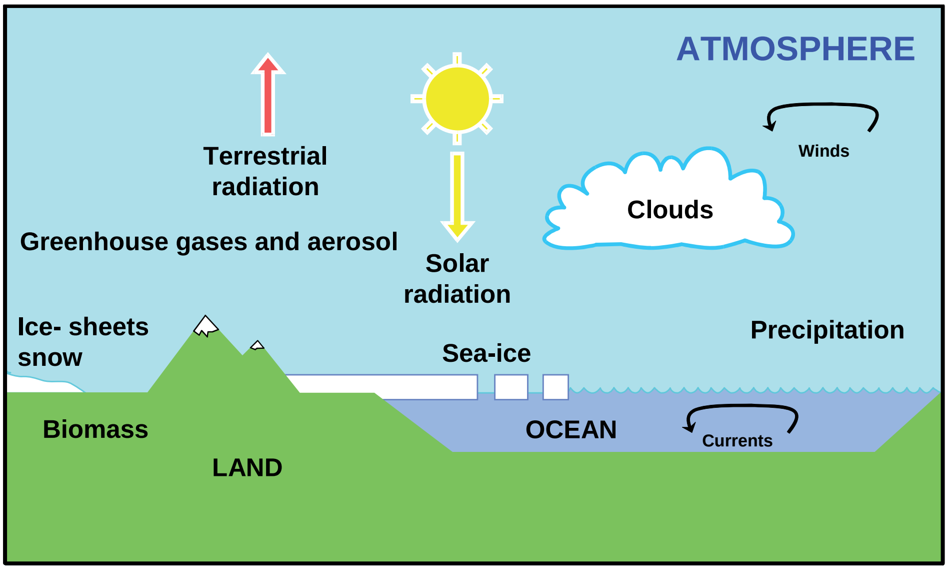
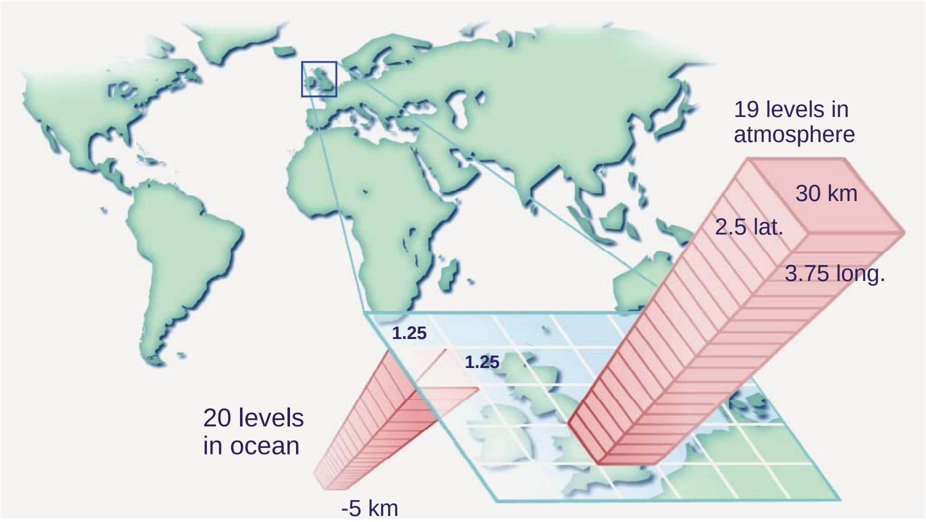


Figure 2.6: Schematic depiction of an atmosphere-ocean General Circulation Model. The details refer to the Hadley Centre model HadCM3 that was used for the IPCC Third Assessment Report



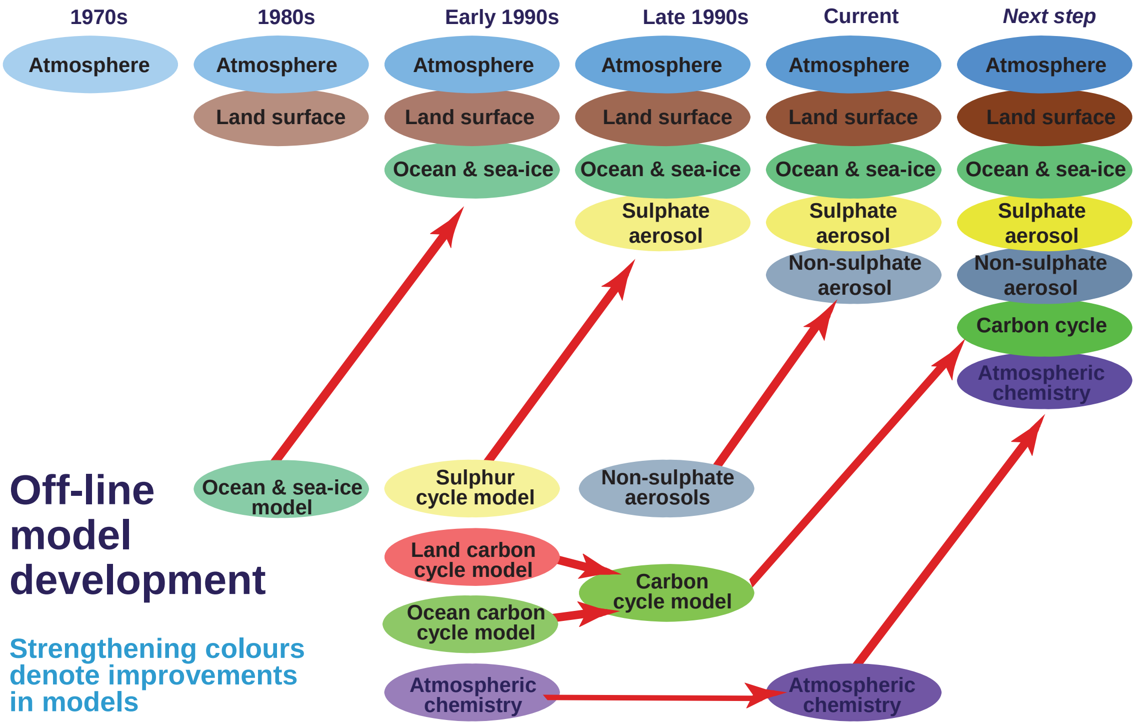
39. The effect of GHGs and aerosols on the atmosphere is simulated by the climate model's radiation scheme. This scheme divides up the spectrum of radiation from the sun into a few small wavelength bands that cover the range from the ultra-violet through the visible to the infra-red. The absorption, scattering and emission of this radiation lead to heating and cooling of the model's atmosphere and surface.

40. Where climate models differ most noticeably from weather forecasting models is that they need to include components of the climate system that are practically unchanging over the few days of a forecast, but change considerably over the hundreds of years of a CC experiment. The most important of these is the ocean. The ocean exchanges heat, water and CO_2 with the atmosphere and because of its large mass and heat capacity, it slows the response of the climate system to changes in forcing. The ocean is also the main driver of climate variability on timescales of decades to centuries. Ocean models are constructed in a similar way to the atmospheric GCMs. The resolution of ocean models tends to be higher than that of atmospheric models since the spatial scale of dynamical features is smaller in the ocean. Typical ocean model resolutions are around 100 km horizontally and 100 m vertically. The atmosphere and ocean models are coupled together as sub-models of the overall climate model, sometimes called an atmosphere-ocean GCM (AOGCM) to allow the exchange of information on heat, momentum and other variables. The coupling timescale is usually the same as the atmospheric timestep, about 30 minutes.

41. As climate models become more sophisticated (Figure 2.7), they now include modules to enhance their representation of the real world. For example land and ocean ice modules permit the extent of the ice cover to vary dynamically with the climate; carbon-cycle modules interactively represent the exchange of CO_2 between the atmosphere, ocean, vegetation and marine organisms; and dynamic vegetation modules allow the vegetation cover and type to evolve in response to a changing climate.

42. Of particular relevance to this report is the inclusion of modules to simulate the atmospheric composition of aerosols and GHGs that are chemically reactive. Nearly all climate models include an interactive sulphur cycle in which anthropogenic and natural emissions of SO_2 and dimethyl sulphide (DMS) are oxidised to sulphate aerosol. Other aerosol components are now being included in climate models such as anthropogenic BC and natural mineral dust. These aerosol schemes are necessarily highly simplified to reduce the computing time needed for long climate simulation. They thus lag a long way behind the sophisticated aerosol models used as research tools.

Figure 2.7: The increasing sophistication of climate models. The modules are usually developed offline before being coupled fully into the climate model. The timeline is only approximate and refers to the times when sub-models were (or will be) incorporated into a climate centre's standard climate prediction runs, rather than simply being coupled for research purposes



43. Apart from simplified schemes to generate sulphate aerosol, reactive chemistry schemes have not yet been implemented in operational climate models. Instead, the concentrations of reactive radiatively active gases are read in from data files generated by separate chemistry models. These gases include CH_4, N_2O, O_3 and HCFCs. By failing to simulate the chemicals interactively, the models are, firstly, not accounting for correlations between the chemical species and the meteorology in the model, and secondly, not allowing the changing climate to affect the chemical concentrations. Sophisticated chemistry models have been developed. These models tend to be designed to simulate the chemistry of either the stratosphere or the troposphere. There are few models that can simulate comprehensively the chemistry of both regions simultaneously. The stratospheric chemistry models are more advanced in that they are already run in a coupled mode, with the concentrations of the radiatively active gases interacting with the climate model's radiation scheme. Tropospheric chemistry models are usually run with one-way coupling: the meteorology affects the chemistry, but the chemical concentrations do not affect the radiation schemes. Both types of model are only run for short periods (up to a few decades) for research purposes. The major climate centres are currently trying to incorporate chemistry schemes into their operational climate models, but the computational expense of calculating all the chemical reaction rates means that some way of simplifying the chemistry is needed.

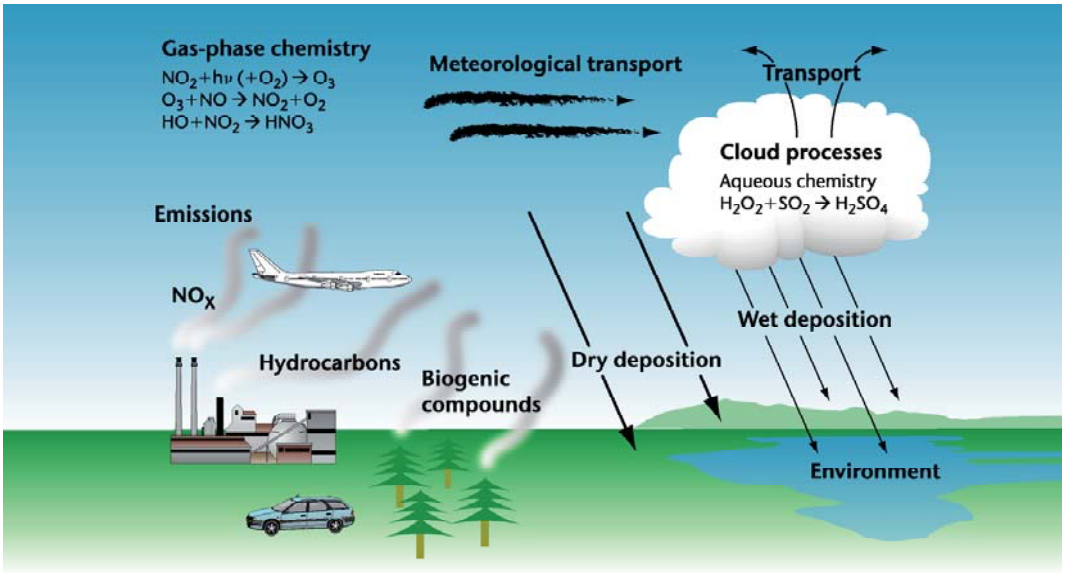
44. There are considerable uncertainties involved in modelling the climate. The most obvious is the limited spatial resolution. Climate models typically have a horizontal resolution of approximately 150 km compared to approximately 12 km resolution of the models used to forecast the UK weather. This means that important meteorological features such as frontal systems are poorly represented. These features can impact on the large-scale dynamics such as storm tracks and monsoon patterns. Similarly in the ocean, most current climate models cannot resolve the ocean eddies that, together with the atmospheric circulation, are responsible for the poleward transport of heat. Each 2-fold increase in resolution requires an 8-fold increase in computing power (since the timestep needs to be halved as well). Hence it will be many years before the amount of computing power available to climate modellers will allow them to model at sufficient resolution to capture these important processes. As mentioned earlier in this section, climate models try to represent processes they can not resolve by parameterisations. These can only be approximate representations, but are often tested against very high resolution large-eddy simulations or cloud-resolving models to quantify the effect of the approximation. There are other processes, such as the nucleation of ice particles by aerosols that are not represented at all in climate models because the underlying science is poorly understood. It is highly likely that there are processes not yet discovered that may be important in the Earth-Climate system.

2.3.2 Atmospheric chemistry models

45. To study the effects of atmospheric chemistry on climate and vice-versa, chemistry transport models are often used. These usually have a similar format to the climate models, in that the atmosphere is divided up into grid points and the calculations that predict the evolution of the chemical species are carried out for each grid point in turn every timestep. These calculations involve the transport (advection) of chemical species, emission of species, their chemical reactions and their removal at the surface via the processes of dry deposition wet deposition (precipitation) (see Figure 2.8).

46. The simplest chemistry models only include the chemistry of the NO_X, O_3, CH_4 and carbon monoxide (CO) – a total of about 20 species. Complex chemistry models, such as used for simulating urban pollution, may need to treat over 100 species. For global tropospheric chemistry-climate modelling, typically about 50 or 60 species are treated including higher hydrocarbons such as isoprene and its degradation products, and organic nitrogen compounds such as peroxyacetyl nitrate (PAN). Some include chemistry to form secondary aerosols from sulphur compounds and ammonia (NH_3) (around another 15 species), and from terpenes (around another 10 species). None of these models can represent all the important chemical species found in the atmosphere.

Figure 2.8: Schematic representation of the processes represented in an atmospheric chemistry model



47. The chemical schemes include both thermal and photolytic reactions (and aqueous reactions for the sulphur/ammonia chemistry). The photolysis rates are calculated using radiative transfer codes. These can either be pre-calculated and supplied as look-up tables to the model, or calculated interactively each timestep within the chemistry model.

48. The emissions from natural sources such as vegetation or lightning can be specified as fluxes from data files, but chemistry models are becoming more sophisticated in modelling these fluxes interactively based on the changing properties of the vegetation or convective clouds. Similarly, interactive schemes are being added to models whereby the rate of deposition of chemical species to the Earth's surface depends on the changing vegetation and soil properties.

49. Atmospheric chemistry models can either be run online or offline. In online models, the chemistry code is run within the climate model. This has the advantage that all the climate variables used in the climate model are accessible to the chemistry model, and that the radiatively active chemical species can feedback on the climate. The disadvantages are that the resolution of the chemistry model usually has to the be the same as the climate model, and the extra expense of running the climate model every time means longer computing times. Offline chemistry models (sometimes called chemistry transport models – CTMs) are run completely separately from the climate models. They get their climate information by reading in archived data files. This makes them quicker to run and allows them to be run at any desired resolution. However they require archiving of appropriate climate variables in the preceding climate model run, and hence need large amounts of data storage. It is rarely feasible to store these at the 30 minute resolution of the climate model, so the data are usually averaged over

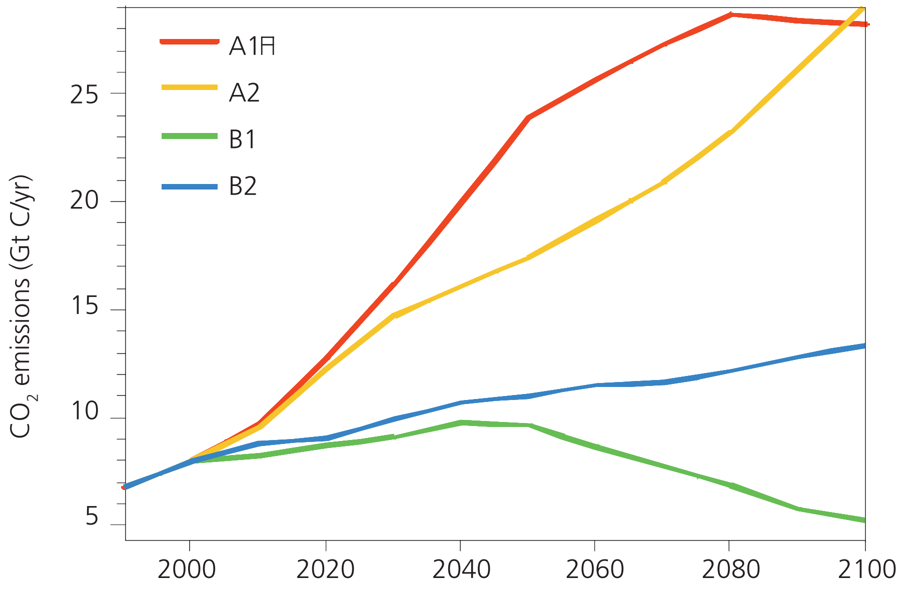
3 or 6 hours – losing information in the process. Detailed climate information such as convective transport is often not archived by the climate model. In this case the information has to be recreated inside the CTM by replicating the convective parameterisation code used by the climate model, but based on time-average driving data. Offline chemistry modelling is becoming less common as the sophistication of the chemistry models grows.

2.3.3 Emissions scenarios

50. Emission inventories are a fundamental part of most AQ and climate modelling, forecasting and policy assessments. They quantify the mass of a primary pollutant emitted from different sources over a period of time. Inventories are the means by which the relative importance of different sources to emissions of a given pollutant can be expressed and therefore allow an appreciation of how measures brought in to control one pollutant (e.g. an AQ pollutant) might affect another (e.g. a GHG).

51. However, inventories can vary in spatial scale and coverage (regional, national or local), in time and in sector allocation, depending on the purpose for which it was constructed. Many countries develop their own national emission inventories and these are generally constructed in a consistent manner. There are international obligations for countries to report emissions annually to bodies like the UN Framework Convention on Climate Change (UNFCCC), the UN Economic Commission for Europe (UNECE) and the EU following strict reporting guidelines in terms of definitions of emission sources. This offers the advantage that these countries' inventories are comparable and updated on a regular and consistent basis. However, the focus of these inventories is on national responsibility, so emissions from certain sectors that cross national boundaries such as international aviation and shipping are excluded, as are emissions from many natural sources. Separate, more global or regionally-based emission inventories are usually reported for these specific sectors by bodies looking beyond the national frame, but these are produced periodically and may not be updated on a regular basis. The future GHG emissions are commonly taken from the IPCC Special Report on Emission Scenarios (SRES). They are based on a variety of different assumptions about population, economic and technological growth. The variety in the assumptions leads to a large range of predicted future emissions. Predictions of CO_2 emissions from the four scenarios most commonly used by climate models are shown in Figure 2.9.

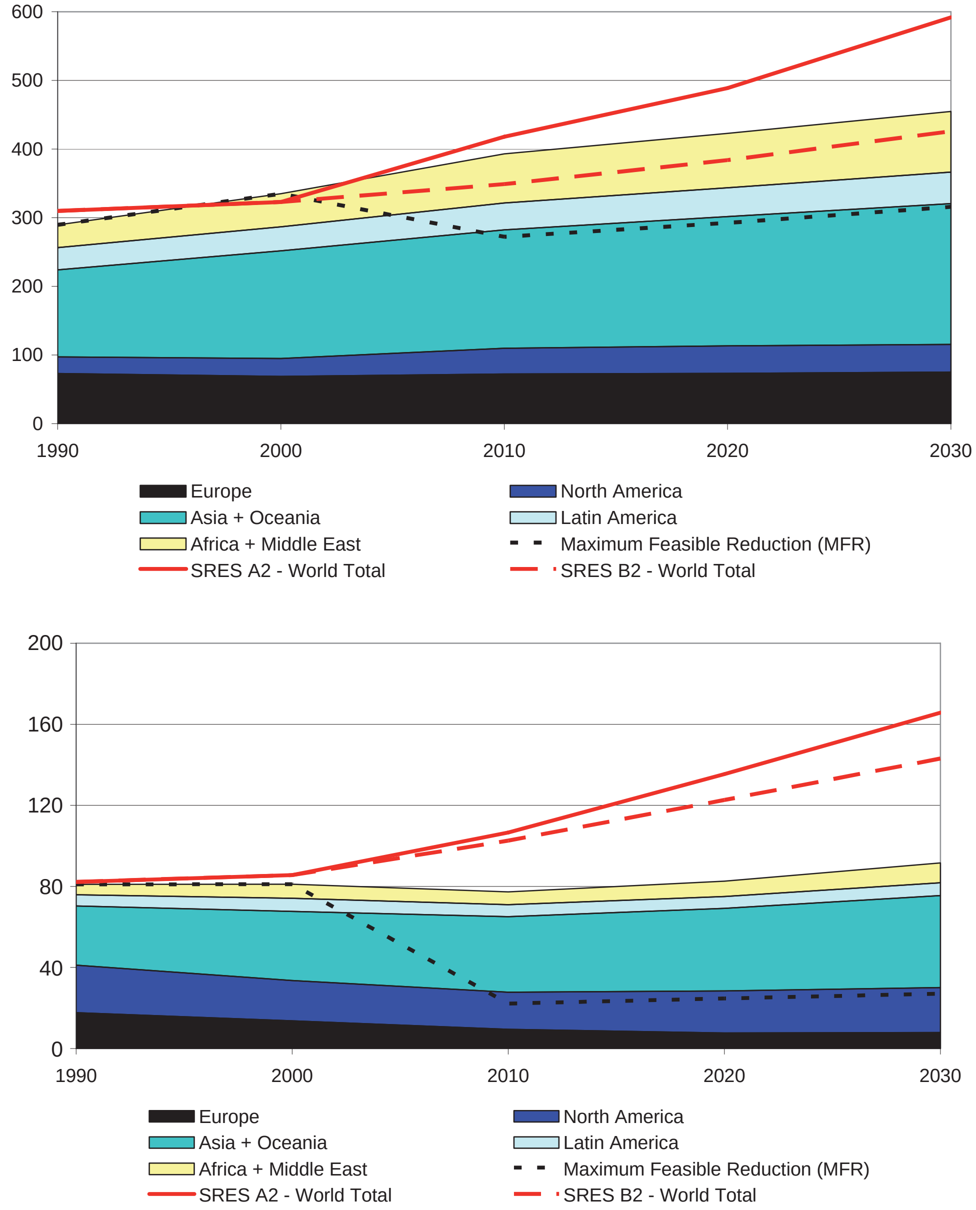
Figure 2.9: Predictions of future carbon dioxide emissions according to the four most commonly used SRES scenarios



52. Climate models use emission inventories and projection scenarios that are a composite of both national inventories and these more sector-specific inventories (e.g. aviation, shipping), e.g. the SRES projections. Air quality models generally use national inventories. Inventories and projections developed by the International Institute for Applied Systems Analysis (IIASA) covering different regions (e.g. Europe, Asia, North America) are used in both AQ and climate models.

53. The SRES scenarios specifically do not assume that any action will be taken to limit emissions under international treaties such as the Kyoto protocol. They do, however, allow for expected controls on emissions in order to improve AQ. This concept is taken further by a new set of predictions of reactive gas emissions by IIASA, which has generated two scenarios for emissions to 2030 (described in Dentener *et al*., 2005; Dentener *et al*., 2006) called 'current legislation' (CLE) and 'maximum feasible reduction' (MFR). The CLE scenario assumes that current national legislation to control pollutant emissions will be enacted and adhered to. This legislation includes that of many developing countries and particularly limits emissions from transport sources. The CLE scenario is put forward as the most realistic estimate. The MFR scenario explores the consequences if the most advanced technologies currently available were applied to control pollutant emissions. Application of these technologies will involve some cost, so the MFR scenario is not expected to be the most realistic; rather it is an example of what could be achieved. The population and economic growths assumed by IIASA are similar to those assumed by SRES. Examples of the predicted CH_4 and NO_X emissions by IIASA and SRES are shown in Figure 2.10.

Figure 2.10: Global annual emissions of methane (upper plot) in Tg (CH_4) yr^{1} and nitrogen oxides (lower plot) in Tg (NO_2) yr^{1}. The coloured areas depict the IIASA CLE (current legislation) emission scenario, the dotted black line IIASA MFR (maximum feasible reduction) and the red solid and dotted lines SRES A2 and B2. Taken from Dentener *et al*. (2005)



54. In the UK, AQ models generally use emissions data taken from the National Atmospheric Emissions Inventory (NAEI). The NAEI provides a historic time-series in UK emissions for AQ pollutants (including O_3 and secondary aerosol precursor emissions) and GHGs from different sectors. The NAEI also provides projections of AQ pollutant emissions to 2020. The NAEI UK emission projections are tied to Department for Trade and Industry (Dti) energy forecasts which are periodically updated, traffic forecasts from the Department for Transport and various sources for agriculture. The Dti provides the UK's projections for CO_2 emissions from its UK Energy Model and includes impacts of policy measures included in the Climate Change Programme. There are also UK projections of non-CO_2 GHG emissions produced on a consistent basis on behalf of Defra.

55. Details of the methods and assumptions used for compiling emission inventories and emission projections in the UK for the AQ pollutants were given in detail in previous AQEG reports (AQEG, 2004; 2005).

56. This report explores numerous linkages between emissions of the pollutants contributing to AQ and CC. Emission inventories, principally, but not solely, from the NAEI are used to provide the quantitative information required to assess these interactions and for identifying trade-offs and synergies between mitigation measures for AQ and CC. There are various stages in the report where, in answer to the specific questions posed by Defra and the Devolved Administrations, reference is made to emission inventory information at a sector level, but it is in Chapter 5 covering policy issues in relation to Questions 4 and 5 on mitigation measures where the contribution of different sources to AQ pollutants and GHG emissions are discussed in detail. Chapter 5 considers from a policy context measures that produce win-win outcomes, i.e. reducing both AQ pollutant emissions and GHGs, and those which lead to a trade-off of one group of pollutants against another. Classic examples are measures brought in to reduce NO_X and primary particulate matter (PM) emissions and how they affect emissions of CO_2, e.g. through fuel switching (coal to gas or petrol to diesel) and through introducing end-of-pipe abatement.

57. To an extent, the quantitative conclusions are based on the UK emission projections from the NAEI. Reference is made to a number of potential transport and non-transport measures being examined by Defra in the current review of the Air Quality Strategy through analysis of the projected emission changes and ensuing impacts on concentrations of NO_2 and PM_{10} against AQ targets and the effects on CO_2. However, Chapter 5 highlights where there is a need to look beyond "end-of-pipe" emissions, as presented by inventories, to consideration of impacts over a whole life cycle or fuel cycle, covering emissions at various stages from generation and supply of a fuel through to its final use. This is particularly crucial to understanding the impacts on CO_2 emissions, where the point of release is unimportant, compared with those on AQ pollutant emissions, where the point of release is critical. This is relevant to mitigation measures based on switch to biofuels and hydrogen as fuels, for which emissions associated with growth and supply may become more important than those associated with point of use. The fact that natural emissions, and uptake, of both AQ pollutants and GHGs are not considered in current inventories, means that the net impact of changes in land use on emissions inventories needs to be assessed with care.

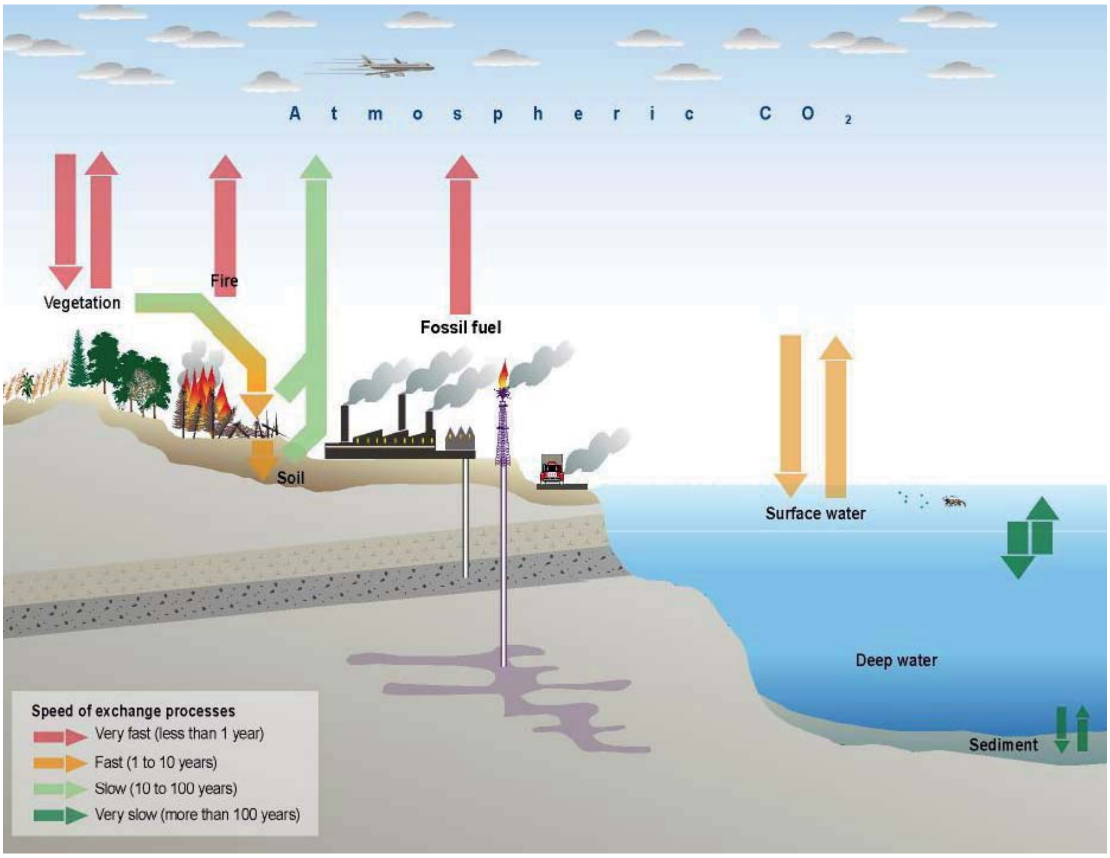
2.3.4 Feedbacks

58. It is possible to calculate the direct change in the Earth's radiation balance caused by the introduction of GHGs without using a complex 3D climate model. If the meteorology of the Earth (other than the temperature) was unchanged then radiation changes could easily be converted into a global temperature change. However, in a warmer climate other aspects of the climate system will change too, leading to climate feedbacks, either enhancing (positive) or dampening (negative) the CC. The most important of these is the water vapour feedback. Climate

models predict that the *relative* humidity of the atmosphere will remain largely constant in a warmer atmosphere but since warmer air can hold more moisture, the absolute amount of water vapour will increase. Since water vapour is a GHG this will increase CC further in a positive feedback. Another example of positive feedback is through changes in snow and ice cover. As the surface of the Earth warms, the ice and snow cover will decrease. Since the land and sea are darker than ice and snow, more solar radiation will be absorbed by the Earth, causing more warming. A more complicated example is the effects of clouds. Clouds can reflect and absorb solar radiation, thus cooling the Earth's surface. But they can also absorb and emit the long-wave radiation emanating from the surface, thus warming the Earth. Whether the net effect is a warming or a cooling depends on the height and characteristics of the clouds. Climate scientists have not yet reached a consensus on whether clouds induce a positive or negative feedback on CC.

59. Further important feedbacks relate to climate effects on the carbon cycle. This is illustrated in Figure 2.11, which emphasises the large bidirectional fluxes between the atmosphere and the biosphere, soils and the surface ocean. The size of these fluxes means that the perturbation of the underlying processes by changes in climate can lead to significant changes in net carbon uptake or release. For example, Cox *et al*. (2000) explored the effect of CC on the natural terrestrial carbon cycle, and found that by 2100 increasing temperature decreased the amount of CO_2 taken up by plants, and increased the amount of CO_2 released by decaying matter in soils, causing a positive feedback on the rate of increase of atmospheric CO_2 concentrations.

Figure 2.11: The carbon cycle (from IPCC, 2001b)



60. There are both positive and negative feedbacks involving atmospheric chemistry. Warmer conditions may cause circulation changes that lead to a redistribution in lightning and to lower concentrations of CH_4 and O_3 in the troposphere – a negative feedback (e.g. Stevenson *et al*. 2005; Grewe, 2005) while a positive feedback has been shown to occur through an increase in O_3 transferred to the troposphere from the stratosphere (Collins *et al*., 2003; Sudo *et al*., 2003; Zeng and Pyle, 2003). The faster chemical reactions in a warmer atmosphere with more water vapour will decrease the concentrations of CH_4 and O_3 (e.g. Johnson *et al*., 2001) – a negative feedback on climate. Changes in cloud cover and precipitation will affect the rates of photolytic reactions and the rate of removal of soluble species. It is not clear how these will be affected by CC.

61. The following are two important examples of known feedbacks associated with the coupling between climate and chemistry via ecosystem responses. Firstly, warmer temperatures are likely to increase the natural emissions of reactive gases, such as CH_4 from wetlands and tundra (e.g. Gedney *et al*., 2004; Gauci *et al*., 2004a) and VOCs from vegetation (e.g. Sanderson *et al*., 2003; Guenther *et al*., 1995), while drier and warmer conditions may increase emissions of various gases from wildfires. Secondly, in a climate with higher CO_2, the uptake of O_3 by plant stomata will decrease, thus increasing O_3 concentrations in the atmosphere, but decreasing O_3 damage to vegetation. This latter effect may offset to some extent the impact of higher O_3 levels in reducing the uptake of CO_2 and hence in increasing CO_2 concentrations. It is not yet known whether the overall impact of atmospheric chemistry on CC is a net positive or negative feedback.

62. Further examples of climate feedbacks involve aerosols. In the so-called CLAW hypothesis, Charlson *et al*. (1987) postulated that increasing sea temperatures would increase the emissions of DMS from phytoplankton which would generate more sulphate aerosol, thus cooling the climate. Some modelling studies (e.g. Woodward *et al*., 2005) show that mineral dust aerosol will increase in future due to changes in winds, aridity and vegetation cover; others (e.g. Mahowald and Luo, 2003) suggest that increases in vegetation cover in a CO_2-rich atmosphere will cause decreases in dust. Mineral dust is also an agent in a climate feedback loop involving marine phytoplankton; increasing dust deposition to the oceans provides iron which increases phytoplankton growth and hence absorption of CO_2 from the atmosphere.

63. Feedbacks could lead to sudden changes in climate. One example is the release of CH_4 hydrates from the deep ocean which would cause a sudden warming. Another is the Atlantic Ocean's thermohaline circulation (of which the Gulf Stream is a part). If this were to shut down, it would cause a cooling of Western Europe. However, while current climate models suggest that this circulation might weaken, it is very unlikely to shut down during the 21st Century.

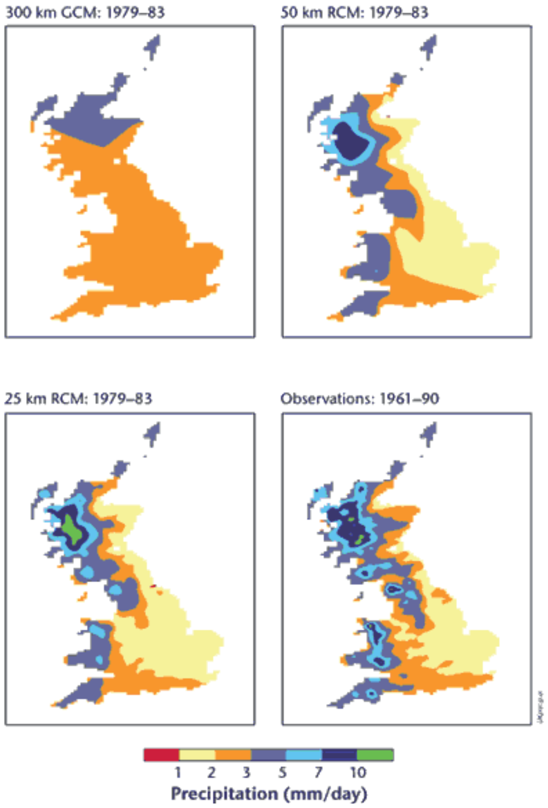
2.3.5 Regional modelling

64. Global coupled climate models that are computationally expensive are required to simulate the climate over many centuries. This limits the spatial resolution that can be afforded to approximately 100 – 200 km. However, the local climate is often determined by features smaller than this, such as the surface topography. Small mountain ranges such as the Pennines cannot be resolved by global models,

but can cause very different climates on either side of them. One solution to this problem is to use a regional climate model (RCM) embedded within the global model. RCMs can be configured to simulate the climate for a small sector of the planet at finer resolution, enabling the representation of important topography and processes otherwise not presented. The RCM can be supplied with meteorological data on its boundaries at 6-hourly intervals from an AOGCM. Sea surface temperatures and sea ice can be provided on a monthly basis, again from an AOGCM.

65. The large-scale CC signal in the RCM is therefore driven by the global AOGCM. The main way the RCM adds detail to the large-scale signal is through the use of higher resolution land surface data. The predicted changes in surface temperature due to CC will vary according to land surface type. For instance the amplitude of the CC signal is generally larger over areas with little vegetation, and smaller over areas with dense vegetation. For example, by resolving different land surface types over the UK, the RCM is able to give more accurate predictions of surface temperature changes over a particular UK location, rather than an average for the UK as a whole. Predicted precipitation changes are very sensitive to the small-scale orography (height of land). Figure 2.12 shows simulations of UK precipitation from an AOGCM (HadCM3) with a 300 km resolution compared to an RCM (HadRM3) run at 50 km and 25 km resolutions. The physical formulation is the same for all models, and the 300 km global model is used to provide the boundary conditions for the regional model. It is obvious that a regional model is needed to represent UK precipitation patterns, although lower resolution models may be able to simulate the broad-scale changes.

Figure 2.12: Simulated annually-averaged precipitation rates from the HadCM3 family of models with different resolutions, and observed data


300 km GCM: 1979–83

50 km RCM: 1979–83

25 km RCM: 1979–83

Observations: 1961–90

66. A use to which RCMs would be well-suited, but are not currently applied, is the effect of regional air pollution (particularly aerosols) on regional climate. Aerosol concentrations vary widely across the UK, so measures to control them will have different climatic implications at a regional level.

67. Although the large-scale simulated changes generated by RCMs are broadly comparable with those modelled by GCMs, there can be a tendency for some RCMs to overestimate the variability of some small-scale processes. For example there is more scope for unrealistic positive feedbacks to occur, e.g. between precipitation and soil moisture. In this case, a higher frequency of extremes, such as heavy precipitation, may be predicted than is realistic. This has implications for predictions of changes in frequencies of extreme pollution events. Moreover, if there are biases in the driving data from the global model, such as excessive summertime drying, then the regional model is unlikely to correct this and may even amplify it.

68. Another way of making use of more detailed surface-type data is through tiling. Typically a global resolution grid square will contain several surface types such as water, bare soil, urban and vegetation. The surface characteristics for that square will be assigned an average of the different types weighted by the fraction of the grid square each occupies. In tiling, the surface exchange scheme, which calculates the interaction between the surface and the atmosphere, is run for each surface type ('tile') separately, and it is the net effect on the atmosphere that is averaged over the grid square, rather than the original surface types. This means that the model calculates a set of different surface temperatures for each surface type within the grid square. Thus, although one model grid square may cover much of SE England, it is possible to distinguish the different expected CC effects on surface temperature over urban areas from those over grassland or forests.

2.3.6 Current predictions

Figure 2.13: Predicted global surface temperature rise for four different emission scenarios

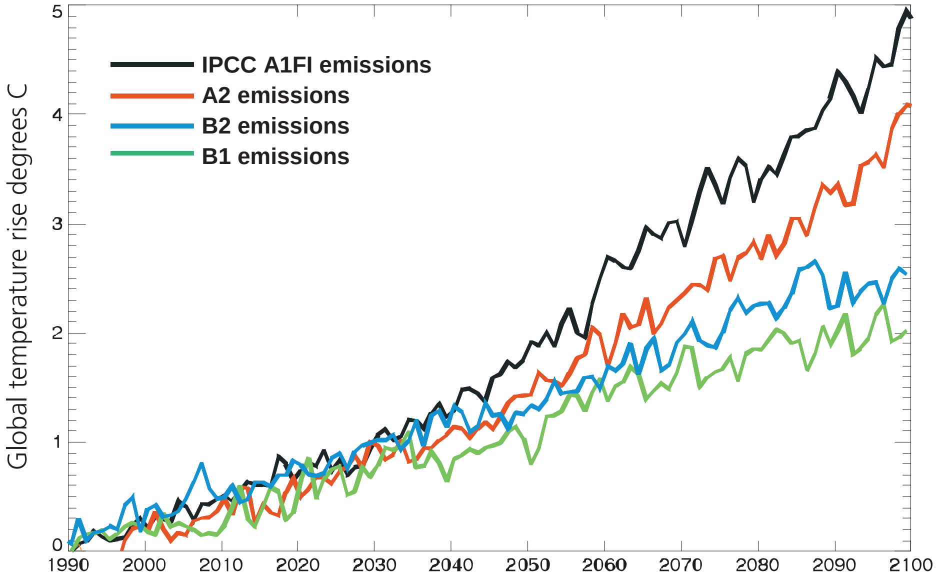
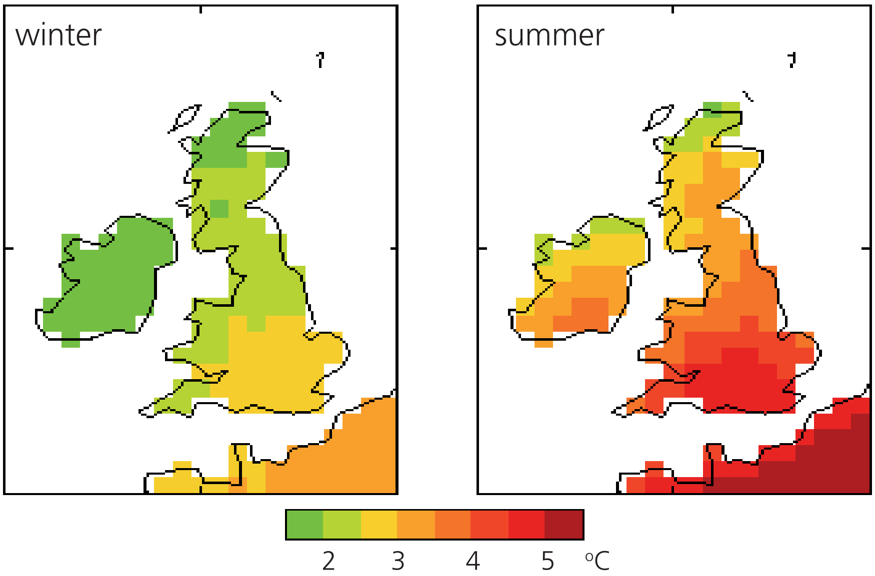


Figure 2.14: Changes in surface temperature by 2080s predicted by a regional climate model. The emission scenario corresponds to SRES A2



69. Some current predictions for global surface temperature rises, for four different emissions scenarios, are shown in Figure 2.13. These do not include the carbon cycle feedbacks found in Cox *et al*. (2000). They show that changes in emissions scenarios do not lead to significant changes in global surface temperature until about 2040. An example of the predicted future temperature changes from a regional model is shown in Figure 2.14.

2.4 Tropospheric chemistry

2.4.1 Impact of tropospheric chemistry on greenhouse gases

70. Both CH_4 and O_3 are important GHGs. Their atmospheric concentrations and their radiative forcing depend on the chemistry occurring in the troposphere. Methane is emitted directly to the atmosphere, and is removed mainly by chemical reaction; its concentration depends on the balance between these two processes. As discussed above, O_3 is produced by chemical reaction in the atmosphere and is thus a secondary pollutant. Its precursors are VOCs and NO_X. Volatile organic compounds include compounds such as butane and benzene that are emitted from a range of anthropogenic sources (e.g. fuels and solvents), as well as compounds such as isoprene that are emitted by vegetation. These compounds are not significant direct GHGs, because of their short atmospheric lifetimes. Their impact on CC occurs mainly though their effects on O_3 formation and on CH_4 removal. Nitric oxide is emitted from combustion and from soils and is also formed higher in the troposphere by lightning.

71. The chemical reactions occurring in the troposphere are discussed in Box 2.1 (and are described in more detail in Section 2.4.2 below). A key concept is the oxidising capacity of the atmosphere, which refers to its ability to remove chemical compounds, such as CH_4 and VOCs. These compounds are removed by oxidation, through complex sequences of chemical reactions that convert them to CO_2 and water.

72. The oxidation sequence, e.g. of CH_4, is initiated by reaction with the hydroxyl radical (OH). The atmospheric lifetime of CH_4 is, to a good approximation, equal to $1/(k_{CH4}[OH]_{av})$, where k_{CH4} is the rate coefficient for the reaction of OH with CH_4 – a measure of how fast this reaction is. The square brackets around OH signify its concentration, which refers, in this instance to its average throughout the atmosphere. The lifetime of CH_4 is about eight years, which is sufficiently long for it to be distributed throughout the troposphere – its concentration varies little with latitude, longitude and altitude. The atmospheric burden of CH_4 is approximately equal to its rate of emission multiplied by its atmospheric lifetime. Thus $[OH]_{av}$ influences radiative forcing through its effect on the atmospheric CH_4 concentration; future changes in atmospheric chemistry resulting from CC can lead to feedbacks through their influence on $[OH]_{av}$.

73. Ozone plays a role in both AQ, through its influence on human health and on plant growth, and in CC. It is formed in the atmosphere by the photolysis of NO_2. The complex chemistry involved in the oxidation of CH_4 and of VOCs converts NO into NO_2 and hence leads to the formation of O_3. While other compounds are also important (see below), OH is a key species in initiating this oxidation chemistry. The hydroxyl radical is formed by the photolysis of O_3, in the presence of water vapour. The efficiency of O_3 formation following reaction of OH with a VOC depends on the local concentration of NO_X (NO + NO_2). Near the surface, where the VOC concentrations are highest, NO_X concentrations are greater close to anthropogenic emission sources, which are primarily located in the continental northern hemisphere. At low NO_X, the oxidation can lead to destruction of O_3.

74. Volatile organic compounds have shorter atmospheric lifetimes than CH_4, because their rate constants for reaction with oxidants, such as OH, are larger. The lifetime for butane, for example, is about five days, while that for isoprene is about three hours. As a result, they are not so widely distributed throughout the atmosphere, but have higher concentrations closer to their sources. While they absorb infra-red radiation, they do not act directly as GHGs because their concentrations are low in the upper troposphere. They act indirectly, however, through their impact on the oxidising capacity of the atmosphere, e.g. on OH concentration, and through their influence on O_3 formation.

75. Atmospheric oxidation leads to the formation of secondary aerosol. Sulphate aerosol is formed from the oxidation of sulphur dioxide (SO_2) to produce sulphuric acid. Emissions from the combustion of sulphur containing fuels are the major source of SO_2. Secondary sulphate aerosol is also formed from the oxidation of DMS, which derives from plankton. The importance of this process for CC was briefly discussed in Section 2.3.4. Nitrate contributes to secondary aerosol via the formation of nitric acid (HNO_3) from NO_2 (reaction 9 in Box 2.1). The oxidation of VOCs leads to oxygenated intermediates, some of which have very low volatility, so that they condense onto existing aerosol and contribute to their growth and to their radiative properties. The main VOCs that contribute to Secondary Organic Aerosols are aromatics and terpenes.

2.4.2 Chemical mechanisms in the troposphere

76. Box 2.1 outlines the chemistry involved in the oxidation of CH_4, as a result of its reaction with OH in the presence of NO_X. Carbon monoxide is also oxidised following reaction with OH, and a similar mechanism to that shown in Box 2.1 applies to the oxidation of other VOCs. Ozone can also initiate the oxidation of certain VOCs, as can nitrate (NO_3), which is the main oxidant at night. Hydroxyl relies primarily on sunlight for its formation and its concentration is very small at night. In assessing the relationship between AQ and CC in this and the following chapter, several features of the chemistry outlined in Box 2.1 are important:

- Nitric oxide is primarily emitted from the combustion of fossil fuels, although lightning, soils and biomass burning are significant sources. Both NO and NO_2 are short-lived in the atmosphere and are found primarily close to their sources; a mechanism for long range transport of NO_X is discussed below.

- The formation of OH from O_3 photolysis leads to loss of O_3, which depends on the competition between the reactions 2 and 3. The excited oxygen atom, O^1D, can either be converted to ground state oxygen atoms, O^3P, on collision with nitrogen (N_2) and oxygen (O_2), which leads to regeneration of O_3, or can react with water to form OH, which leads to net loss of O_3. Increasing the concentration of water vapour, through increases in the global temperature, leads to an increase in the rate of destruction of O_3 through photolysis.

- The net production of O_3 in the reaction sequence shown in Box 2.1 depends on the concentration of NO:

  - At low concentrations of NO, the peroxy radicals (CH_3O_2, HO_2) react primarily via reactions 10 and 11 and their oxidation does not generate NO_2, the precursor of O_3. These conditions apply in the background troposphere. The loss of O_3 from O_3 photolysis, coupled with low rate of formation via NO reactions leads to an overall consumption of O_3.

  - At high concentrations of NO, the peroxy radicals react mainly with NO (reactions 6 and 8), generating NO_2 and hence O_3 by NO_2 photolysis.

- These observations suggest that O_3 is not formed in regions that are far from NO_X sources, where many biogenic emissions occur. It is possible to transport NO_X into such regions via so-called reservoir species such as PAN (Box 2.1). This compound is produced from the reaction of the peroxyacetyl radical, formed in the oxidation of a wide range of VOCs, with NO_2 (reaction 14). Peroxyacetyl nitrate dissociates quite rapidly at the earth's surface, but much more slowly at the lower temperatures found at higher altitudes. Once it has been lifted to such altitudes, PAN can be transported considerable distances before it subsides to lower altitudes. The resulting higher temperatures lead to dissociation (the reverse of reaction 14) to form NO_2. This process provides a mechanism for transport of NO_X into regions not directly subjected to anthropogenic emissions, and for the formation of O_3 from the oxidation of biogenic emissions. Increases in the global temperature will lead to a more rapid rate of dissociation of PAN and hence to a reduction in the efficiency of transport of NO_X to less polluted regions. Thus the impact of short-lived biogenic VOCs on CC, through O_3 production, may be reduced.

Box 2.1 Oxidation of methane in the atmosphere and the formation of ozone

1. The major route for forming the hydroxyl radical (OH) in the atmosphere is through ozone photolysis. The reaction produces an excited oxygen atom, labelled O^1D:

   O_3 + light → $O^1D + O_2$ (R1)

   which can either react with water to form OH, or lose energy to form unexcited oxygen atoms, O^3P, on collision with nitrogen (N_2) or oxygen (O_2) molecules.

   $O^1D + H_2O \rightarrow 2OH$ (R2)

   $O^1D + N_2, O_2 \rightarrow O^3P + N_2, O_2$ (R3)

   The unexcited oxygen atom combines with an oxygen molecule to form ozone:

   $O^3P + O_2 \rightarrow O_3$ (R4)

2. The OH react with CH_4, CO and VOCs. The mechanism for CH_4 is given here to illustrate the reactions involved. The OH takes a hydrogen atom from the CH_4 to form water and CH_3 which in turn reacts with oxygen to form a peroxy radical CH_3O_2:

   $OH + CH_4\ (+O_2) \rightarrow CH_3O_2 + H_2O$ (R5)

   A key reaction follows in which CH_3O_2 reacts with NO to form NO_2:

   $CH_3O_2 + NO \rightarrow NO_2 + CH_3O$ (R6)

   A sequence of reactions then occurs which generates a hydroperoxyl radical, HO_2, which also reacts with NO to form NO_2 and to regenerate OH, which can start this reaction sequence again by reacting with a VOC:

   $CH_3O + O_2 \rightarrow HO_2 + HCHO$ (R7)

   $HO_2 + NO \rightarrow OH + NO_2$ (R8)

3. This reaction sequence would go on and on indefinitely, but it is limited by reactions that remove radicals. The reactions involved depend on the concentrations of NO_X:

   At high NO_X, OH reacts with NO_2 to form nitric acid,

   $OH + NO_2 \rightarrow HNO_3$ (R9)

   At low NO_X, hydroperoxyl radicals react with other hydroperoxyl radicals

   $HO_2 + HO_2 \rightarrow H_2O_2$ (R10)

   $CH_3O_2 + H/RO_2 \rightarrow$ Products (R11)

   Reactions 10 and 11 compete with reactions 6 and 8. At low NO_X, 10 and 11 win, so that the oxidation of the VOC does not lead to NO_2 formation.

Box 2.1 Oxidation of methane in the atmosphere and the formation of ozone

4. The NO_2 formed in reactions 6 and 7 can be photolysed to form unexcited oxygen atoms:

$$NO_2 + \text{light} \rightarrow NO + O^3P \qquad (R12)$$

which then form O_3 via reaction 4. From the perspective of both regional air pollution and CC, this step – the formation of O_3 – is a key one. The importance of NO in promoting O_3 formation arises from the competition outlined above.

5. Formaldehyde (or methanal), HCHO, formed in reaction 7 is an example of an aldehyde. Ethanal, CH_3CHO, formed in the oxidation of ethane, C_2H_6, provides a further example. Ethanal reacts with OH in the same way as CH_4 above, to form the radical CH_3CO, which reacts rapidly with O_2 to form the peroxyacetyl radical, CH_3CO_3.

$$CH_3CHO + OH (+O_2) \rightarrow CH_3CO_3 + {}_{H2}O \qquad (R13)$$

CH_3CO_3 reacts with NO_2 to form peroxyacetyl nitrate (PAN):

$$CH_3CO_3 + NO_2 \rightleftharpoons CH_3CO_3NO_2 \qquad (R14)$$

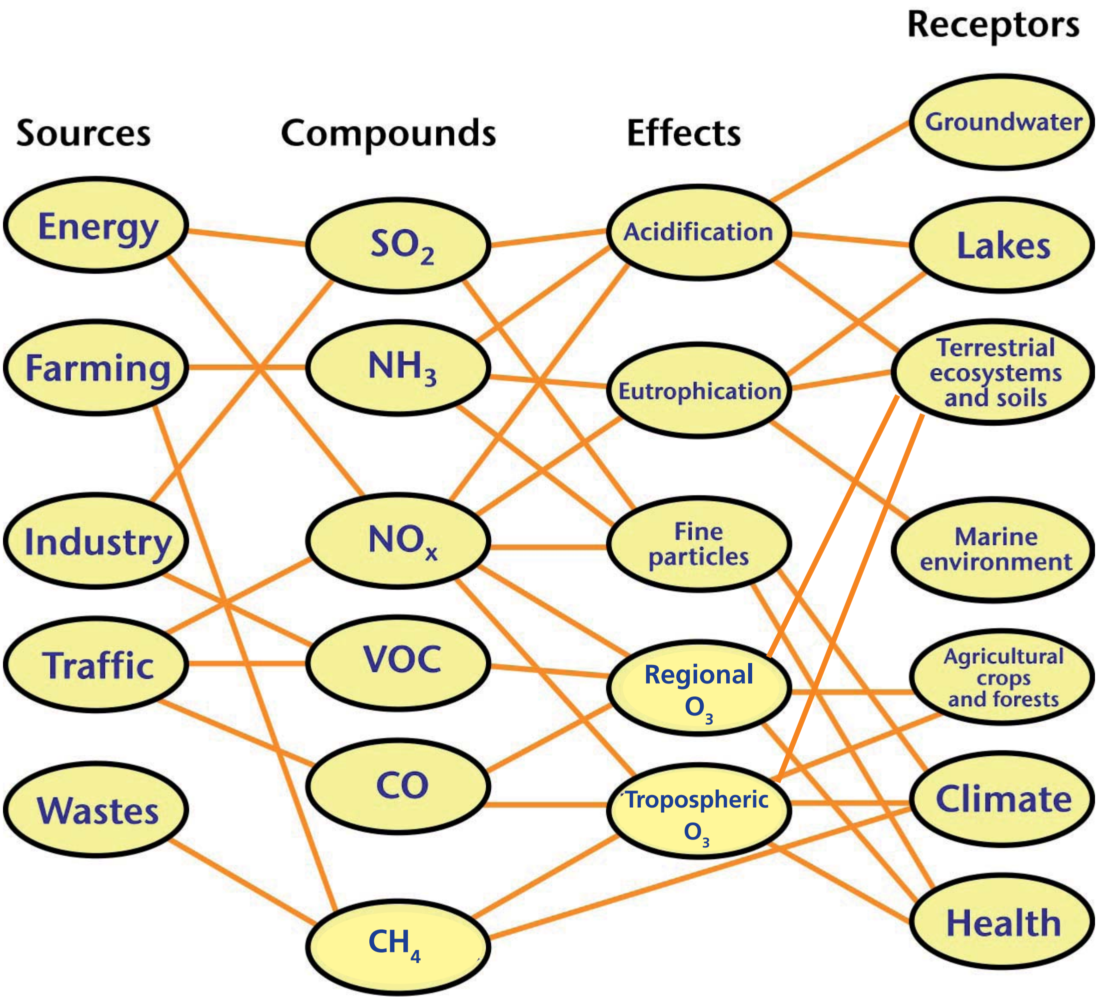
The reaction is reversible, so that PAN can dissociate to regenerate $CH_3CO_3 + NO_2$. This reaction occurs rapidly at the higher temperatures found near the surface, but if the PAN is lifted up to higher altitudes and lower temperatures, then its lifetime increases considerably and it can be transported large distances. As it subsides to lower altitudes, it dissociates and provides a source of NO_X in locations that may be well removed from direct anthropogenic pollution.

2.5 Air quality issues and links to climate change

2.5.1 Local and regional pollution controls and their ramifications for climate change

77. In principle, any pollutant that contributes to both local and regional pollution problems and also acts as a radiative forcing agent or changes the distributions of radiative forcing agents, may potentially produce a linkage between AQ and CC issues. Figure 2.15 shows some of the potential linkages.

Figure 2.15: Examples of some of the potential linkages between regional air quality and climate changes issues (after Grennfelt *et al*. (1994))



78. Black carbon and black smoke (BS) are local and urban scale pollutants and radiative forcing agents. Black smoke is a product of incomplete combustion and contributes to health effects in urban and industrial centres. Black carbon has been identified as a global warming agent because it absorbs solar radiation (Haywood and Shine, 1997; Chylek *et al*., 1996). Actions taken to reduce emissions of BS on the urban and regional scales will therefore reduce global warming and make CC goals more achievable. Furthermore, because of the short atmospheric lifetime of BC, the impact of emission reductions on radiative forcing is more or less instantaneous.

79. The linkages between BS and AQ and BC and the positive forcing of CC are important issues in the context of the environmental consequences of petrol versus diesel car usage. The CC consequences of CO_2 emissions are only one aspect that needs to be taken into account in evaluating these competitive vehicle technologies. A further CC issue is the radiative forcing from the BC emissions (Jacobson, 2002).

80. The linkages between BS, AQ and climate forcing are also relevant in the discussion of AQ problems in Asia. The use of biomass as a fuel for cooking and space heating in Asia has important consequences for indoor AQ and human health (Smith *et al*., 2002). There is also the concern that BC emissions, from this

and other sources, perturb the passage of solar radiation through the atmosphere and that, in addition to radiative forcing at the top of the atmosphere, there are also changes in surface radiation, evaporation and precipitation patterns. This is the Atmospheric (Asian) Brown Cloud phenomenon. Again, actions taken to reduce BC emissions because of indoor and local AQ concerns should make global CC goals appear more achievable.

81. Sulphur dioxide emissions in Europe have caused widespread acidification of sensitive soil and freshwater ecosystems in areas such as Scandinavia and upland Britain. Sulphur dioxide is oxidised in the atmosphere and in cloud droplets to form particulate sulphate. Sulphate aerosol contributes a major anthropogenic cooling term in the climate system. Ammonium sulphate is an efficient scatterer of atmospheric radiation and drives visibility reduction and climate cooling. Without treating the formation of particulate sulphate from the burning of fossil fuels, particularly since the 1940s, it would be difficult for the global climate models to reproduce the global temperature records during the 20th century. Action to control SO_2 emissions to reduce regional scale acidification will necessarily lead to a reduction in this climate cooling term. Hence, action to control regional acidification will make CC goals appear less achievable (Charlson *et al.* 1992)).

82. Emissions of NO_X and NH_3 contribute to regional scale acidification and eutrophication across Europe. These emissions drive the deposition of oxidised and reduced N_2 compounds and increase plant growth and microbial activity particularly in N_2-limited ecosystems. The increased N_2 deposition may increase the growth rate of forests in N_2-limited ecosystems, and this is thought to have led to the increasing uptake of atmospheric CO_2 in northern hemisphere boreal forest ecosystems (Schimel, 1995). This increased sink for CO_2 is an important part of the global carbon cycle and is thought to account for a significant fraction of current man-made CO_2 emissions. However, in the longer-term, increased N_2 deposition may have negative effects on forest growth because of nutrient imbalances and decreased stress tolerance. Hence, measures to reduce European NO_X and NH_3 emissions, because of concerns about regional scale eutrophication and acidification, need to be carefully evaluated in terms of their long-term effects on the strength of the boreal forest sink for CO_2.

83. The enhanced regional scale deposition of oxidised and reduced N_2 compounds may also stimulate production of N_2O through nitrification-denitrification processes in soils. Nitrous oxide is an exceedingly long-lived trace constituent of the atmosphere that is also an important radiatively active trace gas with a GWP that is about 300 times that of CO_2. Actions taken on the regional scale to halt eutrophication may therefore reduce emissions of N_2O and hence may make CC goals more achievable.

84. Background O_3 concentrations are rising and are influenced by global man-made CH_4 emissions. Methane emission controls would help meet both CC and AQ goals everywhere in the northern hemisphere (Fiore *et al*., 2002).

85. There is much current action within Europe, North America and Asia to control the emissions of the major urban and regional scale O_3 precursors, VOCs and NO_X. These precursors, in addition to CH_4 and CO, also take part in tropospheric chemistry on the global scale. This chemistry establishes the tropospheric distribution of OH, which provides the main removal process for CH_4 (the second most important GHG after CO_2). Actions taken to control urban and regional O_3 formation will necessarily influence the global distribution of OH. If this action leads to reductions in man-made NO_X emissions that are not supplemented by significant reductions in man-made emissions of CO, CH_4 and VOCs, then tropospheric OH levels may decrease exacerbating the build-up in global CH_4 burdens and hence making CC goals less achievable.

86. The capacity of the global tropospheric chemistry system to produce tropospheric O_3 is immense and is controlled by the combined source strength of the man-made and natural sources of CH_4, CO and VOCs. Only a small fraction of this huge capacity is currently harnessed and this small fraction is controlled by the combined emissions of NO_X from man-made and natural sources (Crutzen, 1973). Since tropospheric O_3 makes the third most important contribution to GHG radiative forcing, after CO_2 and CH_4, regional NO_X emissions have important global consequences that follow on from regional O_3 formation and its subsequent intercontinental transport (Li *et al*., 2002). Actions taken on the regional scale to control NO_X emissions also affect CC by decreasing global O_3 formation; this will also be the case for regional scale actions to reduce CO and VOC emissions. Changes in NO_X emissions have other effects on CC, e.g. through the formation of nitrate aerosol. The net effect of NO_X on CC is difficult to assess; attempts to do so are discussed in section 3.2.1.2.

2.5.2 Climate change and its ramifications for local and regional air quality

87. In principle, any CC outcome that influences local and regional pollution problems may potentially produce a linkage between CC and AQ issues.

88. The global climate system responds to the radiative forcing introduced by the increasing burdens of the radiatively-active trace gases. This global system response will be experienced through changes in surface and atmospheric temperatures, changes in winds and the global circulation, clouds and precipitation, ice cover and ocean currents. The climate of the UK will change as a result of all of the myriad of responses within the global climate system. Confidence in our ability to describe and predict these responses is very limited.

89. It is highly unlikely that the frequency of wintertime pollution events in the UK will remain unchanged as a result of CC. Such pollution events brought the Great Smog of 1952 and the major pollution episode in London during December 1991. These events were associated with stable, calm and cold conditions, conditions that are anticipated to become less frequent in the UK as a result of global warming. It is likely that episodes of poor, wintertime AQ will become less frequent in the future and so CC may well make local and regional NO_2 and PM AQ goals become more achievable in the future (Anderson *et al*., 2001).

90. By the same arguments, it is highly unlikely that the frequency of summertime pollution events in Europe will also remain unchanged as a result of CC. The intense O_3 episodes in the UK during 1976 and in France and Switzerland during 2003 were brought on by sustained high temperature and drought conditions. Such conditions favour O_3 production and minimise O_3 destruction through the uptake by vegetation at the earth's surface. These conditions are anticipated to become more frequent as a result of global warming. Climate change may well make local and regional O_3 AQ goals become more difficult to achieve in the future (Anderson *et al*., 2001).

91. Regional acidification will also be influenced by CC (Alcarno *et al*., 2002). Climate change will bring about changes in the major weather systems that influence the patterns and intensity of rainfall. There will be impacts on the scavenging of the acidic pollutants that will drive changes in the acidic pollution loads (Langner *et al*., 2005). As precipitation patterns change, there will also be impacts on the deposition of base cations from wind-blown dusts. Sensitive catchments will also be impacted by changes in run-off and evaporation, and the frequency of drought events. Hence there will be CC impacts, not only on the rates of acidic deposition, but also on the capacity of ecosystems to buffer the incoming acidity. Changes in soil temperature and moisture content will also influence the N_2 cycle and may increase leaching of nitrate from soils (Posch, 2002). It is too early to tell, however, what the overall impact of CC will be on the soil and water acidification and eutrophication across Europe in response to decreased emissions of sulphate, nitrate and ammonium.

92. The climate of the Arctic is already being strongly influenced by man-made CC. A wide range of toxic and persistent substances, including PCBs and mercury, have been steadily accumulating in cold, wet Arctic ecosystems as a result of decades of human activities at lower latitudes. As the Arctic climate changes, there may be potentially a change in the behaviour of the persistent organic pollutants (POPs) and mercury which could change the global circulation of these substances.

93. As the global climate system responds to increased radiative forcing, atmospheric temperatures will inevitably rise and with them there will be increases in humidity and water vapour mixing ratios. Increases in water vapour mixing ratios will lead to an increases in the photolytic source of OH from O_3. In turn, this will increase the oxidising capacity of the troposphere, decrease the build-up in the global CH_4 burden and hence provide a negative feedback on CC. In regions close to NO_X emissions, this increase in the photolytic source of OH will stimulate O_3 production and exacerbate regional O_3 AQ problems. In remote regions, such as over the oceans, the increase in the photolytic source of OH will lead to increased O_3 destruction, lower global burdens of tropospheric O_3 and a negative feedback on CC.

94. What are more difficult to assess are the ecosystem responses to CC. The physical changes in terms of atmospheric CO_2 concentration, surface and atmospheric temperatures, rainfall amounts and radiation will induce biological responses in terms of changed growth, pests and competition with other species, and soil microbial activity that ultimately will drive ecosystem responses. The ecosystem responses will drive changes in the natural biogenic emissions of trace gases such as isoprene and the terpenes, and these may impact upon the oxidising capacity of the troposphere and the distribution of tropospheric O_3. Because of the efficient intercontinental and interhemispheric transport of O_3, there may be impacts on regional AQ as a results of this ecosystem feedback on CC.

95. In addition, CC mitigation measures may have local and regional AQ consequences. For example, the hydrogen economy may ultimately displace fossil fuel combustion and lead to significant improvements in local and regional AQ. However, increasing reliance on biofuels and biomass may result in increasing soil emissions linked to the fertiliser applications required for high production rates, and increasing biogenic emissions, depending on which species and cropping systems that are used. These emissions may have impacts on eutrophication and O_3 formation.

Chapter 3

The role of air quality pollutants in climate change

Key points

- Air quality (AQ) pollutants, in addition to having effects on human health and ecosystems, may also have effects on climate. Dependant on the pollutant, these climate effects may be warming or cooling, or a combination of the two. AQ pollutants can affect climate directly, through their own radiative forcing, and indirectly, for example through the formation of secondary pollutants or the modification of the radiative properties of clouds. Biogenic greenhouse gas (GHG) emissions and the uptake of GHGs by the biosphere may also both be modified by air pollution.

- Effects of AQ pollutants on climate can be divided into two classes: effects related to gas-phase photochemistry, and effects related to aerosols and clouds. Some AQ pollutants participate in both of these, e.g. nitrogen oxides (NO_X) and volatile organic compounds (VOCs) control tropospheric ozone (O_3) and methane (CH_4) burdens as well as forming secondary inorganic and organic aerosols.

Gas-phase photochemistry

- After the well-mixed GHGs carbon dioxide (CO_2) and CH_4, tropospheric O_3 is responsible for the third largest single components of radiative forcing of climate. Precursors of O_3 (NO_x, VOC, CH_4, carbon monoxide (CO) and hydrogen (H_2)) therefore have indirect effects on climate. Ozone and nitrogen dioxide (NO_2), and their precursors, are also controlled as AQ pollutants.

- The indirect climate warming effect of VOC, CO and H_2 is enhanced because they increase the lifetime of the GHG CH_4. Emissions of NO_x, however, act to increase the rate of CH_4 destruction thus decreasing its lifetime. Integrated over time, the positive radiative forcing (warming) effect of NO_x via O_3 production, and the negative (cooling) effect through a decrease in CH_4 lifetime are approximately equal, but with a high degree of uncertainty in both. The net climate effect of NO_x emissions on O_3 and CH_4 may be slightly negative for ground-based sources and slightly positive for aviation. In general, combustion sources with a typical ratio of NO_x to CO_2 emissions have a net radiative forcing due to NO_X emissions two orders of magnitude smaller than that due to the co-emitted CO_2.

Aerosols and clouds

- Particulate matter (aerosol) is an important AQ pollutant, with particular attention given to the smaller (< 10 and 2.5 µm) size fractions, PM_{10} and $PM_{2.5}$. Aerosol-associated processes are responsible for the largest negative radiative forcing (cooling) of climate, which may be locally capable of reversing the positive forcing due to GHGs. Precursors of secondary sulphate, nitrate and organic aerosols all therefore have the potential to affect climate as well as being AQ pollutants.
- Black carbon (BC) aerosols are known to exert a positive direct radiative forcing of climate (warming). In addition they contribute to primary particulate matter (PM) that is important in the local control of AQ.
- Most aerosols are a mixture of components with cooling and warming effects on climate as well as effects on human health. The mass mode particle size of $PM_{2.5}$ is close to that which has the largest effect on climate. The full effects of these complex interacting pollutant mixtures on climate and human health continue to be an area of scientific uncertainty.
- Some climate change (CC) assessments calculate a total BC positive radiative forcing from fossil fuel and biomass burning. This forcing, however, is likely to be partially or fully offset by the negative radiative forcing associated with organic carbon (OC) aerosol from the same sources.

Trends in air quality pollutant emissions and implications for climate change

- UK emissions of sulphur dioxide (SO_2) rose from pre-industrial levels to a maximum during late 1960s and early 70s and since then have declined rapidly. Sulphate aerosol formed from SO_2 significantly affects radiative forcing locally, leading to cooling. Its short atmospheric lifetime however means that the main effect will have been merely to delay the onset of warming by a few decades. Some studies suggest that climate model underestimation of the associated negative forcings has masked model underestimates of climate sensitivity, such that the effect of aerosol abatement will be much greater warming than is currently anticipated.
- Whilst European aerosols are abated, concentrations elsewhere in the world continue to rise, so the spatial pattern of these trends is quite complex and there remains uncertainty over the impact of these changes on climate.
- For O_3, source apportionment and response to emissions trends are complex. There is a hemispheric contribution to European background concentrations.
- UK and EU emissions of well mixed GHGs will contribute a decreasing fraction of the global total emissions as the Asian economies grow.

- It is not clear whether the current metrics (radiative forcing and global warming potentials (GWPs)) used for quantifying the effects of long-lived GHGs are suitable for assessing the relative climate effects of short and long-lived pollutants. In particular, even though summing radiative forcings of different signs may give a zero net result, this might not necessarily mean that there would be no climate impact.

Local and regional climate impacts of air quality

- Most climate assessments have focused on radiative forcing as a globally averaged quantity, and its global effects on climate. Regional and local effects may be greater for pollutants that have very inhomogeneous global distribution, especially PM, but these regional effects have been little studied and spatial variability in AQ pollutants is not considered in regional climate models.
- Observations of decreases in the amount of radiation reaching Earth's surface may be attributable to AQ pollutants. This phenomenon, called Global Dimming, is spatially inhomogeneous and in some places has been reversed in recent years. The 'brown cloud' of pollution over Asia has been shown by modelling to be capable of causing notable decreases in surface temperature.

Box 3.1 Summary response to Questions 1 and 2

Question 1: What are the links between sources of emissions responsible for CC and AQ? What are the main scientific issues associated with the interactions of GHGs and air pollutants in the atmosphere and their impacts on CC and AQ?

Most sources emit a mixture of pollutants having impacts on AQ and CC. The CC impact arising from combustion of fossil fuels is dominated by the emission of CO_2 for all ground-based sources, and current estimates of the climate impact of aviation emissions indicate this is probably true also for airborne sources. For non fossil fuels and non-combustion emissions however, it is important to consider the non-CO_2 climate effects as these can dominate the overall impact. In these cases, the same pollutants generally have multiple effects on AQ and CC. Tropospheric O_3 and its precursors are important for AQ, while O_3 is also a GHG. PM_{10} is also important for AQ, while the particles have cooling and warming effects on climate and can modify rainfall patterns. The links between CC and AQ are most complex for emissions of NO_X, as NO_2 is important for AQ as well as being a precursor of tropospheric O_3 and secondary PM. When considering all these links, a number of scientific issues emerge:

- The net impact of O_3 precursors on climate is the sum of numerous positive and negative effects, some of which can be large even when the net effect is small.
- Global mean effects of AQ pollutants on climate obscure many regional and transient impacts that may be significant.

- Impacts of poor AQ on the biosphere can have knock-on effects on climate; numerous processes and linkages have been identified and observed, but quantitative analysis to identify which are most important remains difficult.
- Abatement of CH_4 emissions is especially valuable as a means of addressing poor AQ, due to its role in the formation of tropospheric O_3, as well as the climate impacts of CH_4 and O_3 as important GHGs.
- Black carbon is an important constituent of PM_{10} in AQ, and also has direct and indirect impacts on climate that need to be quantified with care, since emissions are from biogenic and fossil fuel sources and co-emitted OC may have effects of opposite sign to BC.
- The science of atmospheric aerosol particles raises several issues that link AQ and CC, especially the determinants of the number and mass of particles, their effects on clouds and rain alongside the effects on human health of particle composition and size.

Question 2: What do future trends in UK air pollutant emissions tell us about the potential impact on climate for the UK and Europe? Given that some air pollutants cause AQ concerns on a regional scale, over what scale will their impact on climate be felt?

Carbon dioxide and CH_4 remain in the atmosphere much longer than most AQ pollutants, long enough to become globally well mixed. Their impacts on the climate of the UK and Europe are therefore associated with global mean perturbation of Earth's radiation balance as global pollution accumulates slowly over several decades. Most studies of the climate effects of AQ pollutants have not focused on the heterogeneous nature of the climate forcing from regional variations in air pollution, as regional climate variation tends to be dominated by other factors such as land use. Some short-term regional suppression of rainfall may be observed in certain locations, but most research to date points to global climate impacts of regional air pollution. In future, as emissions are projected to decrease in Europe and continue increasing in Asia, the global climate impact of air pollution may continue to rise, but the regional variation will shift from Europe to Asia, and the implications of this are unclear. For sectors where a trend of continuing increases in emissions are predicted, it is especially important to consider the different timescales of effect of CO_2 and non-CO_2 emissions, as the significance of long-term CO_2 accumulation may be masked by comparison with the transient effect of rising non-CO_2 emissions.

3.1 Introduction

96. AQEG's detailed analysis in support of the answers outlined in Box 3.1 can be found in the three main sections of this chapter as follows:

- In this Introduction Section 3.1, we define the scope of the Expert Group's analysis in terms of the pollutant emissions considered. For each emitted pollutant, we identify if it is an 'AQ pollutant', or if it is a contributor to CC. Many pollutants are in both of these categories. We identify secondary pollutants, not emitted directly, that may be AQ pollutants or contribute to CC or both, where the precursors of these secondary pollutants may also be AQ pollutants and/or contributors to CC. We thus consider direct and indirect effects on climate, including the impacts that primary pollutants have via the secondary pollutants that are formed from them in the atmosphere, as well as the climate effects that pollutants have through modifying the radiative properties of clouds.
- In Section 3.2 we review the current state of scientific understanding of the processes that determine the magnitude of the climate forcing due to AQ pollutants, and hence our capability to quantify this forcing. This includes the processes that control the relationships between primary emissions and changes in concentrations of secondary pollutants, and the interactions between AQ pollutants and GHGs in the atmosphere. Our focus here is initially on the effects of current pollution levels on the forcing of climate, but this section also considers the change in forcing arising from future changes in emissions.
- In Section 3.3 we review current understanding of how climate responds to the forcing due to AQ pollutants, contrasting this with the forcing due to GHGs that are not AQ pollutants. We focus especially on the different lengthscales and timescales over which the emission and concentration changes are occurring and over which the climate effects are likely to be felt.
- A final Section 3.4 closes the chapter by highlighting some areas for further research where the analysis of the preceding sections has been hampered by paucity of available information, or where clear gaps in current knowledge and predictive capability have been revealed.

97. Table 1.1 in Chapter 1 and Figure 2.2 in Chapter 2 summarise all the pollutants that influence climate. The mechanisms by which these pollutants influence climate are described in Sections 2.2 and 3.2. Changes in land use and solar radiation included in Figure 2.2 are beyond the scope of this report, except where land use changes are attributable to the effects of AQ pollutants on ecosystems, or where a land-use change has an effect on the concentration of AQ pollutants as well as influencing climate. The effects of stratospheric O_3 depletion on climate are also outside the scope of this report; we consider stratospheric O_3 changes only where these constitute an influence of CC on AQ in Chapter 4.

98. We consider ‘AQ pollutants’ to be those listed in the Air Quality Strategy (DETR *et al*., 2000):

- benzene
- 1,3-butadiene
- CO
- lead
- NO_2
- O_3
- PM_{10}
- SO_2.

99. We also consider the precursor emissions of these pollutants. As reviewed by AQEG (2004) we include nitric oxide (NO) as a precursor of NO_2. As reviewed by PORG (1997) we also include VOCs, NO and NO_2 as precursors of O_3. As reviewed by AQEG (2005) we include SO_2, NO, NO_2, ammonia (NH_3) and VOCs as precursors of PM_{10}.

100. Some of these pollutants also have other regional impacts, such as the sulphate and nitrate components of PM_{10} which are responsible for acid deposition and eutrophication. We are therefore examining a system in which multiple pollutants have multiple impacts, that has a complex matrix relating single pollutants to more than one impact and where most impacts are due to the combined effect of more than one pollutant. The focus will remain, however, on the relationship between local and regional AQ, in terms principally of ground-level concentrations of pollutants harmful to human health, and CC.

101. Tropospheric O_3 is both an AQ pollutant, and a GHG. In Figure 2.2 CH_4 appears as the second most important well-mixed GHG, however it is also of interest because of its influence on tropospheric O_3. Even though CH_4 is not an AQ pollutant, the close link between changes in emissions of CH_4 and some air pollution control policies means it is important to understand its role as part of the wider picture of the oxidising capacity of the troposphere and control of tropospheric O_3 concentrations.

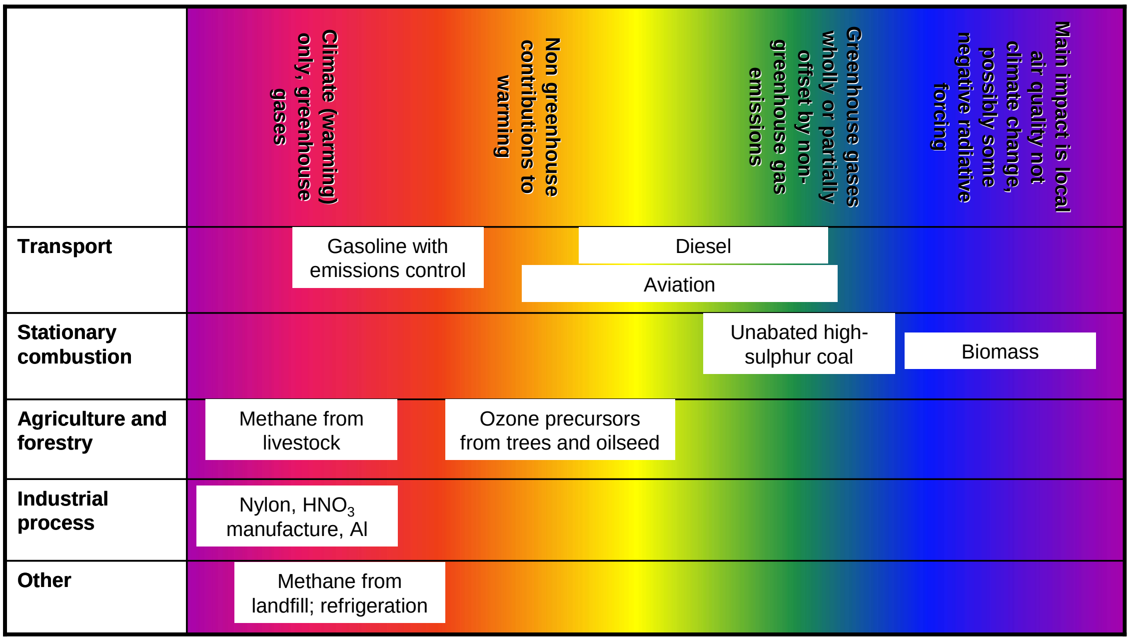
102. Also in Figure 2.2, the aerosol components ‘sulphate, S’, ‘Black Carbon, BC’, ‘organic carbon, OC’, ‘biomass burning’, and ‘mineral dust’ all contribute to what currently appears in the AQ Strategy list of pollutants as PM_{10} (AQEG, 2005). Particulate matter PM_{10} should therefore also be considered as an AQ pollutant that has an influence on climate, although its varied composition means its climate effects are less straightforward than those of O_3.

103. IPCC's earlier assessments of direct negative radiative forcing by aerosols focused on 'sulphates', 'organic carbon', and 'biomass burning'. AQEG (2005) showed nitrates originating from fossil fuel combustion emissions of NO_X are regionally of comparable importance to sulphates as a component of PM_{10}, whilst globally nitrates can largely be considered as originating mostly from biomass burning. We will therefore emphasise issues surrounding nitrate aerosols rather more than IPCC has done in the past, because our focus is on CC and AQ in the UK.

104. The complete list of pollutants, their contributions to AQ and CC directly and indirectly as precursors of secondary pollutants, is summarised in Table 3.1. Whilst the well-mixed GHGs CO_2, nitrous oxide (N_2O) and halocarbons are not AQ pollutants, they are often emitted from the same sources as AQ pollutants. This will be important in Chapter 5, where the combined climate and AQ effects of measures to control emissions will be considered.

105. Not all activities, sectors or sources emit pollutants that contribute to CC and AQ in the same proportions. Some activities emit GHGs and AQ pollutants that all contribute to positive forcing of climate. Other activities emit GHGs but the AQ pollutants that are emitted at the same time might be considered to offset the effect of the GHGs in some way by exerting a negative forcing on climate. Other activities emit AQ pollutants but predominantly those that have rather little effect of climate. Finally, there are activities that predominantly emit GHGs and have negligible effects on AQ. In discussing these four categories of qualitatively different emissions mixtures, the Expert Group came to the conclusion that it was difficult to assign sources into clear categories, but that the variety of combination of effects is more like a continuous spectrum. The analogy of a spectrum is a good one, since the decomposition of the continuum into separate 'AQ' and 'CC' effects is a feature of the way policy 'sees' the variations, just as we can see the colours of a spectrum as a combination of primary colours. Qualitatively different combinations of emissions of AQ and CC pollutants can be identified in all sectors of emissions. These are plotted on a 'spectrum' of effects combinations Figure 3.1.

Figure 3.1: Spectrum of diversity of combination of impacts from different sectors



3.2 Interactions between air quality pollutants and greenhouse gases, and quantification of the resulting radiative forcing of climate

106. In this section we review scientific understanding of the processes linking emissions of AQ pollutants to radiative forcing of climate. The concept of radiative forcing was introduced in Section 2.2.1. Section 3.2.1 reviews how emissions of NO_X, VOCs, CH_4, CO and H_2 influence concentrations of tropospheric O_3 and its action as a GHG. In addition, the oxidising capacity of the atmosphere that is perturbed by the same cycles of chemical reactions determines the lifetime and hence the GWP of CH_4. This subsection therefore includes some complex interactions between GHGs and AQ pollutants in the atmosphere. It concludes with a review of the latitudinal and longitudinal dependence of radiative forcing due to tropospheric O_3, and hence provides an assessment of the contribution to radiative forcing by UK emissions of pollutants that influence the oxidising capacity of the atmosphere as well as tropospheric O_3 concentrations.

107. Section 3.2.2 then does the same for aerosols. This includes the formation of secondary aerosols involving some of the same tropospheric photochemistry that is described in Section 3.2.1, but also considers primary aerosols. The contribution of these to radiative forcing as a function of their composition, size, and location is assessed, both for their direct effects and their indirect effects on forcing via the changes they cause in the properties of clouds.

108. Finally, Section 3.2.3 reviews the impacts of AQ in modifying the uptake and emissions of GHGs by ecosystems. Note that effects of CC in modifying AQ indirectly through its effects on ecosystems are not considered here but in Section 4.3.2 of Chapter 4.

Table 3.1: Summary of pollutant emissions, secondary pollutants, and impacts on climate change & air quality. Emissions of each pollutant from each sector are classified as 'X', 'XX', or 'XXX' on a qualitative scale from minor or small to large or dominant. Areas of uncertainty are indicated '?', and the special case of bidirectional emission (i.e. absorption as well as potential to emit) indicated by '+/ '.

Pollutant:		CO_2	*electrical energy consumed*	CH_4	H_2	N_2O	CFCs etc.		H_2O	CO	VOC	Isoprene	Particles									SO_2	NOx	NH_3	photooxidant	
							HFC_{23}	others					Soot	Dust	Sulphate	Nitrate	Ammonium	Organic	all PM_{10}	all $PM_{2.5}$	particle number				O_3	other
Classification	Greenhouse gas	🟥		🟥	🟥	🟥	🟥	🟥	🟥																🟥	
	"Air quality pollutant"									🟩	🟩		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	
	Direct impact on climate																									
	Warming	🟥		🟥	🟥	🟥	🟥	🟥	🟥		🟥		🟥						🟥	🟥	🟥					
	Cooling								🟦				🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦				🟦	
	Indirect impact on climate																									
	via chemistry			🟨						🟨	🟨											▨	🟨	▨	🟨	🟨
	via cloud											▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	Precursor of…		CO_2, SO_2, NOx,…	O_3					cloud		PM, O_3	PM, O_3	PM		- cloud -			PM	- cloud -		PM	PM	nitrate, O_3	PM	PM	O_3
	Distribution:																									
	Local, short-lived								🟩	🟩	🟩	🟩	🟩	🟩					🟩	🟩	🟩	🟩	🟩	🟩		🟩
	Regional								🟦	🟦	🟦		🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦					🟦	🟦
	Globally mixed	🟪		🟪	🟪	🟪	🟪	🟪	🟪	🟪															🟪	
	Persistent, longer life than CO_2							🟥																		
Sector																										
Transport	Gasoline	XXX				catalyst			X	XX	XX			X				X	X	X	XX		X	catalyst		
	Diesel	XX							X		X		XX	X				X	XX	XX	XX		XX			
	Biofuel	X							X	X	X		X	X				X	X	X	XX		X			
	Gas	XX		X		catalyst			X	X	X			X					X	X	XX		X	catalyst		
	Hydrogen		X		XX				XX					X					X	X						
	Electric		XXX																							
	Shipping	XXX							X	X	X		XX					?	XX	XX	X	XX	X			
	Aviation	XXX							contrails	XX	XX		XX					?	XX	XX	XX		X			
Stationary combustion	Coal	XXX		?					X	X	X		XX	X				?	XX	XX	XX	XXX	XX	?		
	Oil	XXX							X	X	XX?		X?					?	X	X	XX	X	X			
	Gas	XX		X					X	X	X									X	XX		X			
	Waste	X		?					X		X							?	X	X	X		X	?		
	Biofuel	X							X		X		X					?	X	X	XX		X			
Agriculture	Livestock			XX										X					X	X				XXX		
	Fertiliser					XXX								?		?			?	?				XX		
	Pesticide																									
	Ploughing													XX					X	X						
	Forestry	+/-									XX	X		XX					X	X						
Industrial process	Cement	XXX												XX					X		XX					
	Glass		XXX												X				X	X	XX					
	Smelting	?																			X					
	Nylon, nitric acid production		X			X																				
	HFC, HCFC, Aluminium, Electronics		X				XXX	XXX																		
Waste	Landfill	X		XX							XX								X	X				XX		
	Thermal treatment	X		?							XX		X					?	X	X	XX			?		
	Composting	?		?							?								?	?				?		

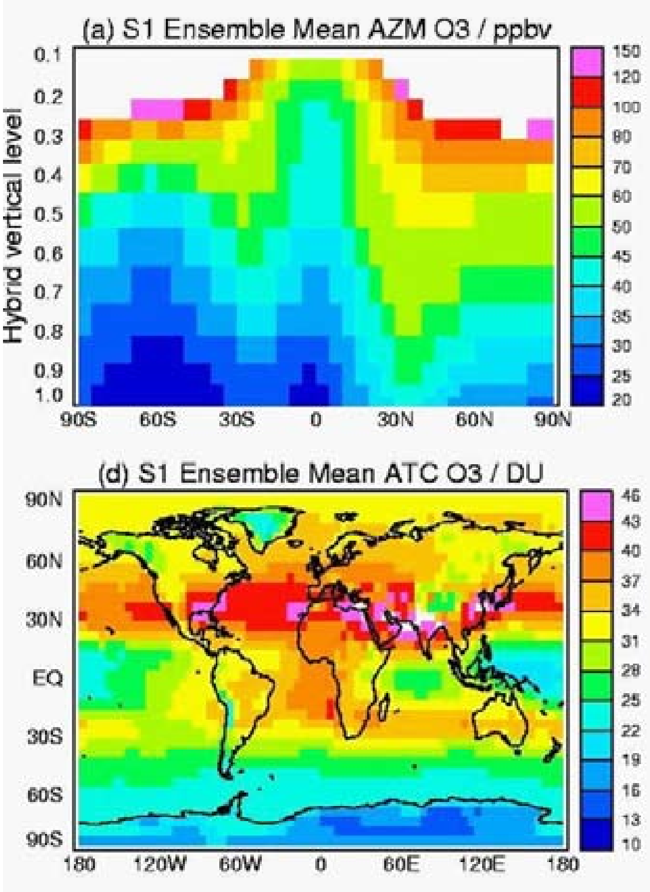
3.2.1 Tropospheric photochemistry and ozone

3.2.1.1 Ozone as a greenhouse gas

109. Tropospheric O_3 is generated by the chemical cycles that were described in Box 2.1 in Chapter 2. In addition, influx of air from the stratosphere provides a substantial source. Ozone is destroyed chemically by photolysis in the presence of water vapour and by reaction with hydroxyl radical (OH) and hydroperoxyl radical (HO_2). It is also lost at the Earth's surface to deposition. Where O_3 is considered as an AQ pollutant, the impact of CC on concentrations through perturbation of its rates of formation and destruction is reviewed in Chapter 4. Where O_3 is considered as a GHG, the influence of CC on concentrations is considered as a climate feedback process. In this chapter we therefore restrict our discussion to the processes that have resulted in changes in O_3 concentration and hence determine the magnitude and nature of O_3's impact on climate. The issue of feedbacks has already been covered in Section 2.3.4.

110. Figure 3.2 shows simulations of the zonal volume mixing ratios (altitude vs latitude in ppb) and the tropospheric O_3 column (Dobson units, DU, 1DU = 2.68×10^{16} molecule cm^{-2}) obtained by averaging results from 25 models. The effects of this O_3 on CC are, of course, related to the change in abundance since pre-industrial times, especially at the latitudes and altitudes where tropospheric O_3 is most effective as a GHG.

Figure 3.2: Simulations of present day (2000) concentrations of tropospheric ozone (average of 25 ACCENT models). Annual zonal mean (AZM, ppb), and annual tropospheric column (ATC, Dobson units) (from Stevenson *et al.*, 2006). To convert to μg m^{-3} units, 1 ppb = 2.00 μg m^{-3} for O_3 at 20°C and 101.3 kPa



111. It has been estimated that the past increase in the tropospheric abundance of O_3 may have provided the third largest increase in direct radiative forcing since the pre-industrial era (Ramaswamy *et al.*, 2001). Volz and Kley (1988) and Marenco *et al*. (1994) present measurements of surface O_3 concentrations suggesting a two to threefold increase in the 20th Century. Measurements at Mace Head on the west coast of Ireland indicate an increase in the background concentration of O_3 of approximately 0.5 ppb yr^{1} (1.0 µg m^{-3} yr^{1}) over the period 1987 to 2003 (Simmonds *et al.*, 2004). It is likely that this increase corresponds to a hemispheric rise in background O_3 arising from increases in emissions of precursors coupled with long range transport.

112. Direct measurements of the global increase in tropospheric O_3 concentration are difficult, because its concentration varies substantially and O_3 sonde measurements have been limited (Logan, 1999). Measurements of the tropospheric O_3 column have also been made from satellites, but these estimates are difficult because of the much larger contribution from the stratosphere. These estimates suggest a mean abundance, throughout the troposphere, of 50 ppb (100 µg m^{-3}) (Ramaswamy *et al.*, 2001).

113. The increase in the total tropospheric burden of O_3 since pre-industrial times has been estimated as 36%, from 270 Tg to 360 Tg (Ramaswamy *et al.*, 2001). Figure 3.3 shows a simulation of the globally distributed radiative forcing due to the change in O_3 concentrations between 1850 to 2000 from one example out of the ten models used in the IPCC Third Assessment Report (Gauss *et al.*, 2003). This model gives a global mean forcing of 0.38 W m^{-2} compared to the multi-model mean and standard deviation of 0.36 ± 0.07 W m^{-2}. Figure 3.4 shows a similar plot from 2000 to 2100 and demonstrates significantly larger increases. This model has a global mean forcing of 0.53 W m^{-2} compared to the multi-model mean and standard deviation of 0.56 ± 0.12 W m^{-2}.

Figure 3.3: Radiative forcing due to changes in tropospheric ozone from 1850 – 2000 using SRES A2 scenario. STOCHEM-HadGEM model used for IPCC Fourth Assessment Report (from Gauss *et al.*, 2003)

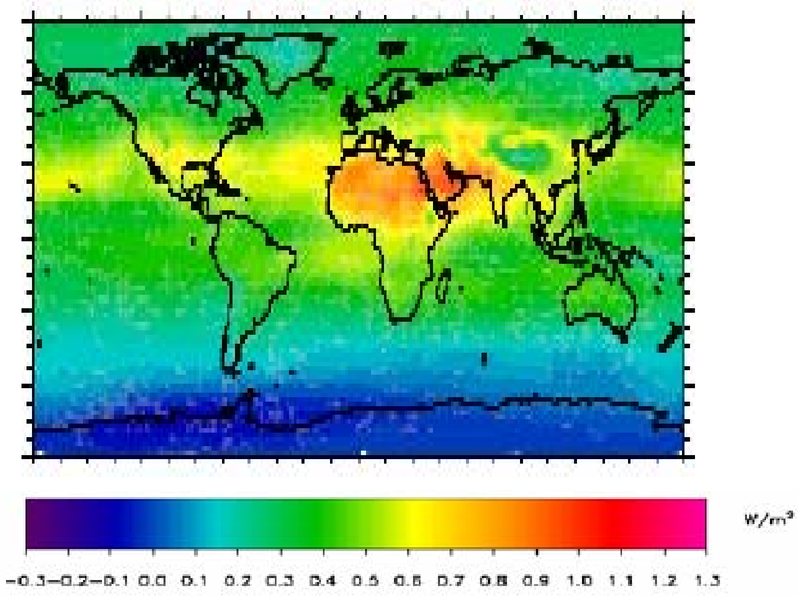
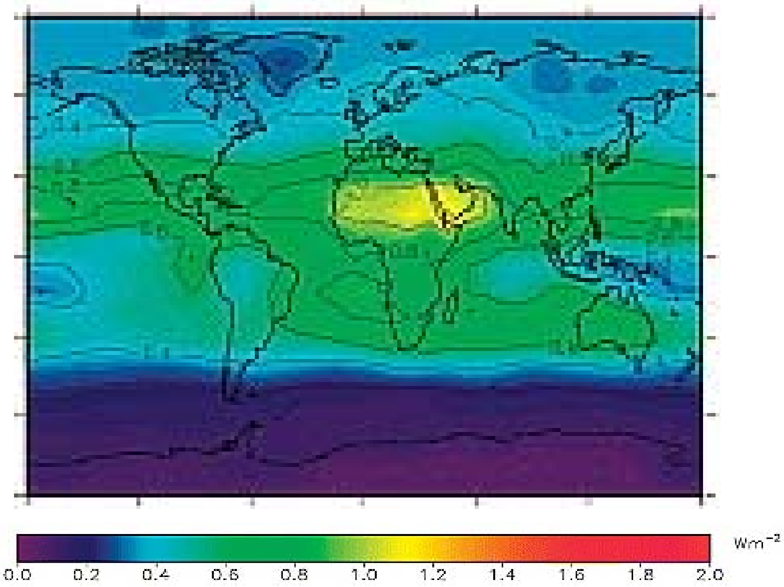


Figure 3.4: Radiative forcing due to changes in tropospheric ozone from 2000 – 2100 using SRES A2p scenario. STOCHEM model used for IPCC Third Assessment Report (from Gauss *et al.*, 2003). Note different colour scale to Figure 3.3



3.2.1.2 Indirect radiative forcing from ozone precursor emissions

114. An important issue for policy is whether the steps taken to reduce O_3 precursor emissions on the regional-scale could exacerbate or ameliorate global and regional CC.

115. Up to 10% of the O_3 formed in European photochemical O_3 episodes may be produced by the oxidation of CH_4 (Derwent, 1995). Methane together with CO, VOCs and NO_X controls the hemispheric levels of O_3, as was outlined in Section 2.4.1. To reduce hemispheric-scale O_3, CH_4 emission reductions have to take place globally and reductions in Europe produce the same effects as reductions elsewhere on the globe. European CH_4 emission reductions would, on this basis, contribute to reducing baseline O_3 levels globally and should be considered along with regional-scale VOC and NO_X emission controls in meeting Europe's clean air targets. Since CH_4 emissions are spread throughout the globe, Europe benefits less from the modest reduction in baseline O_3 by taking action on CH_4 emissions at a regional-scale than it would from global policy action (Derwent *et al.*, 2005b; Solberg and Lindskog, 2005).

116. In addition to CH_4, a range of trace gas emissions from both natural and man-made sources, including CO, VOCs and NO_X, act together to control the oxidising capacity of the troposphere. Actions taken on the regional-scale to control and reduce emissions of these tropospheric O_3 precursor gases will therefore induce changes in the oxidising capacity of the troposphere and may ameliorate or exacerbate CC by changing the rate of global build-up of CH_4 and by changing the rate of increase in global O_3.

117. The balance between exacerbation and amelioration in the response of the climate system to regional-scale emission controls of the tropospheric O_3 precursor gases is finely divided. It appears to be strongly dependent on the precursor gas being controlled and markedly different between the same controls enacted

within North America, Europe, Asia and the Southern Hemisphere and whether enacted upon surface sources or on global aviation (Fuglestvedt *et al*.,1999; Derwent *et al*., 2001; Collins *et al*., 2002; Stevenson *et al*., 2004; Naik *et al*., 2005).

118. The issues here relate to the responses of the global CH_4 and O_3 burdens to changes in regional emissions of the tropospheric O_3 precursor gases: CH_4, CO, H_2, VOCs and NO_X. Depending on the location, sign and magnitude of the emission changes, generally speaking, there are three different responses to be quantified:

- a long-term CH_4 response that builds up and decays with a 10-15 year timescale, driven by any changes induced in the tropospheric OH distribution
- a short-term O_3 response that builds up and decays with a timescale of a few months
- a long-term O_3 response, driven by changes in the CH_4 distribution, that builds up and decays with a 10 – 15 year timescale.

119. These three different responses have different spatial distributions in addition to their markedly different time dependences. Generally speaking, in the AQ arena, the main concerns are focused on the short-term O_3 responses in the regions close to where the emissions have changed. In the CC context, all three responses are potentially important when integrated over a time horizon of say, 100 years. This is why there is an interaction between regional AQ and CC policies.

120. Increases in regional-scale CH_4 emissions bring about a long-term depletion in tropospheric OH levels and hence long-term increases in the global CH_4 build-up and atmospheric burdens. This enhanced CH_4 response to increased CH_4 emissions is termed the CH_4 self-feedback or indirect effect (Isaksen and Hov, 1987; Lelieveld and Crutzen, 1992; Houghton *et al*., 1995). In addition, the long-term increase in CH_4 burdens leads to an increase in tropospheric O_3 burdens. For CH_4 the short-term O_3 response is not distinguished from the long-term one. The long-term CH_4 and O_3 responses to increased regional-scale CH_4 emissions both lead to positive radiative forcing (climate warming) and so they reinforce each other. The O_3 radiative forcing is a small fraction of the CH_4 forcing (Lelieveld and Crutzen, 1992; Derwent *et al*., 2001; Ramaswamy *et al*., 2001).

121. Increases in regional-scale H_2 emissions act in an analogous manner to those of CH_4 discussed above. Short-term O_3 responses are small compared to the long-term O_3 response. The time-integrated radiative forcings from the CH_4 and O_3 responses act to reinforce each other (Derwent *et al*., 2001). Increased regional-scale H_2 emissions therefore lead to positive radiative forcing (climate warming). These impacts of H_2 are of interest because of the growing interest in the H_2 economy (Prather *et al*., 2001).

122. Increases in regional-scale CO emissions generate a short-term increase in O_3 burdens that builds up and decays over a period of up to 6 months and long-term increases in CH_4 and O_3 burdens that build up and decay over 10 – 15 year timescales. All these responses reinforce each other (Fuglestvedt *et al*., 1996; Daniel and Solomon, 1998; Derwent *et al*., 2001) so that increases

in CO emissions lead to positive radiative forcing (climate warming). The time-integrated radiative forcing due to the O_3 response to CO emission changes is about one half that due to the CH_4 response.

123. Increases in NO_X emissions generate a short-term increase in O_3 burden that builds up and decays away within a few months. They also produce rapid increases in local tropospheric OH levels that enhance CH_4 destruction rates and lead to reduced global CH_4 and O_3 burdens that build up and decay over a 10 – 15 year timescale.

124. For aircraft NO_X sources, increased NO_X emissions lead to short-term increases in O_3 burdens (positive radiative forcing) and long-term decreases in CH_4 (negative radiative forcing) and O_3 (negative radiative forcing) burdens. Some of these individual forcings may be comparable in magnitude to the forcing due to aviation's CO_2 emissions. Stevenson *et al*. (2004) report, however, that the three terms in paragraph 118 above sum to approximately zero when considering the globally-integrated long-term annual mean net radiative forcing from increases in aircraft NO_X emissions. Wild *et al*. (2001) report a small positive net radiative forcing showing that the time-integrated CH_4 and O_3 radiative forcing terms are indeed finely balanced. Further studies with a variety of differently formulated models are required to confirm the sign and magnitude of the aircraft NO_X-driven net radiative forcing. Even though the global mean time-integrated net radiative forcing may be small, there are of course potentially significant non-zero local radiative forcings.

125. Increases in surface NO_X emissions generate a somewhat different balance between short-term O_3 increases (positive radiative forcing) and long-term CH_4 and O_3 decreases (negative radiative forcing) compared with aircraft NO_X emissions. Ramaswamy *et al*. (2001) and Penner *et al*. (1999) note that the indirect effects of NO_X on radiative forcing due to O_3 production and shortening of the CH_4 lifetime are approximately equal in magnitude but opposite in sign, with a high degree of uncertainty in both. Furthermore, there are important differences in this balance depending upon the continent in which the NO_X emissions are changed, whether in Europe, North America or Asia (Fuglestvedt *et al*., 1999; Naik *et al*., 2005).

126. On balance, our current view (Derwent *et al*., 2006) is that increases in surface NO_X emissions produce global mean time-integrated radiative forcings that are small and negative (climate cooling). These global mean time-integrated forcings increase in the order from Europe through North America to Asia. Again, as with aircraft NO_X emissions, further studies with a variety of differently formulated models will therefore be required to confirm the sign and magnitude of the surface NO_X-driven net radiative forcing. Although the global mean time-integrated radiative forcings sum to near zero effects, there are, of course, potentially significant non-zero local radiative forcings driven by changes in surface NO_X emissions.

127. Increases in regional-scale VOC emissions produce responses in the global burdens of CH_4 and O_3 that follow those detailed above for CO emissions (see paragraph 122). However, there is an additional factor to take into account with the VOCs because of their markedly different atmospheric reaction pathways. Collins *et al*.

(2002) found that increasing emissions of VOCs gave rise to short-term increases in global O_3 burdens (positive radiative forcing) and long-term increases in global CH_4 and O_3 burdens (positive radiative forcing). All the three responses from paragraph 118 above, therefore, reinforce each other and, by and large, global mean time-integrated radiative forcings from the CH_4 and O_3 responses are similar in magnitude. However, for those VOCs where peroxyacetyl nitrate (PAN) is formed as a substantial reaction product, as is the case with propene, toluene and acetaldehyde, the balance between the forcing terms shifts abruptly. Peroxyacetyl nitrate acts as a temporary reservoir species for NO_X and thus its enhanced formation enhances CH_4 oxidation, leading to further decreased CH_4 burdens than would otherwise be the case.

128. Tropospheric O_3 precursors are not included in the basket of trace gases considered within the UN Framework Convention on Climate Change (UNFCCC). The complications that would need to be addressed, were they to be included, may be substantial. Nevertheless, this remains a major barrier to the consideration of AQ and global CC issues within a holistic policy framework. Within Europe, CC and AQ issues are not linked so that the opportunities brought about through O_3 precursor emission control of baseline O_3 have not been taken into account in the Clean Air For Europe (CAFE) process. For ground-based fossil fuel combustion, typical ratios of CO_2 to NO_X in the emissions mixture ensures the direct climate effects of the CO_2 are orders of magnitude more than even the individual indirect effects of the NO_X. Individual NO_X climate effects of aviation emissions may compete with aviation CO_2 over certain timescales and lengthscales, but probably not if all positive and negative NO_X effects are summed. For fossil fuel combustion, the main impact of non-CO_2 emissions is therefore usually via primary and secondary AQ pollutants. For non-fossil fuel sources however, the above analysis highlights the importance of climate effects of non CO_2 emissions as well as impacts on AQ. Abatement policy should therefore be developed with care, to ensure a coherent approach is adopted that takes these issues into account wherever possible.

3.2.2 Aerosols

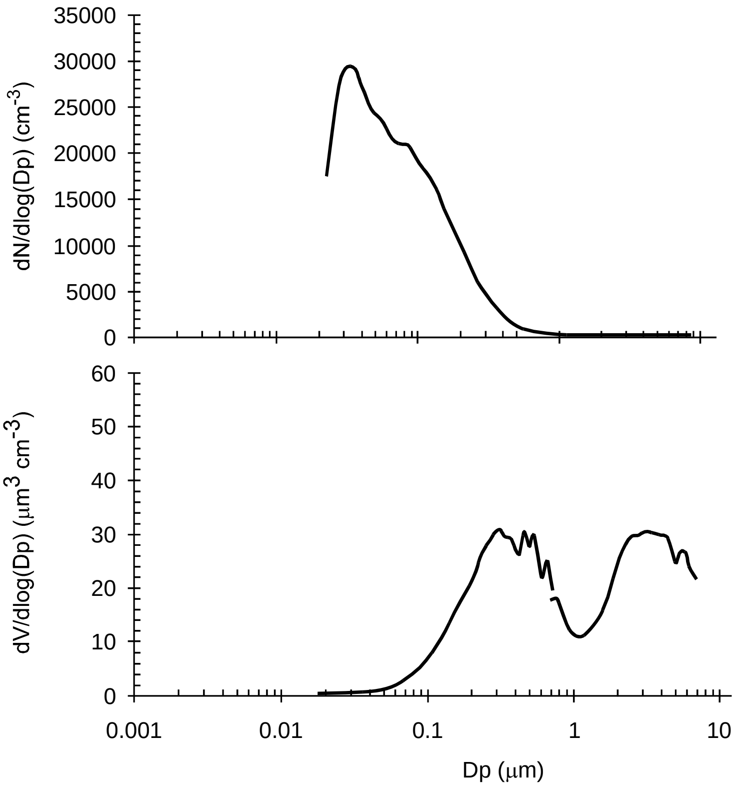
3.2.2.1 Importance of primary and secondary aerosols for air quality and climate change

129. Whereas AQ management is predominantly concerned with the effects of airborne PM on health, the radiative forcing of climate by atmospheric aerosol particles is determined by their optical properties and their role in clouds. In this section we therefore review the formation and properties of the mixture of particles that is found in the troposphere, with a focus on UK conditions, and consider the extent to which the same particles that are of concern to local and regional AQ are also active in the radiative forcing of climate.

130. AQEG (2005) considered how effects of PM on human health is commonly regulated largely in terms of PM_{10} (the total mass of particles smaller than 10 μm), with a trend towards greater consideration of smaller size fractions such as $PM_{2.5}$ as evidence accumulates that these are more toxic per unit mass. Air quality metrics based on the number of particles or their surface area have been considered, but current regulation remains in terms of mass. Figure 3.5 shows

that a substantial contribution to PM_{10}, and an even more significant contribution to $PM_{2.5}$, comes from particles in the size range 0.1 to 1 μm. Even though a single particle within this size range is three to six orders of magnitude less heavy than a single particle of 10 μm diameter, the much larger number of particles at these small sizes is sufficient to compensate for the smaller mass per particle.

Figure 3.5: Number (top) and volume or mass (bottom) of particles as a function of their size ("diameter") D_p, measured in suburban Birmingham (from AQEG, 2005)

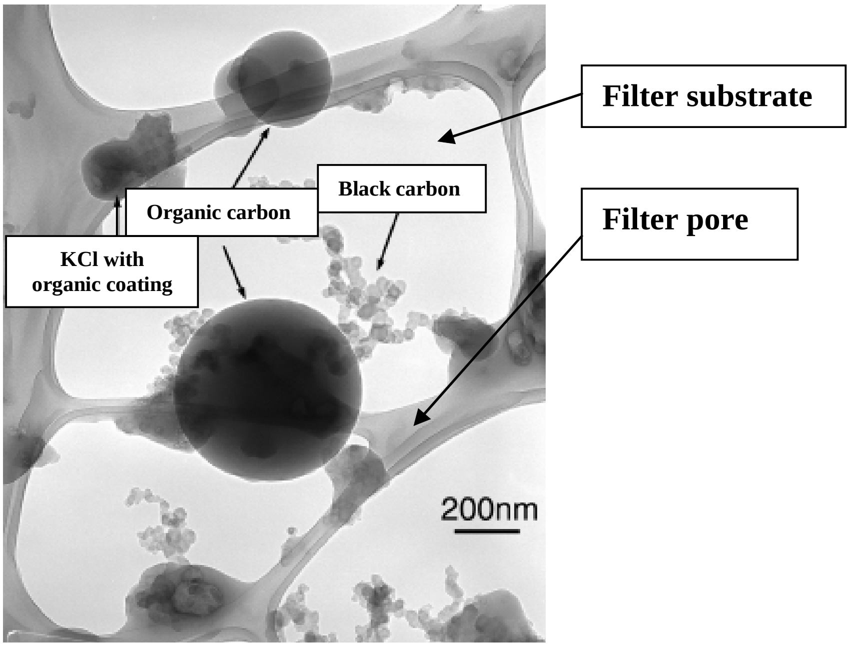


131. Sources of primary PM in the UK were reviewed in detail by AQEG (2005). Ground-level concentrations of primary PM in much of the UK are dominated (in terms of mass) by diesel emissions of BC soot, especially in London where there is a lot of diesel traffic and relatively little heavy industry. These particles are predominantly in the ultrafine particle size range, smaller than 0.1 μm. The largest number of particles is often smaller than 0.03 μm (30 nm) (Figure 3.5), which appear to comprise predominantly semi-volatile organic material, probably with a sulphate core. A much larger proportion of UK total emissions however, come from heavy industry. Whilst unburnt soot is emitted from small and mobile sources, emission of soot is avoided from large combustion plant as failure to burn it would be inefficient. Large combustion plant emissions therefore consist largely of ash from impurities in solid fuels, with much larger particles which are fewer in number than diesel exhaust emissions.

132. The 'black smoke' monitored for urban AQ assessment is often composed of a complex internal and external mixture, where some particles have more than one component and others are made up of a single component, as shown in

Figure 3.6. This can be contrasted with the climate community's work with BC aerosols which are defined as the elemental C emissions from incomplete combustion even though, in effect, both communities are considering similar particles.

Figure 3.6: A scanning electron micrograph showing the particles that make up 'black smoke'. Black carbon aerosol is also shown



133. AQEG (2005) also highlighted the importance of secondary PM as a contribution to PM_{10} and $PM_{2.5}$. This is mostly found in the accumulation mode between D_p = 0.1 and 1 μm in Figure 3.5, with some secondary PM also making a contribution at larger particle sizes.

134. The main precursors of secondary aerosol particles are as follows:

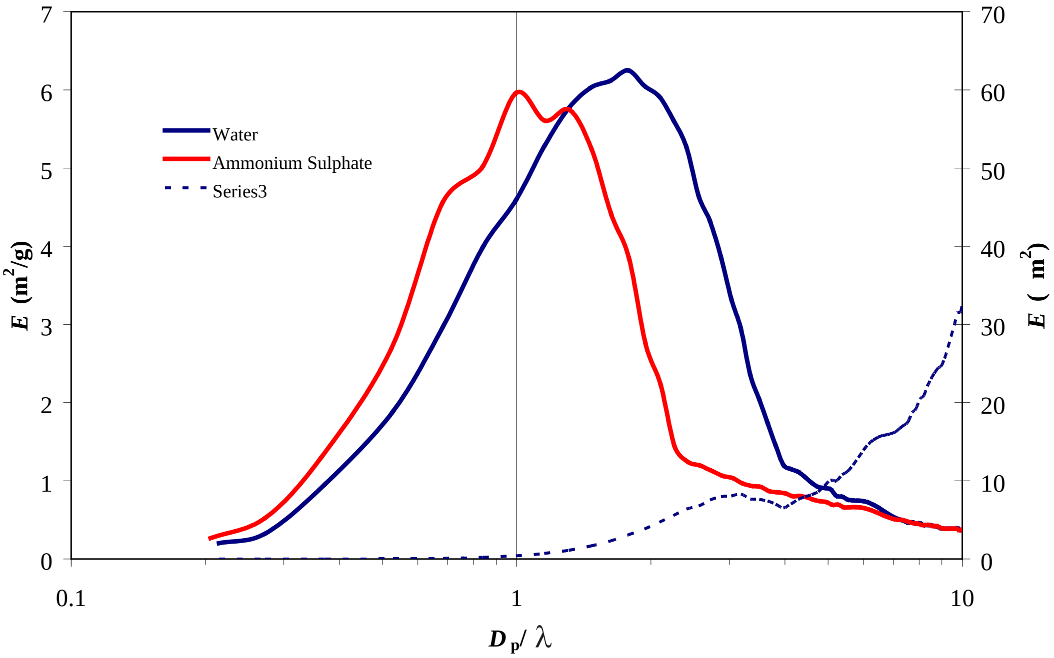
- **Sulphur dioxide and reduced sulphur species** (i.e. hydrogen sulphide (H_2S), carbonyl sulphide (COS), carbon disulphide (CS_2), dimethyl sulphide (DMS) (CH_3SCH_3), methanethiol (CH_3SH), dimethyldisulphide (CH_3SSCH_3)). Oxidation generates sulphate aerosol.
- **Nitrogen oxides.** Oxidation generates nitrate aerosol.
- **Ammonia.** Neutralises acidic aerosols, leading to ammonium (NH_4) aerosol.
- **Volatile organic compounds.** Oxidation of some VOCs generates SOA.

135. AQEG (2005) reviewed in detail how the source apportionment of PM varies with location and in time. Urban AQ management considers local air pollution hot spots where primary PM from local ground-level combustion sources makes up a significant proportion of the total. Regionally however, secondary aerosol material makes up a larger fraction of the total mass over wide areas of land and sea, with more important primary contribution from sea spray and dust. While ground-level urban sources make a smaller contribution regionally, their effects may still be quantifiable, and there are also contributions from tall chimneys and aircraft that are more important for CC than for ground-level AQ.

136. Figure 3.7 shows how aerosol particles scatter light most efficiently if their diameter (approximating them to be spherical, which is an excellent approximation for strongly hygroscopic particles above their deliquescence point) is similar to the wavelength of the light being scattered. For incoming solar radiation (visible and near ultraviolet), this is therefore submicron particles.

137. Comparison of Figures 3.7 and 3.5 shows that maximum scattering efficiency per unit mass corresponds to the accumulation mode aerosol mass distribution for light of visible and ultraviolet wavelengths of light (0.2 to 0.8 μm). Figure 3.7 also explains why only large particles with diameters such as mineral dust and hydrated sea-salt particles are efficient at interacting with terrestrial radiation at wavelengths close to 10 μm.

Figure 3.7: Single scattering efficiencies *E* for light of wavelength λ scattered by homogeneous spherical droplets of diameter D_p, per unit mass of aerosol (solid line, left axis) and per droplet (dotted line, right axis) (adapted from Seinfeld and Pandis, 1998)



138. The change in concentration of anthropogenic aerosol since pre-industrial times has therefore increased the amount of incoming solar radiation reflected back out to space, giving rise to a negative radiative forcing of climate. This has been extensively studied and modelled, especially for sulphate aerosol, and is therefore the best understood and quantified contribution of atmospheric aerosols to the anthropogenic radiative forcing of climate. This is known as the direct radiative forcing effect of aerosols. The contribution of the same particles both to local concentrations of PM_{10} and $PM_{2.5}$ and to the radiative forcing of climate is thus an important interaction between AQ pollutants and CC. There are additional effects of aerosol, concerned with their blackness and interactions with cloud, which were outlined in Chapter 2, most of which make the contribution of components of PM_{10} and $PM_{2.5}$ to CC even more significant. The following sections therefore review in depth the main issues surrounding the formation, properties, and climate effects of the main components of PM_{10} and $PM_{2.5}$.

3.2.1.3 Chemistry of secondary aerosol formation

139. There are four physical processes by which these precursor species can become incorporated into solid or liquid-phase aerosol material:

- **Heterogeneous nucleation or condensation**. Occurs when low volatility products of the oxidation of emitted precursor gases condense onto existing particles causing them to grow.
- **Homogeneous nucleation**. Occurs when particularly low volatility products nucleate new particles.
- **Reactive uptake**. Occurs when gaseous species react with existing aerosol, with the products of such reactions remaining either wholly or partially in the aerosol phase.
- **In cloud oxidation**. Occurs when soluble gases are oxidised in cloud droplets to generate additional aerosol mass upon evaporation.

140. Reduced sulphur gases (particularly DMS) predominantly from biogenic sources contribute globally to sulphate aerosol formation. These tend to be oxidised to sulphate via SO_2 formation, but possess a wide range of atmospheric lifetimes (see Table 1.1 in Chapter 1). The largest impact is over the remote ocean, where phytoplankton lead to DMS release.

141. The oxidation of emitted SO_2 occurs by both gaseous phase and aqueous phase routes. This chemistry was described in AQEG (2005). At a typical background OH concentration of 106 molecules cm^{-3} (0.04 ppt) the gas phase oxidation rate of SO_2 initiated by reaction with OH is about 0.3% hr^{1} based on the rate coefficient recommended by Atkinson *et al*. (2004).

142. The initial product of SO_2 oxidation is gaseous sulphuric acid (H_2SO_4). This is sufficiently involatile to generate secondary particles by the processes of nucleation and condensation. The gas phase oxidation of SO_2 may therefore result in the formation of new particles, or the growth of existing ones.

143. In-cloud oxidation of SO_2 occurs more rapidly than gas phase oxidation. It is governed by the solubility of SO_2 in cloud droplets, the aqueous phase oxidation rate, and how frequently polluted air masses encounter clouds. It has been estimated to occur at a rate of about 1% hr^{1}, on average, under UK conditions (e.g. Metcalfe *et al*., 1995).

144. Nitrate aerosol is formed similarly from the oxidation of NO_2, which is itself mainly derived from the oxidation of emitted NO from combustion processes. Oxidation may be initiated by reaction with OH (most important during the day), and by reaction with O_3 (most important during the night). At a typical background OH concentration of 106 molecule cm^{-3}, NO_2 is converted to gaseous nitric acid (HNO_3) at about 5% hr^{1} based on the rate coefficient recommended by Atkinson *et al*. (2004). Nitrate formation thus tends to occur somewhat more rapidly and closer to sources of NO_X than sulphate formation to sources of SO_2 and, furthermore, does so irrespective of the presence of cloud.

145. Reaction of NO_2 with O_3 also leads to nitrate aerosol, via the formation of nitrate radicals and the higher oxide, nitrogen pentoxide (N_2O_5). This reaction sequence is very inefficient during the day, and at higher levels of NO, because nitrate photolyses and reacts with NO rapidly, leading to NO_X regeneration. During the night, significant NO_2 to N_2O_5 conversion can occur, with the potential for nitrate aerosol generation from the reaction of N_2O_5 with water on existing particle surfaces or aqueous droplets. The conversion of NO_2 to nitrate aerosol, via N_2O_5, potentially occurs at a comparable rate to that from OH initiated oxidation during daytime.

146. Ammonia is the most abundant alkaline gas in the atmosphere, and therefore plays a significant role in neutralising acids. It reacts with H_2SO_4 and HNO_3 formed by the processes described above, leading to the formation of ammonium aerosol. Incorporation into ammonium sulphate is irreversible, whereas ammonium nitrate can dissociate back to NH_3 and HNO_3 vapour. It also promotes the formation of sulphate in clouds where a lack of other oxidants means O_3 is the main oxidising agent, by raising the pH and increasing the solubility of SO_2 which determines the rate of oxidation if the oxidation is not acid catalysed.

147. Secondary Organic Aerosol is formed when the oxidation of emitted non-methane volatile organic compounds (NMVOC) generates oxygenated products which undergo gas-to-particle transfer. Important precursor VOC may be emitted from both anthropogenic and biogenic sources. The gas-phase oxidation of each VOC leads to the production of a set of organic products containing polar oxygenated functional groups which tend to make the products less volatile and more water soluble.

148. Certain classes of VOC are more likely to lead to aerosol formation by virtue of their general high reactivity and types of oxidation product formed. Large, cyclic, unsaturated compounds are believed to be of particular importance, since the oxidation products tend to be of comparatively high molecular weight, and contain two or more polar functional groups: these products are therefore of lower volatility. Two such classes of emitted VOC, which have been shown to generate SOA, are monoterpenes (e.g., α and β pinene) and aromatic hydrocarbons (e.g., toluene and xylenes), although other classes may also contribute. Monoterpenes are naturally-emitted VOC, which are estimated to account for a substantial fraction (20-80%) of the UK total of biogenic VOC, with an important contribution made by coniferous trees (e.g. Dore *et al*., 2003a; EMEP-CORINAIR, 2004). Aromatic hydrocarbons are primarily of anthropogenic origin, accounting for about 12-15% of the UK anthropogenic VOC total (e.g. Dore *et al*., 2003b). The majority of this derives from road transport emissions.

149. Current understanding of the oxidation mechanisms and the types of product observed in the aerosol phase in chamber studies suggest that the ability of VOC to generate SOA may be NO_X -dependent, being more efficient at lower NO_X concentrations.

150. The results of chamber studies and some atmospheric observations (and associated modelling studies) strongly suggest that partitioning of organic species can be further stabilised in the condensed phase by association and accretion reactions, which may be enhanced in acidic aerosols. Such reactions lead to the formation of very high molecular weight 'humic-like substances', and it is probable that such processes play an important role in atmospheric SOA formation.

3.2.1.4 Possible trends in the rates of secondary aerosol formation processes

151. In the UK, emissions of SO_2, NO_X and anthropogenic VOC have decreased significantly in recent years, and are projected to continue decreasing. Ammonia emissions are decreasing slowly. Biogenic VOC emissions depend on temperature and light and therefore show year-on-year variability. Projected increases in temperature may be accompanied by increases in biogenic VOC emissions.

152. Although a substantial trend to lower SO_2 emissions has occurred in the UK, this has almost certainly been accompanied by an increased fractional oxidation rate of SO_2 to sulphate. In particular, the in-cloud oxidation route is likely to be more efficient because cloud droplets are less acidic. This increases the solubility of SO_2, and its oxidation rate by reaction with dissolved O_3. Ozone availability in the UK has also increased, partly because of the increasing trend in background O_3 concentrations, but even more significantly because of the reduction in NO_X emissions – i.e. the area of the UK where O_3 has been 'titrated out' by reaction with emitted NO has reduced. Reductions in NO_X have probably also increased average OH concentrations, such that the rate of gas phase SO_2 oxidation has also increased. It is also probable that greater radical densities have also increased hydrogen peroxide (H_2O_2) formation, further promoting in-cloud SO_2 oxidation.

153. Although a substantial trend to lower NO_X emissions has occurred in the UK, this has almost certainly been accompanied by an increased fractional oxidation rate of NO_X. The reduction in NO_X emissions has increased O_3 availability, such that a greater proportion of NO_X is in the form of NO_2. The fractional rates of both NO_2-to-nitrate oxidation routes has almost certainly also increased. The 'night-time' route also relies on O_3 availability, and is severely inhibited by the presence of NO. The regime where this oxidation route can operate is realised more quickly after NO_X release, as NO_X emissions (and concentrations) decrease. Reductions in NO_X have probably also increased average OH concentrations, such that the 'daytime' oxidation rate by reaction with OH has also increased.

154. There are many factors which can potentially influence SOA formation. Although anthropogenic VOC emissions are decreasing, biogenic emissions are probably increasing. Reported information suggests that biogenic VOC are generally more efficient SOA producers. The oxidation of terpenes by reaction with O_3 is of particular significance, such that increased O_3 availability resulting from NO_X reductions will increase the oxidation rate. In addition, there is evidence that SOA yields from terpene ozonolysis increase as NO_X decreases. These factors all suggest that there may be a trend towards increasing SOA formation. However, this may be partially offset by a reduced efficiency of condensed phase accretion reactions if aerosol acidity is decreasing.

155. Implications of these trends for CC are considered in Section 3.3.2.1 of this chapter.

3.2.1.5 Determination of the number of particles

156. Control of the number of particles in an airmass is determined initially by the number of primary particles. These then determine the particle-size dependence of the secondary aerosol formation processes that were listed in paragraph 134. The importance of particle size has already been mentioned for AQ and CC in paragraph 136, while important implications of the number of particles for CC will be discussed in Section 3.2.1.8.

157. In the gas phase, whether the formation of secondary PM is by chemical reaction or by cooling, there is a competition between formation of new particles and condensation onto the surfaces of existing particles. New particle formation occurs only if the rate of reaction (or cooling) is very great, or if the substance being formed by a gas-phase reaction has a very low volatility. If there are any existing particle surfaces in the air, it is much easier for condensation to occur onto those surfaces instead of forming new particles. Formation of new, very small, secondary particles therefore only occurs where the pre-existing aerosol concentration is low.

158. In practice, H_2SO_4 is the only major product of atmospheric chemistry that has a low enough vapour pressure to form new particles. Nitric acid and most organic acids are much more volatile.

159. When air enters cloud or fog, the particles that contain a largest mass of soluble material are most likely to grow to become droplets, whilst particles that are small or predominantly oily or sooty are more likely to remain in the air between the droplets. After chemical reactions in the droplets have formed more sulphate or nitrate salts in solution, and the droplets evaporate on leaving the cloud, the end result therefore is that cloud processing tends to separate particles into two distinct modes – larger, soluble particles that grow in cloud by addition of sulphate and nitrate, and smaller or less soluble ones that are less able to have secondary sulphate and nitrate added to them.

160. Hygrophobic soot or oily particles (usually ultrafines) can initially acquire hygroscopic material outside of cloud or fog, simply by providing sufficient surface area to comprise an effective sink of the gases in competition with scavenging by larger particles. Given enough time in the atmosphere, they can also coagulate by colliding to make a larger particle that contains more hygroscopic material. If they have gained sufficient hygroscopic mass by condensation or by collision with other particles, particles that initially consisted almost entirely of oily, hygrophobic particles may eventually become able to form cloud or fog droplets. These particles then experience the additional growth processes described above.

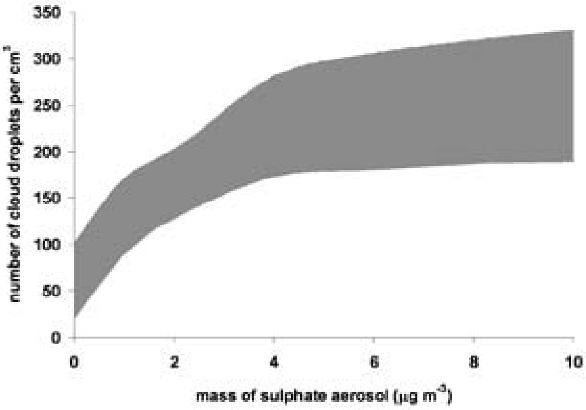
161. An aerosol is thereby generated that is largely internally mixed (i.e., the hygroscopic and hygrophobic material is present together in individual particles), and where the number of particles is controlled in a complex manner by the initial size distribution of primary PM, even though the mass may become dominated by secondary material that has been added to it.

162. It is well known that the number of aerosol particles per unit volume of air varies very greatly from polluted urban air to clean remote locations, as well as with meteorological conditions in urban and suburban areas. For example, Paatero *et al*. (2005) found particle number concentrations (with a lower size cut-off sufficiently small to include most of the ultrafine or nucleation mode) between 10,000 and 60,000 per cm^3 in five European cities, showing the number of particles was most strongly correlated with concentrations of NO_X.

163. Despite the fact that cloud droplets form on individual aerosol particles, the relationship between number of particles and number of cloud droplets is non-linear. The number of droplets in a cloud is somewhat less variable than the number of aerosol particles. This is because, when there is available a large amount of aerosol material capable of being activated to form droplets, the total droplet surface area at the point where a parcel of air enters a cloud is large enough to take up water vapour very rapidly. This decreases the water vapour supersaturation that is driving the activation process, such that the smaller particles that have a higher thermodynamic barrier to their growth are less likely to activate. In clean air, the small number of aerosol particles limits the droplet surface area so that the cloud generates strong water vapour supersaturation sufficient to cause smaller particles to grow.

164. Despite the mechanism above implying that the number of particles and cloud droplets might be related to the number of sooty ultrafine particles, and observational evidence in support of this, the focus of climate modelling on the effects of sulphate aerosols has led to the most widely used quantification of this effect being via empirical correlation between droplet number and sulphate mass (Figure 3.8).

Figure 3.8: Empirically observed correlations between number of cloud droplets and sulphate mass over oceans and continents (shaded area shows range found by Jones *et al*. (1994) and Boucher & Lohmann (1995), figure adapted from Penner *et al*. (2001)



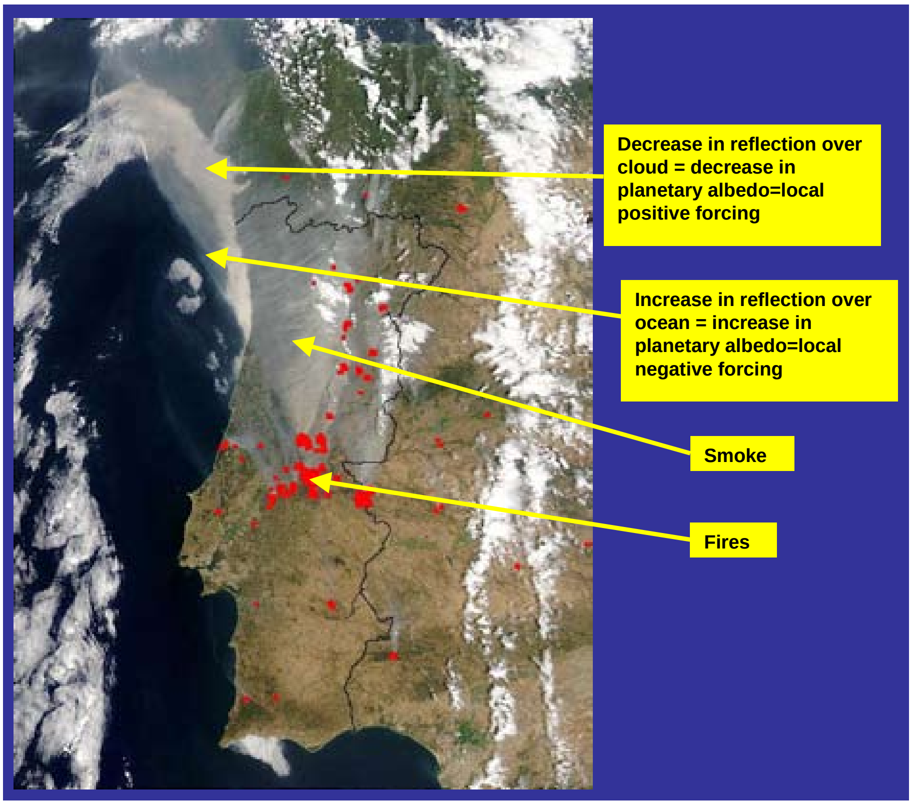
3.2.1.6 Direct effect of black aerosols on climate

165. Ramaswamy *et al*. (2001) provides a succinct and detailed review of the contribution of BC and other absorbing aerosols to radiative forcing, so only a summary is provided here. Radiative forcing was also introduced in some detail in Section 2.2.1 of Chapter 2.

166. Figure 3.9 provides a graphic illustration of how the radiative forcing due to absorbing aerosols depends on the albedo of the underlying surface. Over a dark surface such as ocean or forest the forcing can be negative, while over a bright surface such as desert or snow or above cloud the forcing is positive (e.g. Haywood and Shine, 1995; Chylek and Wong, 1995). In Figure 3.9 the location of the fires relative to the sea, and the altitude of the smoke relative to the cloud, are therefore both important in determining the contribution to radiative forcing of climate. Had the wind blown the smoke predominantly over the sea, the dominant contribution would have been negative forcing, but in the example shown the presence of cloud and land surfaces beneath the smoke mean that its dark colour also contributes to some positive forcing. There is also a direct longwave radiative effect, but this is small unless the particles are large and present at higher altitude (e.g. Tegen *et al*., 1996), so is of less importance for climate effects of lower altitude $PM_{2.5}$ or PM_{10}.

167. Earlier studies of the effects of primary aerosols on radiative forcing of climate considered only the effects of BC in cloud-free air, but more recent studies including a crude parameterisation of the effects of BC in cloud droplets indicated that the total effect including the effect on clouds is approximately double that without clouds. This is considering only the heating effect of the carbon in the clouds and not the effect of the heating thereafter on the lifetime, liquid water content or precipitation of the clouds.

Figure 3.9: MODIS image showing the emission of biomass smoke from Portugal on 3 August 2003



168. Some C aerosol modelling studies have assumed external mixing of sulphate and C aerosols (the C and sulphate are in separate particles, no mixed particles), while others have considered them to be internally mixed. The internally mixed option may be more realistic (see paragraph 165). Indeed, a pure soot particle is quite hygrophobic and will have some difficulty participating in the formation of cloud

droplets, only becoming incorporated into cloud droplets by the less efficient process of coagulation, while soot internally mixed with soluble material will easily get into cloud droplets by nucleation scavenging during the initial droplet formation from the hygroscopic cloud condensation nuclei. Furthermore, the radiative forcing due to BC is sensitive to its vertical distribution in the atmosphere relative to the top and bottom of cloud layers. The direct radiative forcing of climate by BC is therefore intricately linked to the way soot may be influencing the number of cloud condensation nuclei and hence cloud droplets, as discussed in paragraphs 164 *et seq*.. Earlier climate modelling studies assumed BC bears a constant ratio to sulphate which, globally and over decadal timescales may be a reasonable empirical approximation, but it would be wrong to over-interpret the results of the modelling where no account is taken of the different sources that emit soot and sulphur (S). Whilst S is emitted from large combustion plant, emissions of soot are minimised since to emit unburnt C would be inefficient. Improvements to take into account this distinction in more recent climate modelling studies therefore mean it is easier to reconcile the results of climate and AQ modelling in this area.

169. Differences between model estimates of the radiative forcing due to C (once models excluding the in-cloud effect have been removed from the review) are smaller than differences between models of sulphate forcing. Whilst it is true that hygrophobic soot particles may be less sensitive to the interactions with humidity that contribute to the uncertainty in the sulphate modelling, the fact that the aerosol is more likely to be internally mixed complicates this. Ramaswamy *et al*. (2001) conclude that the similarity of models is an artefact of all modellers having chosen rather similar assumptions, such that the true uncertainty in the forcing is greater than the difference between models.

170. There has been a great deal of debate regarding the climate efficacy of BC aerosols. Hansen *et al*. (2002) and Jacobson (2002) suggest that the climate efficacy for atmospheric fossil fuel BC aerosols is significantly higher than for an equivalent atmospheric concentrations of CO_2. Jacobson (2002) goes further and suggests that the the control of fossil-fuel BC and organic matter is possibly the most effective method of slowing global warming, suggesting a reduction of surface air temperature of 0.35ºC within five years could be obtained. However, the paper by Jacobson (2002) provoked several criticisms from Feichter *et al*. (2003), Penner (2003), and Chock *et al*. (2003). They suggest that the atmospheric model had not undergone the necessary rigorous testing; that the integration time for inferring temperature response from the model is too short, so that the efficacy cannot be adequately determined; and that the timescale for the temperature reduction is too short, owing to the misrepresentation of the thermal lag of the ocean. They question the assumption that a combination of direct and indirect radiative forcings from BC and organic matter from fossil fuel burning should lead to a positive forcing of climate, and find inconsistencies between the emission data used and the referenced emission inventories. Furthermore, the study by Roberts and Jones (2004) using a more rigorously validated global model actually suggests that the climate efficacy for BC is less than that for CO_2. Such debate and contradictory evidence suggests that a higher climate efficacy from BC emissions is highly questionable.

3.2.1.7 The direct effect of white aerosols on climate

171. Reflective aerosols have much reduced effect if they are above a surface that already has a high albedo. The most efficient direct forcing of climate by reflective aerosols therefore occurs over the sea, which has a low albedo. Similar considerations for primary PM were raised in Figure 3.9 and the accompanying text. Since anthropogenic aerosols are most abundant over land close to land-based sources of the precursor emissions, the spatial variation of the concentration of PM is important. The lifetime of the accumulation mode particles in the atmosphere and the extent to which they are hence able to be transported out to sea from continental source areas is therefore important. The direct forcing of aerosols is also influenced by correlations between aerosol concentrations and the presence of cloud, because of the role of clouds not only in producing sulphate but also in its removal, and not least the large effect of clouds on radiation that tends to swamp the effect of any aerosols in cloud-free air nearby. Finally, the forcing is strongly sensitive to insolation, giving rise to seasonal, diurnal, and latitudinal variations.

172. Because of these complexities, accurate quantification of the direct radiative forcing of climate by aerosols requires detailed aerosol models coupled to climate models, including careful computation of the movement of radiation through the column of aerosol that has concentration varying with height. Penner *et al*. (2001) provides a succinct and detailed review of progress in this area up to 2000, for sulphate aerosol. Causes of variability between models arise from the following factors:

    - differences in the amount of sulphate (e.g. arising from more rapid deposition causing shorter lifetime)
    - differences in the treatment of optical properties of the aerosol, especially its non-linear dependence on relative humidity, which may be subject to marked sub-grid spatial variability and short-term temporal variability that is not resolved by all models.
    - differences in the treatment of interactions between aerosols, clouds, and aerosol forcing
    - differences in assumptions about the size of the particles.

    The understanding of direct climate forcing by sulphate aerosols is therefore now very solid, but limitations in the speed of development of the most complex climate models within the constraints of available computational power necessitates simplifications that give rise to some uncertainty.

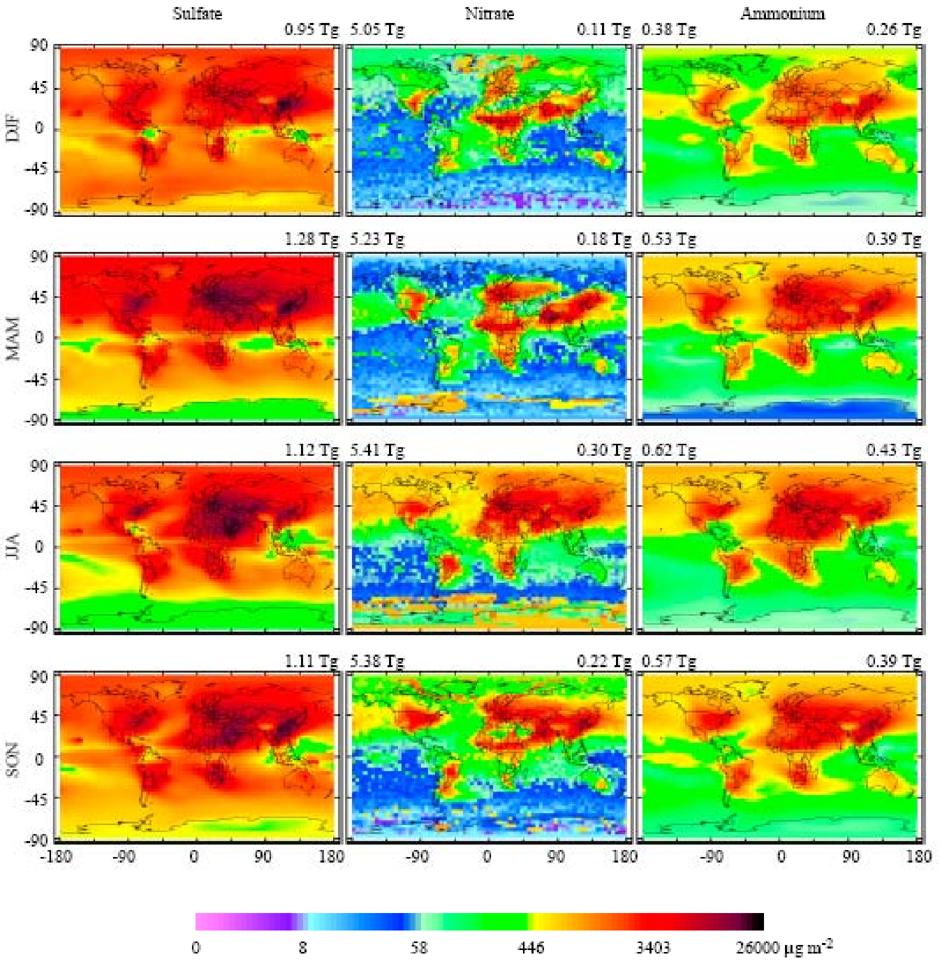
173. The global mean direct radiative forcing due to sulphate aerosol was estimated by Penner *et al*. (2001) to be within a factor of two either side of -0.4 W m^{-2}, based on their review of all model calculations available at that time. The forcing is a factor of 2 to 6.9 higher in the northern hemisphere than the south, a factor of 1.3 to 3.4 higher over land than over the ocean, and a factor of approximately 3.3 greater in summer than in winter.

174. The published literature since 2001 is mostly concerned with some refinements of the biogenic sulphate and progress in the quantification of the indirect effect. Several field experiments to consolidate and extend understanding of the atmospheric processing of the aerosols and their interactions with humidity and cloud have published their results (e.g. Conant *et al*. (2003); Pelon *et al*. (2002); Leon *et al*. (2002); Podgorny and Ramanathan (2001)). Despite these advances, improvements to modelling of the direct effect are being implemented slowly because of the complexity that the modelling has now reached in this area and hence the significant resources that are required to modify and re-test the parameterisations. The comprehensive modelling study published by Johns *et al*. (2003) includes some improvements to earlier versions, but still retains some uncertainty similar to that in earlier studies at the same time as being broadly in agreement with the results of other models reported by Penner at al. (2001).

175. Penner *et al*. (2001) consider nitrate aerosols in much less detail than sulphates. This can be justified in that current global sources of nitrate are nearly a factor of ten less than sulphate by mass, but it is also the case that the number of species involved in nitrate formation constitutes an obstacle to the inclusion of nitrates in climate models. Nitrates have nevertheless been considered in more recent studies, and their significance especially under certain future emissions scenarios is becoming recognised.

176. Nitrates are considered specifically by Martin *et al*. (2004), Adams *et al*. (2001), Jacobson (2001), and Metzger *et al*. (2002). The most recent of these, Martin *et al*. (2004), considers in detail the effects of the hysteresis in response of particles to changes in humidity and the role of nitrate in changing the partitioning of sulphate between ammonium sulphate, leviticite, and ammonium bisulphate. Globally, there is agreement between this study and the earlier work of Adams *et al*. (2001) that including nitrate gives a total direct forcing 14 to 20% higher than that due to sulphate alone. Adams *et al*. (2001) predict higher forcings per unit mass because of low cloud coverage and differences in the treatment of relative humidity. Figure 3.10 shows that, despite the dominance of sulphate globally and over the USA, Europe is one of several polluted regions where concentrations of nitrate regionally are comparable with those of sulphate. Further quantification of this can be found in Section 3.3.3 below.

Figure 3.10: Seasonal mass column concentrations of aqueous sulphate, nitrate, and ammonium calculated by Martin *et al*. (2004)



177. Organic aerosols (primary and secondary) are reviewed by Penner *et al*. (2001). Globally, organic aerosol is more abundant than nitrate aerosol, but since the former is dominated by tropical biogenic emissions, the abundances of both types of aerosol are more similar at higher latitudes. Because fossil fuel emissions have changed appreciably whilst biomass emissions have not, the fossil fuel emissions contribute most to direct radiative forcing by organic aerosols. However, there is an additional indirect anthropogenic effect, namely the influence of anthropogenic NO_X emissions on the formation of SOA from biogenic emissions of VOCs. Since the amount of biogenic VOC emitted is very large, Penner *et al*. (2001) note that small increases in the amount of anthropogenic NO_X transported to regions where tropical forests are present, could result in significant increase in secondary biogenic aerosol and the associated radiative forcing. The low albedo of forest contributes to the forcing effect of the reflective water-soluble organic aerosol. Artaxo *et al*. (1998a,b) and Roberts *et al*. (1998) note that biogenic VOCs in clean conditions produce little SOA, whilst Kanakidou *et al*. (2000) note that the presence of NO_X may have resulted already in a 3- to 4-fold increase of biogenic aerosol production since pre-industrial times.

3.2.1.8 Indirect effect of aerosols and other cloud forcings (including contrails)

178. Globally, clouds are estimated to reflect 48 W m^{-2} incoming solar radiation and trap 30 W m^{-2} outgoing longwave. They therefore have overall a net cooling effect on climate, but a small perturbation to either of these large radiation fluxes can potentially dwarf the forcings due to GHGs or other effects of aerosols. Changes in the radiative properties of clouds are caused by changes in temperature or circulation, and these are climate feedbacks not forcings. However, any change in a cloud that is directly attributable to an anthropogenic emission that has changed since pre-industrial times can be considered to be a forcing of climate. Here we consider the change to be an aerosol forcing of climate, whether it acts on the radiative properties of the cloud or its persistence and abundance. Where the cloud is heated by the presence of absorbing aerosol, the heating is a direct radiative forcing effect of the aerosol, and the cloud may additionally respond to the change in temperature resulting in a change in cloudiness. Whether the change in cloudiness is considered to be an additional forcing or a feedback depends on the precise definition of forcing used.

179. There are two main ways in which aerosols influence the radiative properties of liquid water clouds, as discussed in paragraphs 165 *et seq*.:

- Reduction in the droplet size and increase in the droplet number, which causes the cloud to become more reflective. This has been called the Twomey effect, or first indirect effect, but more recently has been referred to simply as the cloud albedo effect.

- Reduction in the droplet size causing reduction in the cloud's ability to form rain and hence an increase in its persistence. (Here we consider the negative radiative forcing of climate arising from this, but we will revisit the same phenomenon in Section 3.3.6 of this chapter in terms of rainfall being directly effected by pollution.) This has been called the second indirect effect but more recently is termed simply the cloud lifetime effect.

180. If a definition of radiative forcing is used that requires 'temperatures and state' to be held constant in calculating radiative forcing of a pollutant, then technically the cloud lifetime effect is not purely a forcing but includes some climate feedback in the response of the atmosphere to the pollutant. Lohmann and Feichter (2005) suggest some ways of avoiding some inconsistencies that arise if one uses this definition with the understanding that cloud is included in 'state' while secondary pollutants are not, but the intricacies of this are beyond the scope of this report. We merely note that the total climate response to indirect forcing by aerosols is likely to be greater than what would initially appear from the estimates of its magnitude, since these estimates include only the cloud albedo effect and not the cloud lifetime effect.

181. Ice and mixed liquid/ice clouds exhibit some variations on the above mechanisms, concerned with the effect of pollution on ice nucleation or the onset of glaciation. There remain however a host of uncertainties and unknowns surrounding the details of ice cloud nucleation and physics. We have not considered the implications of these for the conclusions of this report.

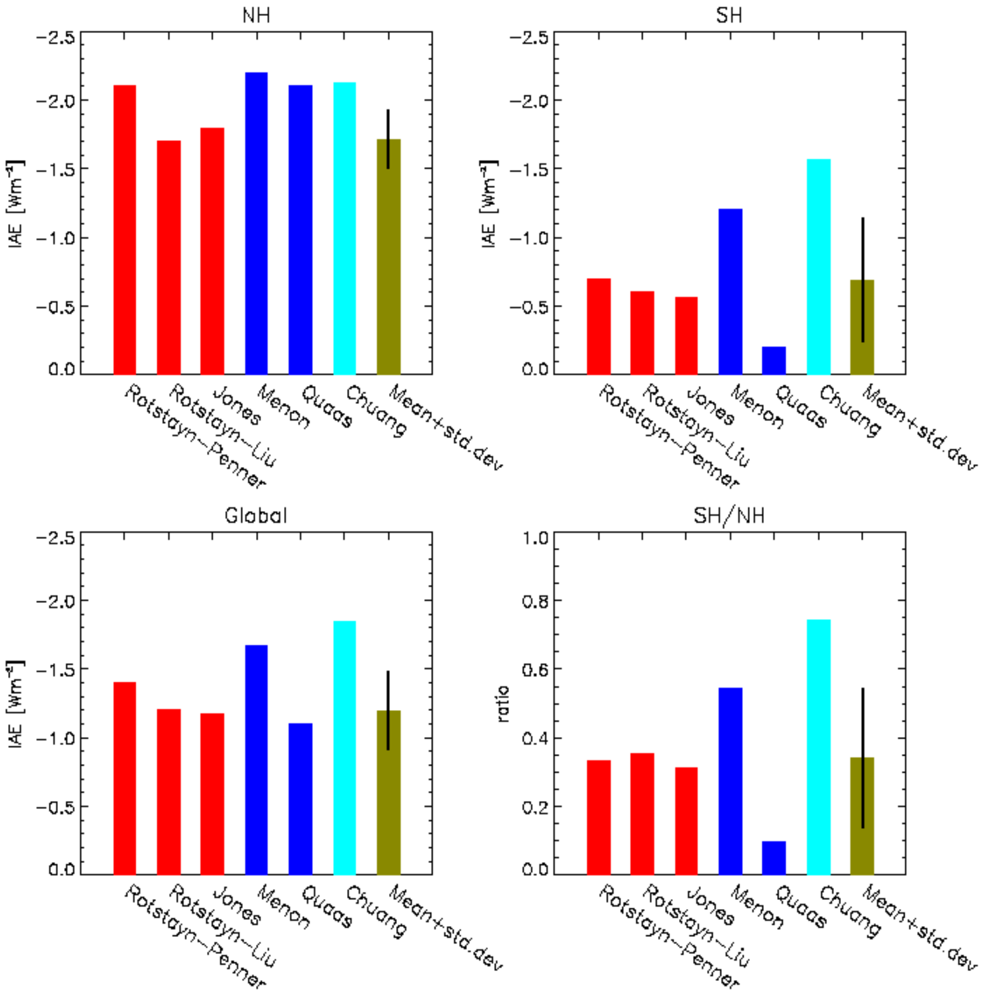
182. A slightly separate clouds and forcing effect which also requires highlighting concerns aircraft contrails. These are partly an indirect forcing effect because the particle emissions from the aircraft modify the ability of aircraft contrails to undergo ice nucleation which influences the contrail's formation, thickness, and persistence. But a contrail is also part of the direct forcing of water vapour after it condenses to form cloud. Aircraft contrails were highlighted in an IPCC special report (Penner *et al.*, 1999) as possibly one of the largest climate effects of aviation, although still small compared with the forcing from terrestrial emissions. Contrails reduce the amount of incoming solar radiation reaching the surface and absorb outgoing longwave radiation. Cirrus clouds, the occurrence and persistence of which is linked to aircraft contrails, provide an additional effect. The net effect is highly uncertain. The amount of contrails is projected to increase more rapidly than total fuel consumption by aviation, because more efficient aircraft form more contrails per unit fuel burnt, including changes in engine exhaust temperature. The most important point to note is that the timescale of these changes is associated with the slow rate of turnover of the aircraft fleet, in contrast to the forcing by aviation emissions of CO_2 that is determined by the build-up of gases in the atmosphere.

183. Quantification of all the indirect effects of aerosols from all sources remains complicated by a number of observations, e.g. correlations between pollution and cloud thickness that have the opposite effect to the changes in number of droplets. But at the same time, observations are accumulating providing empirical support for the existence and significance of the indirect effects (e.g. ship track experiments).

184. Quantification of the combined first and second indirect effect of aerosols on the radiative forcing of climate is therefore gradually getting closer. The emergence of a new generation of global aerosol microphysics models (see Section 3.3.3 for example of modelling results from Spracklen *et al*. (2005) that is very relevant to quantification of the indirect forcing effects), supported by a steady proliferation of the number of field studies being made, may cause the rate of progress to accelerate.

185. The indirect effects of aerosols on climate has recently been reviewed by Lohmann and Feichter (2005). They point to a revision of Ramaswamy *et al*. (2001)'s estimate of the first indirect effect from '0 to -2 W m^{-2}' to '-0.5 to -1.9 W m^{-2}' (see Figure 3.11). They also review the most recent evidence that the cloud lifetime effect is similar in magnitude and sign to the cloud albedo effect, although it remains at least as uncertain.

Figure 3.11: Global mean cloud albedo (Twomey) effect as reviewed by Lohmann and Feichter (2005)



186. Andreae *et al*. (2005) have pointed out that the existence of negative forcings not included in models that successfully reproduce observed temperature trends implies that the same models have climate sensitivity that is too low. Modelled scenarios in which AQ pollutants are abated but GHGs remain in the atmosphere may therefore in future predict more severe CC than the information currently being used to support policy.

187. Despite the link often implied between the indirect effect and sulphate in many climate modelling studies, it is in principle an effect related to the number of particles, and hence is linked to all sources of primary and secondary PM as implied by the description in Section 3.2.1.5 of how the number of particles is determined. In modelling studies where sulphate is used to try and quantify the indirect effect, sulphate is being used as a surrogate for all anthropogenic aerosol particles. This is another area where model performance may struggle for certain emissions scenarios that include different abatement of classes of pollutants that have been correlated with each other in the past.

3.2.3 Effects of air quality on climate via impacts on ecosystems

188. Ecosystem-mediated links between AQ and CC processes are numerous and very complex, with many interacting processes. The net direction of the various effects, let alone their significance, are very uncertain, and will certainly vary between ecosystems and on different temporal scales. Particular uncertainty is attached to understanding of the contribution of below-ground microbial processes. It is not possible for this section to review all the processes in detail, instead some of the issues are identified for emissions and uptake of different GHGs in turn, considering the possible effects of the regional pollutants O_3, sulphur (S) and nitrogen (N) deposition and aerosols.

3.2.3.1 Carbon dioxide uptake and net carbon balance

189. The biosphere is a major sink and source of CO_2, and there are many potential feedbacks in understanding the impacts of air pollution on the C budget, both for the UK and globally. In predicting future scenarios, it is essential to consider the effects of increased atmospheric CO_2 concentrations, which will have a major impact on C storage. While increased forest growth and C storage is expected in Europe with increased CO_2 concentrations and warmer temperatures, increased aerobic and anaerobic respiration with a warmer climate may lead to increased C emissions from soils. Recent estimates from the CarboEurope project (Janssens *et al.*, 2005) suggest that countries with a high forest cover, such as Austria and Switzerland, are net C sinks, while those with low forest cover, such as Ireland and Denmark, are net C sources. A recent re-sampling exercise in the National Soil Inventory of England and Wales suggests that there has been a net C loss from soils of 0.6% over the period 1978 – 2003, with losses being most marked on organic soils with a high C content (Bellamy *et al.*, 2005). Further work is needed to confirm this finding nationally and Chapman *et al.* (2001) conclude some of the shorter half-lives used in C loss calculations can result in exaggeration of the effects of land-use change.

190. Increased deposition of N may increase the uptake and storage of CO_2, especially through promoting the growth of forest species in nutrient-poor ecosystems. The difficulty in assessing the long-term impacts of N deposition is that positive effects in early decades may be offset in the longer-term by negative effects through nutrient imbalances and decreased stress tolerance when systems become N-saturated. For example, Nelleman and Thomsen (2001) analysed long-term growth patterns of spruce in Norway, and found that sites with high N deposition increased in growth from the 1960s to the 1980s, but subsequently growth on these plots has declined below that on plots receiving less N deposition. An integrated approach considering both the C store in vegetation and the C store in soils is needed in assessing these effects. For example,. Burton *et al*. (2004) recently reported that simulated nitrate deposition decreased soil respiration, probably through effects on the microbial community, leading to increased C storage. A recent model simulation of forest C storage showed that insect herbivory (which is commonly increased by increased N availability) led to C storage saturating at lower rates of N deposition (Throop *et al.*, 2004).

191. Ozone, and specifically the projected increase in global background O_3 concentrations, may reduce primary production and hence C uptake. There is a significant body of experimental work on O_3 and CO_2 interactions which can be used to assess qualitatively how O_3 might reduce the size of the increase in C uptake under elevated CO_2, and identify any other secondary effects of significance, but these experiments reveal differences in response between and within species (Karnosky *et al*., 2005). It is also important to consider effects of C flows and storage below ground, a factor which many studies omit. For example, five years of O_3 exposure in the Aspen FACE (Free Air Carbon Dioxide Enrichment) experiment (the most important long-term field experiment) halved the increase in soil C due to elevated CO_2 concentrations (Karnosky *et al*., 2005; Loya *et al*., 2003).

192. There is a need to consider the combined effects of all these factors; e.g. Ollinger *et al*. (2002) modelled C dynamics in hardwood forests of North America over the period 1700 – 2000. When the positive modelled effects of increased CO_2 concentration and increased N deposition were combined with the negative effects of O_3, and the effects of historic land-use, the net effect was that growth rates were similar to those modelled in pre-industrial periods.

3.2.3.2 Methane

193. Wetlands are the largest natural source of CH_4. While temperature and soil moisture are identified as the major environmental influences on CH_4 fluxes, there is evidence that pollutant deposition can also have significant effects.

194. In the case of sulphate, a negative feedback has been shown between sulphate deposition and CH_4 emissions from wetlands, because the increased populations of sulphate-reducing microbial populations competitively exclude methanogens. Gauci *et al*. (2004a,b) modelled the global effect of S deposition, and estimated that it is a significant constraint on increased climate-induced wetland emissions, reducing current emissions by 8% and modelled 2030 emissions by 15%. Gauci *et al*. (2005) also recently suggested that a large acidification pulse could suppress wetland CH_4 emissions for up to a decade, and hence that the effect of a large volcanic eruption has a bigger long-term cooling effect through reduced CH_4 emissions than through direct aerosol-produced radiative cooling. The effect of S from fossil fuel combustion appears not to be as strong as the effect of volcanoes, because of the global distribution of major wetlands, many of which are remote from industrial emissions but within the deposition range of large volcanic eruptions. In the UK, Gauci *et al*. mention evidence that parts of Scotland may in the past have been affected by S deposition from large Icelandic volcanic eruptions.

195. Nitrogen deposition has also been reported to have significant effects on CH_4 fluxes, due to both effects on emissions and microbial CH_4 oxidation. There is evidence that increased soil N decreases CH_4 oxidation rates, thus increasing CH_4 fluxes (e.g. Tlustos *et al*., 1998; Wang and Ineson, 2003), or decreasing fluxes to soils that are net sinks for CH_4. Nitrogen deposition can reduce the cover of Sphagnum mosses and increase that of cotton grass (*Eriophorum virginicum*) in peatlands, and there is some evidence that this effect might be more important

than direct effects of N deposition on microbial activity (e.g. Nykanen *et al*., 2002). There is evidence that N deposition increases CH_4 emissions from oligotrophic and mesotrophic soils, but not from eutrophic soils. In acidic peat soils, in particular, increased N deposition can cause reduced CO_2 emissions, probably because of acidification affecting microbial respiration (Aerts and de Caluwe, 1999). Hence, in terms of assessing the overall impacts of N deposition on C fluxes of wetland soils, effects on both CH_4 and CO_2 need to be considered.

196. A recent study has also suggested that O_3 might increase CH_4 emissions from boreal peatlands (Niemi *et al*., 2002), although further work is needed to confirm this.

3.2.3.3 Nitrous Oxide

197. UK field studies have demonstrated, as for CH_4, the importance of soil temperature and water content as major controls on the microbial denitrification processes leading to N_2O emissions. However, N inputs, soil pH and available ammonium and nitrate also influence N_2O emissions. Skiba *et al*. (1998) derived a simple equation to estimate N_2O emissions, which predicts that a two-fold increase in N_2O emissions would be caused by approximately a five-fold increase in N deposition, a 2°C increase in soil temperature or an absolute 20% decrease in soil moisture content.

198. These relationships give emissions fluxes strong spatial and temporal variability. This is further modified by soil type. The responsiveness to land management, through fertiliser application also makes emissions characteristics episodic in nature. In the most recent national inventory (Skiba, 2005), N_2O emission are estimated as 1% of N deposition, but this only contributes an estimated 4% of the national GB inventory of 164 kt N_2O y^{-1}, compared to 52% from direct application of mineral fertilisers.

3.3 The response of climate to radiative forcing due to air quality pollutants

199. Future projections of AQ pollutants can look rather similar to GHG projections, or very different, depending on three factors:

- Whether one considers emissions or concentrations.
- Whether one considers the cumulative effect of emissions occurring from some point in the past until the present, or solely the effect of current emissions, or the future effect of emissions occurring in the future as well as now.
- Whether one looks at the local to regional situation in the UK and Western Europe, or globally (especially since, where there are global effects, the most damage often occurs far away from the UK; it is also important to take account of the distant emissions associated with the manufacture and transport of goods from overseas that are consumed in the UK).

This section therefore starts by comparing and contrasting emissions of AQ pollutants and GHGs at global and regional scale. It then considers the response of atmospheric concentrations to these emissions time series, the radiative forcing of climate that results from these concentrations, and finally the response of climate that results from this forcing.

3.3.1 Future trends in air quality pollutants

200. The timescale over which well-mixed GHGs have an influence is usually considered by calculating GWPs over different time horizons. A formal definition of GWP is given by Shine *et al*. (1990) and the concept has been introduced already in Section 2.2.2. Penner *et al*. (1999) adopts a different approach, comparing the radiative forcing due to CO_2 and non-CO_2 emissions from aviation. For short-lived AQ pollutants, Shine *et al*. (2005) explain reasons why the definition and application of metrics such as GWP is difficult, but comparing radiative forcings fails to take account properly of issues of timescale for short-lived pollutants and Forster *et al*. (2006) warn of difficulties in attempts to compare mixtures of co-emitted pollutants from different sources.

201. Factors determining the response of atmospheric CO_2 concentrations to changes in emissions are reviewed in depth by Prentice *et al*. (2001) and will not be repeated here. The important features of the C cycle are shown in Figure 2.12, which emphasises how emissions constitute a much larger flux into the atmosphere than the fluxes that remove CO_2 from the surface ocean to the deep ocean and from the deep ocean into sediments. This imbalance results in the well-known accumulation of CO_2 in the atmosphere that has been ongoing since the industrial revolution, as well as reductions in the amount of C held in biomass.

202. The response of atmospheric CO_2 concentrations to changes in global emissions has been quantified by C cycle models of varying degrees of complexity, also reviewed by Prentice *et al*. (2001). These may be run coupled with the climate models that were described in Section 2.3.1, or can be run off-line on their own using prescribed climate data. These models simulate exchange of C between atmosphere and ecosystems, with or without including dynamic changes in ecosystem structure. Ocean transport of C is considered by physical and biological processes. There are several ways of representing the biological processes that control the natural C cycle, e.g. by simulating the food chain directly, maintaining upper ocean nutrient concentrations at observed levels, or using a parameterisation of nutrient export below the surface, according to surface concentrations. The anthropogenic CO_2 uptake is usually controlled by physical transport and surface ocean C chemistry. There have been some recent developments in intercomparisons between ocean models revealing significant differences in the physics (e.g. Doney *et al*., 2004), but the general behaviour of C is well known and can be considered uncontroversial for the purposes of AQEG's current analysis.

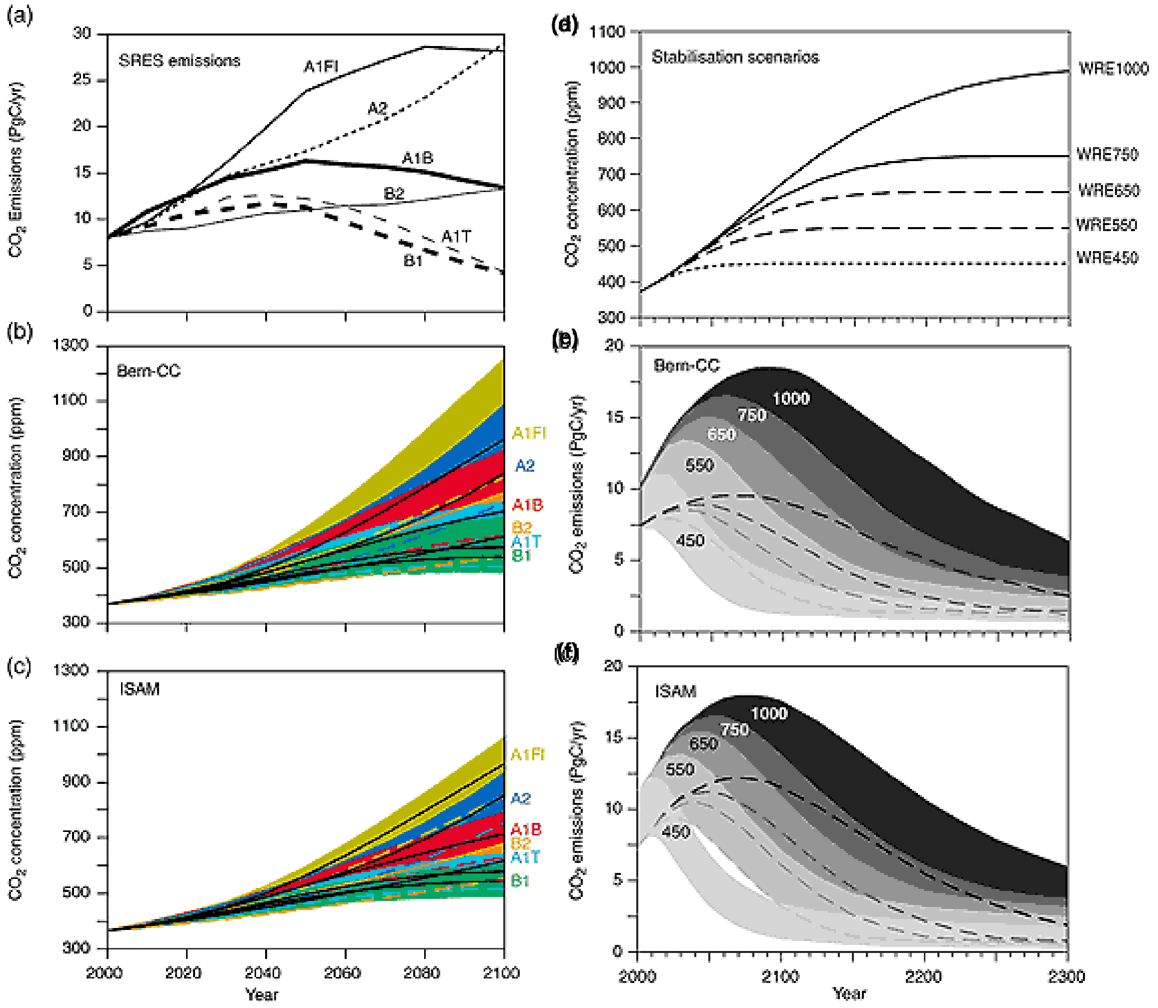
203. Figure 3.12 is a selection of C cycle model results from Prentice *et al*. (2001), showing how slowly atmospheric CO_2 concentrations respond to changes in emissions. Figure 3.12b and c show how even the more optimistic SRES emissions reductions scenarios are too little reduction too late to even stabilise yet alone reverse atmospheric CO_2 concentrations. Figure 3.12e and f show the emissions scenarios required to stabilise atmospheric CO_2 at various levels indicated in Figure 3.12d. Note how Figure 3.12a to c run the C cycle models forwards starting with emissions projections to derive future concentrations, while Figure 3.12d to f are arranged the other way round, starting with desired atmospheric concentrations in Figure 3.12d and working backwards to the necessary rates of emissions reductions in Figure 3.12e and f. Bern CC (Figure 3.12b and e) and ISAM (Figure 3.12c and f) are two different fast C cycle models. The different colours and lines in Figure 3.12b and c represent different model assumptions for the various scenarios and should be interpreted as indicating the general range of outcomes that might be plausible from a range of scenarios taking into account model uncertainty.

204. Figure 3.12d to f shows how CO_2 concentrations will still reach values double those today if emissions of CO_2 return to 2000 values again by the end of the century. The atmospheric concentrations do not start to decrease again until a lot later, because of the approximately 100 year lifetime of CO_2 in the atmosphere and surface ocean. The important point to note is how unresponsive atmospheric CO_2 concentrations are to emissions reductions in the short term. It is because of this 100 year timescale for CO_2 emissions to the atmosphere that a time horizon of 100 years has been adopted in the Kyoto Protocol for calculation of GWPs.

205. It is especially important to consider this accumulating effect of long-lived GHGs for emissions sectors that have emerged more recently and are now growing rapidly. Aviation is a case in point in this respect, although shipping is also growing rapidly.

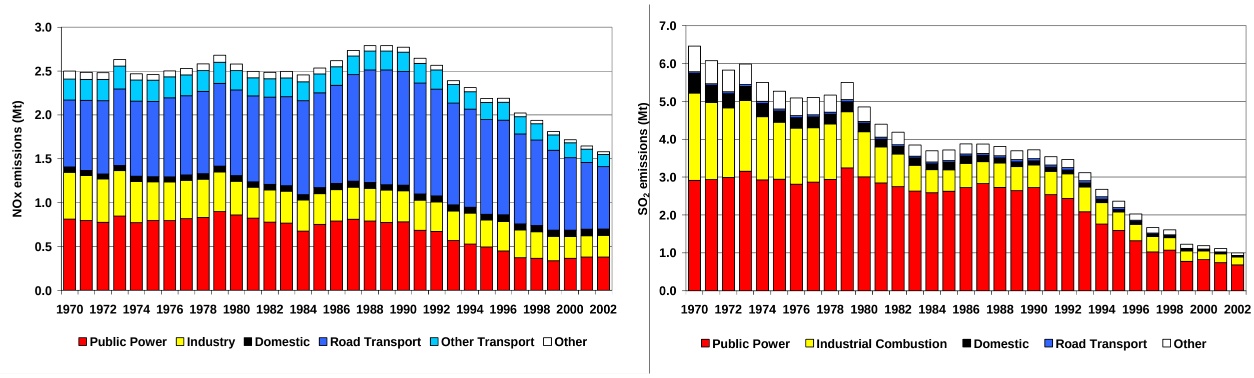
206. Global aviation emissions per annum are currently similar to UK total fossil fuel emissions. The abundance of CO_2 in the atmosphere due to aviation however, and hence its effects on climate, is rather smaller than that of UK terrestrial emissions. This is simply because much of the CO_2 in the atmosphere from terrestrial anthropogenic sources has been emitted during the past fifty years, whilst the CO_2 from aviation has only started to accumulate rapidly more recently. By 2050, when some of the higher estimates of CO_2 emissions from aviation per annum are close to current terrestrial per annum fossil fuel emissions from the USA, the accumulation of 21st Century emissions will start to constitute a much larger fraction of the total.

Figure 3.12: Responses of atmospheric carbon dioxide concentration (a-c) to SRES emissions scenarios, and (d-f) emissions timeseries required to stabilise carbon dioxide concentrations. Model uncertainty gives range of output from top of coloured or shaded area (upper bound) to dotted line (lower bound). (Prentice *et al.*, 2001)



207. Broadly similar patterns to those for CO_2 emerge for the other well-mixed GHGs. Methane and N_2O emissions may be slightly easier to control than CO_2, and the chemical reactivity of CH_4 means its atmospheric concentration responds rather more quickly to emissions reduction than does CO_2. Conversely, the GHGs that lack CO_2's ability to be removed by the oceans and by growth of vegetation and into soils, respond much more slowly to emissions control. The extreme case of this is some of the halocarbons that last many hundreds of years.

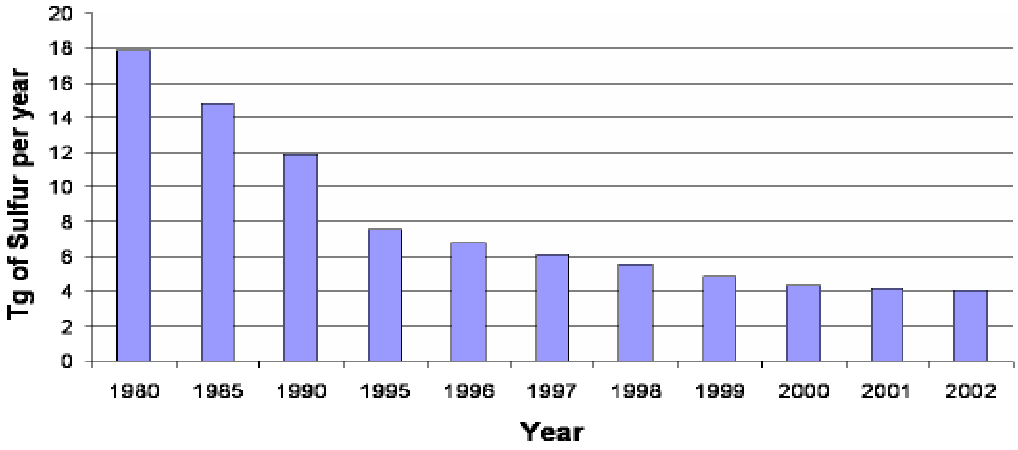
Figure 3.13: UK emissions of nitrogen oxides (left) and sulphur dioxide (right)



208. The situation for AQ pollutants is very different to that the well-mixed GHGs. For the UK, time series of national emissions of many pollutants, such as for NO_X and SO_2 in Figure 3.13, show a decline over a relatively short period from a high level of emissions in earlier years. Future projections predict an even more dramatic decrease being achieved. This is in stark contrast to even the most optimistic global SRES CO_2 emissions projections shown in Figure 3.12a.

209. Emissions of SO_2 from 25 countries in Europe have reduced from approximately 18 TgS y^{-1} in 1980 to 4 TgS y^{-1} in 2002 (Vestreng *et al*., 2004, Figure 3.14). However, over the same period SO_2 emissions have been increasing significantly in Asia and developing countries. When combining these regional reductions and increases there is uncertainty as to whether global SO_2 emissions have risen or fallen since the 1980s (e.g., Lefohn *et al*., 1999; van Aardenne *et al*., 2001; Boucher and Pham, 2002).

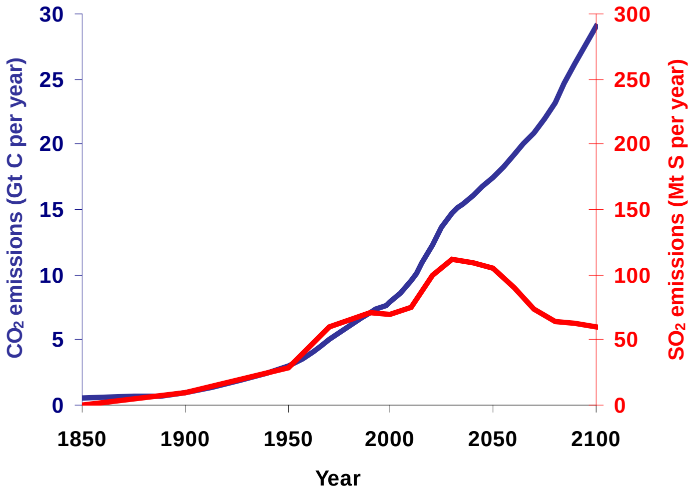
Figure 3.14: European sulphur emissions (Vestreng *et al*., 2004)



210. It is also possible to draw misleading conclusions from these graphs because of the shortness of the timeseries covered. Figure 3.15 contrasts global emissions of SO_2 and global emissions of CO_2 on the longer timescales more often considered in relation to CC studies. The difference is striking, and shows how currently available technology is much better able to deliver reductions in emissions of AQ pollutants than reductions in CO_2.

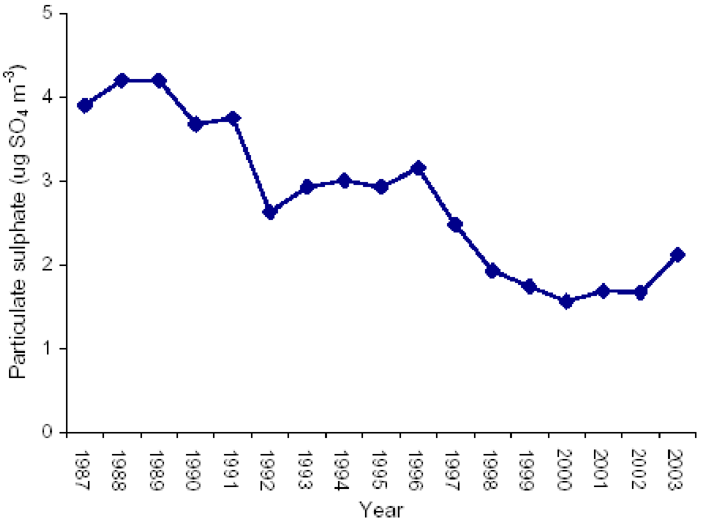
211. An even more important difference between AQ pollutants and well-mixed GHGs, is the rapid response of atmospheric concentrations to changes in emissions. Despite the nonlinearity of H_2SO_4 formation from SO_2 Figure 3.16 shows a decline in sulphate aerosol concentrations that is following closely the timing of decline in SO_2 emissions (compare with Figure 3.13b). The lifetime and budget of sulphate is shown in Table 3.2 according to the calculations of several chemical transport models. Despite some uncertainty between models, the contrast with the situation for CO_2 is very clear. Whereas for CO_2 the annual emissions were a small fraction of the total atmospheric reservoir, for primary AQ pollutants and directly formed secondary products of their oxidation, the annual emissions are much bigger than the total amount in the atmosphere. The response of atmospheric concentrations to emissions abatement is therefore almost instantaneous. (There is, however, an important non-linearity in the response, which can be seen by comparing Figure 3.16 with Figure 3.13b and was discussed in Section 3.2.1.4).

Figure 3.15: Historical global total carbon dioxide and sulphur dioxide emissions from 1850 to 2000, followed by projected values to the year 2100 from the SRES A2 scenario



212. Other atmospheric aerosols have a rapid reponse to emissions changes similar to that of sulphate. Tropospheric O_3 is like atmospheric aerosols in that it has a much shorter lifetime than CO_2. Trends in O_3 concentrations however, are less directly linked to trends in precursor air pollutant emissions, because of the complexity of the non-linear chemistry that was outlined in Section 3.2.1.

Figure 3.16: UK network average concentrations of sulphate



213. Emissions from aviation are projected to grow more rapidly than other sectors. Growth based in the UK and flights originating in the UK are projected to grow more rapidly than the rate of introduction of emissions control. Whilst terrestrial sources therefore make a long-lived contribution to concentrations of well-mixed GHGs and a temporary increase in AQ pollutant concentrations, aviation is projected to make monotonically increasing contributions to both GHG and AQ pollutant concentrations.

Table 3.2: Lifetimes of sulphate aerosol calculated using several Chemical Transport Models (from Derwent *et al*., 2003)

Study	Gas phase Tg y^{-1}	In cloud Tg y^{-1}	Emission Tg y^{-1}	Dry Depn Tg y^{-1}	Wet depn Tg y^{-1}	Burden Tg	Lifetime days
Langner and Rodhe (1991)	7.8	42.0	3.5	8.6	41.5	0.77	5.3
Pham *et al*. (1995)	6.5	55.5		17.0	45.0	0.80	4.7
Feichter *et al*. (1996)	16.8	34.5		6.7	44.6	0.61	4.3
Chin *et al*. (1996)	7.5	41.6		5.6	43.5	0.53	3.9
Barth *et al*. (2000)	9.2	44.3	1.3	3.7	51.1	0.57	3.8
Koch *et al*. (1999)	13.1	31.6	1.9	9.2	37.4	0.73	5.7
Chuang *et al*. (1997)	6.1	42.3		5.2	43.2	0.55	4.1
Roeloffs *et al*. (1998)	16.2	57.8	3.3	17.0	61.0	0.96	4.7
Restad *et al*. (1998)	11.0	39.7		8.6	42.1	0.62	4.5
Rasch *et al*. (2000)	9.4	44.6	1.1	3.9	51.1	0.60	4.0
Lelieveld *et al*. (1997)	15.1	53.3	3.6	18.0	54.0	1.10	5.3
Chin *et al*. (2000)	14.0	24.5	2.2	5.1	34.7	0.63	5.8
Derwent *et al*. (2003)	11.8	38.2		7.0	43.1	0.83	6.1

214. Clearly, trends in emissions of AQ pollutants must be seen as being a function of scale, with local projections showing a very different pattern to the situation globally. The general pattern is therefore as follows:

- Well-mixed GHG concentrations are rising monotonically and globally due to a build-up of historical emissions with little or no future reduction in emissions.
- Air quality pollutants have elevated concentrations regionally over a period of several decades corresponding to the delay between maximum industrial output and application of emissions abatement.
- A further time-lag between emissions abatement near the UK and further afield, such that the location of maximum emissions is shifting globally over a period of several decades, including the rapid rise in emissions from aviation.

3.3.2 The response of radiative forcing and climate to temporal trends in aerosol concentrations

3.3.2.1 Effects of aerosols on delaying global warming and increasing future response to elevated carbon dioxide

215. All aerosol types reduce the solar energy flux at the Earth's surface through a combination of absorption and scattering, producing a surface cooling effect (Meywerk and Ramanathan, 1999) referred to as global dimming (Stanhill and Cohen, 2001). The absorption of radiation, by contrast, leads to heating of the atmosphere. It has been suggested (most recently by Andreae *et al*., 2005) that the surface cooling has masked warming from GHGs and that future reductions in aerosols from local and regional air pollution mitigation may lead to an enhancement of future global warming.

216. Andreae *et al*. (2005) examined the impact on CC of reductions in aerosols, driven by the mitigation of air pollution. They used a simple climate C cycle model to examine the impact of a reduction in aerosol, based on the SRES A2 scenario. They found that if typical aerosol forcing estimates of 1 to 2 W m^{-2} were used, then temperature increases significantly in excess of those projected in the IPCC Third Assessment Report are likely. One reason they proposed for this sensitivity to historical aerosol forcing is the effect of the C cycle feedback on future CO_2. For a climate sensitivity, expressed as the global temperature increase for a doubling of CO_2, greater than 3°C, they argue that C cycle feedback will accelerate the growth of CO_2 by more than 50%.

217. It must be remembered that these latter results were obtained using a very simple model. The results do, however, emphasise the extreme sensitivity of the future climate to the atmospheric aerosol burden and the substantial uncertainties in our understanding of aerosol behaviour and of its linkage to climate.

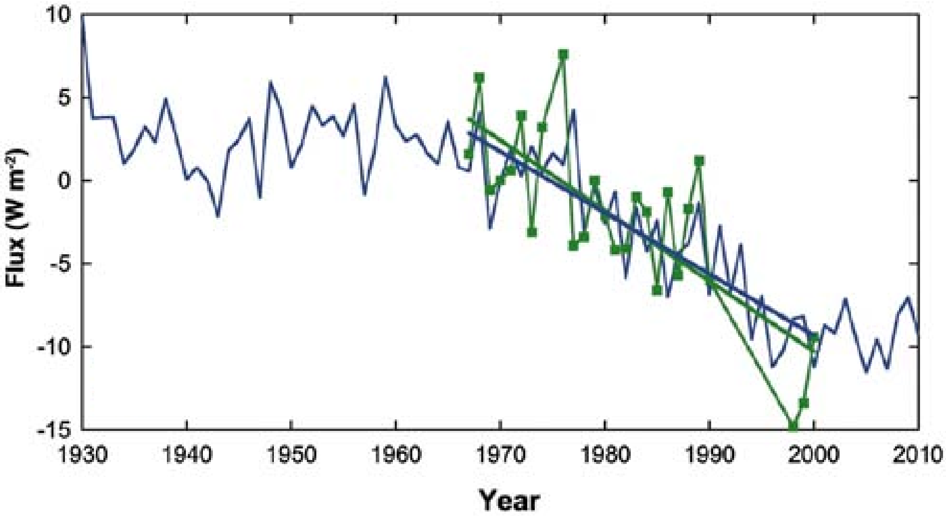
3.3.2.2 Global Dimming

218. In early work, Stanhill and Moreshet (Stanhill 1992; Stanhill and Moreshet 1992 a,b) analysed data from pyranometer sites around the world over a period of 27 years and observed a statistically significant decrease of around 0.5 – 0.6 W m^{-2} y^{-1}. Similarly Liepert *et al*. (1997, 2002) analysed data from twelve sites in Germany over a 30 year period and found a statistically significant decrease of around 0.37 W m^{-2} y^{-1}. More recent work has shown decreases in incident

solar radiation on both global and regional scales (Stanhill, 2005 and references therein) although debate continues into the magnitude of the reduction in radiation with Gilgen *et al*. (1998) and Liepert (2002) calculating a reduction of 0.7 W m^{-2} y^{-1} for the period 1961 – 1990 while Stanhill and Cohen (2001) calculate a much larger reduction of 1.5 W m^{-2} y^{-1}. However, this decline in radiation appears to have reversed at about this time, and a recovery of around 6 W m^{-2} appears to have occurred since then (Wild, 2005).

219. Since the measurements of solar radiation at the surface are integrated over the entire solar spectrum, any change in atmospheric constituents that absorb solar radiation in discrete spectral regions could partly explain these changes. Therefore changes in circulation patterns that change atmospheric humidity and cloud amount, changes in other forcing agents such as tropospheric O_3 and, to a lesser extent CH_4 and CO_2 may all contribute to the observed changes in solar radiation at the surface.

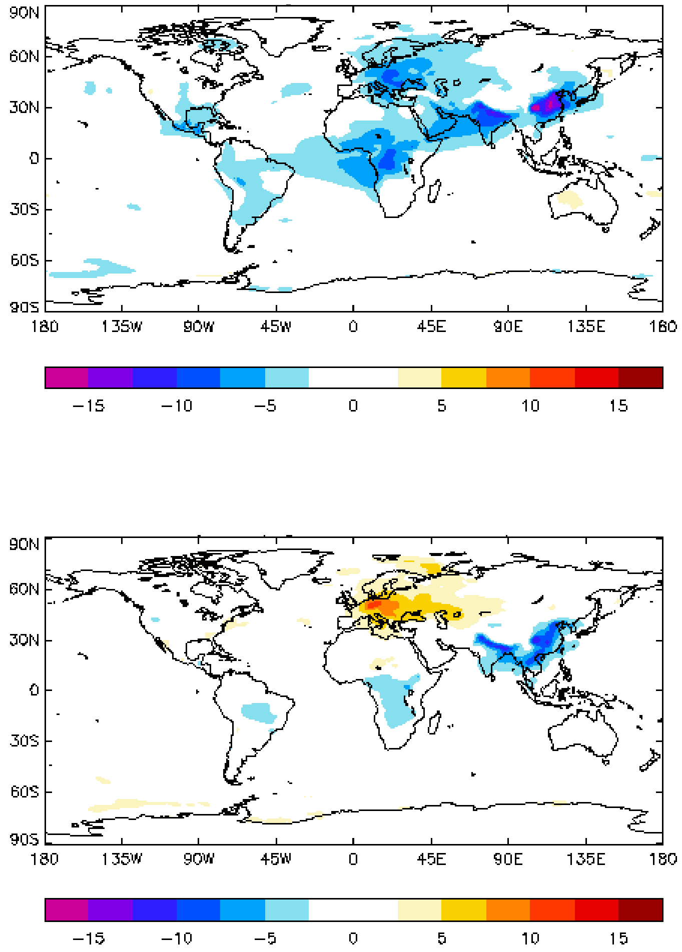
Figure 3.17: Time series of surface heat budget terms. Simulated (blue) and observed (green) annual mean solar fluxes for India at the surface. The fluxes are for average cloud conditions. The simulations are averaged over 5°N to 25°N and from 70°E to 90°E. The observed values are from ten surface stations distributed between eastern, western, northern, and southern India. The trend in Global Energy Budget Archive is -0.42 W m^{-2} per year (±0.15 90% confidence level), and the trend in the Atmospheric Brown Cloud 1998 run is -0.37 W m^{-2} per year (±0.12) (2SD of the trends from the five runs of the ensemble)



220. This phenomenon has received particular attention in relation to the atmospheric brown clouds (ABCs), especially in South Asia. Atmospheric brown clouds are layers of air pollution that contain a wide range of aerosol components including BC and OC, dust, sulphates and nitrates. Figure 3.17 compares the Indian Global Budget Archive surface solar energy data with simulations based on a coupled ocean atmosphere model (Ramanathan *et al*., 2005) that has been run from 1850 – 2050. The comparison was made using an appropriate region of the global model; the measurements are the means from 10 stations covering the whole of India from 1960 – 2000. The reduction in the surface heat flux, that sets in around 1970 in the model results, is reproduced in the measurements. The 1960 – 2000 averaged modelled dimming is -0.37 W m^{-2} y^{-1}, while that from the measurements is -0.42 W m^{-2} y^{-1}.

221. The direct and indirect effect of aerosols have also both been put forward as possible causes for global changes in surface solar insolation. Figure 3.18 shows recent results from the Hadley Centre Unified model for the period 1950 – 80 and 1980 – 2000. These model calculations are driven by historical changes in aerosol precursor emissions such as SO_2, BC, and biomass burning. The Figure shows a significant dimming over Europe during the period 1950 – 80 of up to -10 W m^{-2} (in reasonable agreement with the data from Liepert *et al*. (2002)), and a reversal to significant brightening over Europe during the period 1980 – 2000 (in accordance with Wild, 2005). Additionally, the model results show a continued regional reduction in surface insolation over the Indian sub-continent that appears consistent with the results of Ramanathan (2005) where reduction of approximately -17 W m^{-2} has been noted over the period 1960 – 2000. The dimming/brightening from these model results is far from globally homogeneous, but is confined to areas where the regional aerosol emissions and concentrations have either increased or decreased significantly.

Figure 3.18: Change in cloud-free insolation in W m^{-2} for the period 1950 – 80 (upper panel) and 1980 – 2000 (lower panel)



3.3.3 Geographical distribution of air quality pollutants

222. The interaction between temporal and spatial variation in emissions discussed above can be seen in the modelled concentrations of secondary aerosols produced by Derwent *et al*. (2003) and shown in Figure 3.19. Close examination of the detail in the vicinity of the British Isles reveals a pattern consistent with the short period (decades) of elevated emissions and locally elevated concentrations. There is approximately a factor of three increase over the UK from pre-industrial to present day, followed by a factor of two decrease from now until 2030. The pollution does travel hundreds or thousands of kilometres from the source before completing its sequence of oxidation and removal from the atmosphere, but the spatial variation in emissions is large over similar lengthscales so the spatial variability in concentration is similar to the spatial variability in emissions. The local change over the UK is therefore seen in the global context as the growth of a European aerosol cloud through the 20th Century, followed by a shift of location of this cloud to further east through the early part of the 21st Century.

223. Figure 3.20 shows the UK situation in more detail, indicating how spatial patterns of nitrate, sulphate, and ammonium are broadly similar. The steep gradient in concentration over the British Isles can be attributed to the prevalence of westerly flow and the decreasing influence of easterly flow episodes with distance away from continental Europe. Secondary organic aerosols are not included in Figure 3.20 and may make a contribution similar in magnitude to the secondary inorganic aerosols (SIA) shown. Closer to the equator, SOAs are responsible for the maxima in pre-industrial total secondary aerosol shown in Figure 3.19 over Amazonia, Equatorial Africa, and the Indian Subcontinent.

224. The global distribution of anthropogenic BC is similar to that of present day total inorganic aerosol, especially in north-west Europe where the same steep gradient in concentration from north-west Scotland to south-east England can be seen. In addition, there are much smaller urban-scale and finer spatial variations in BC as it is a primary pollutant emitted largely by the transport sector, as reviewed in detail by AQEG (2005).

225. Figure 3.21 is an example of the most recent model capability to calculate the global variation in the number of aerosol particles. The total number is likely to be underestimated over the continents because only sulphate and sea salt are included (see paragraph 156 *et seq*.), but the similar geographical distribution is again clear. The gradient from continental European aerosols dominated by anthropogenic S emissions and maritime conditions is less steep for Cloud Condensation Nuclei (CCN) number than for mass-based aerosol metrics because of the maritime contribution of sea salt and biogenic reduced S emissions.

226. Defra has specifically asked AQEG to consider the impact of AQ pollutants on climate. This issue includes both the rather rapid (in climate terms) increase and decrease in emissions and concentrations of AQ pollutants over a few decades compared with the longer-term build-up of GHGs, and the regional nature of AQ pollutant distributions that has been discussed above. In the sections that follow, we have attempted a review of current understanding of climate responses according to the following classification:

    - The effect of changes in AQ pollutants on global and hemispheric mean forcing, the UK or EU contribution to this, and the climate response to potentially very rapid changes.
    - The climate response to the inhomogeneous distribution of AQ pollutants and the associated radiative forcing, in terms of large-scale circulation.
    - The local *in situ* effect of regional air pollution on regional climate by way of changes in the local radiation balance and hence temperature of the lower atmosphere.
    - Other local *in situ* effects of pollution on climate, principally the effect of pollution on clouds and rainfall.

Figure 3.19: Global surface layer total secondary aerosol concentrations in ng m^{-3} (a) pre-industrial; (b) present day; (c) in the year 2030 (Derwent *et al.*, 2003)

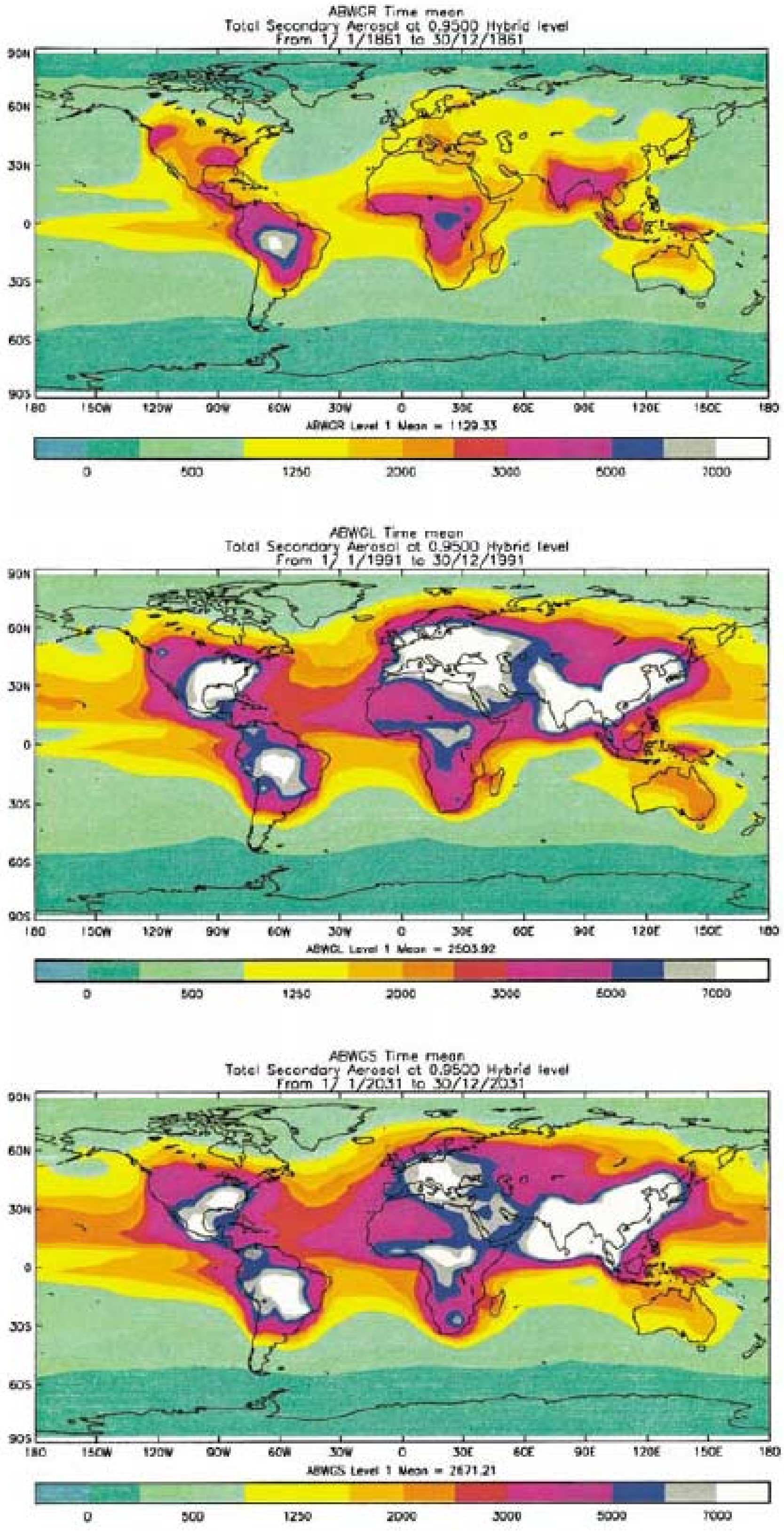


Figure 3.20: Regional surface concentrations of sulphate, nitrate, ammonium, and total inorganic secondary aerosol calculated using the EMEP model using estimated 2003 emissions data and 2000 meteorology (AQEG, 2005)

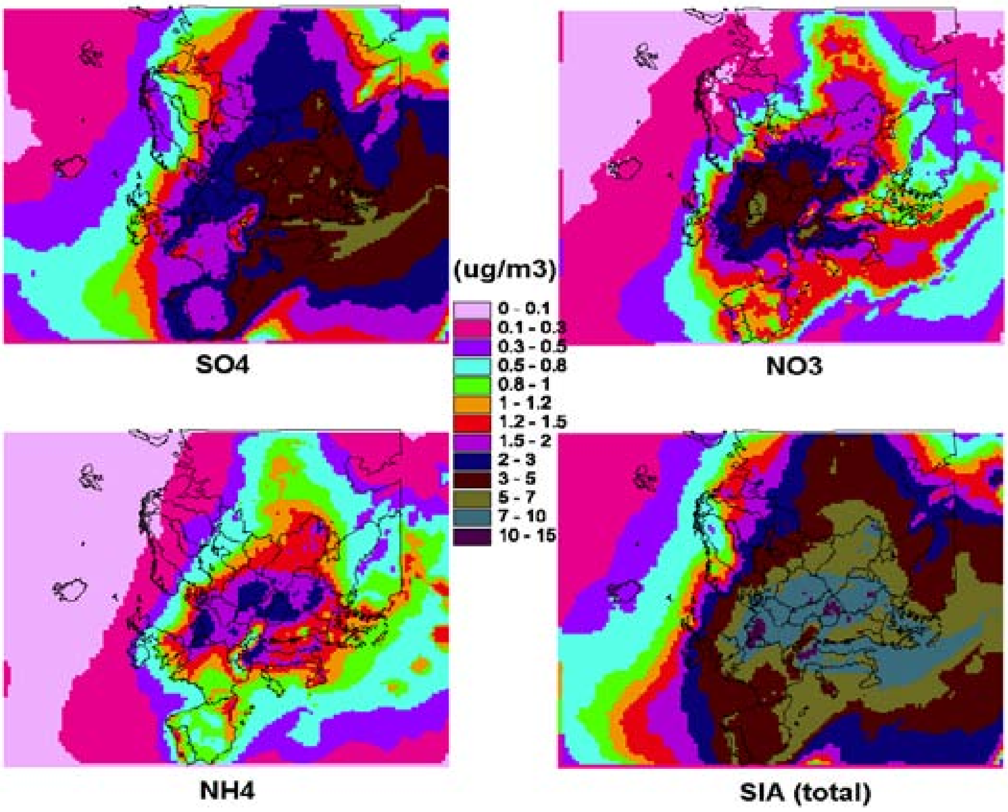
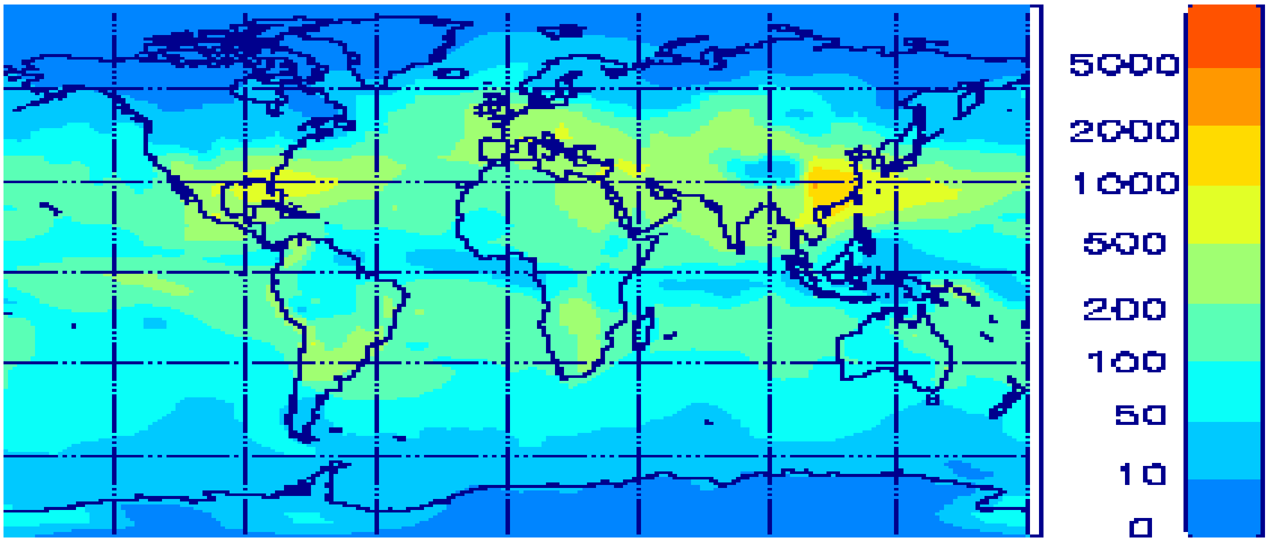


Figure 3.21: Global variation in cloud condensation nuclei (particles per cubic centimetre able to form cloud droplets in a cloud with 0.2% peak supersaturation) at surface level in December 1995 (Spracklen *et al.*, 2005)



3.3.4 Contribution of UK and EU emissions to global totals

227. In this section, the contribution of UK and EU emissions to global total emissions is explored. This gives a first order estimate of the extent to which the UK may be responsible for globally averaged radiative forcing, but it must be emphasised that it would be misleading to make a direct link between proportion of global emissions and proportion of radiative forcing; the intention here is merely to illustrate the orders of magnitude involved.

228. It has already been noted in Chapter 2 that radiative forcing of an inhomogeneously distributed pollutant is sensitive to its altitude and the albedo of the underlying surface. There is also not a globally constant relationship between emissions and concentration, due to differences in boundary-layer depth hence dilution as well as important differences in removal rates especially for pollutants that are removed by rain.

229. Nevertheless, Table 3.3 shows that the UK contribution to global total emissions of AQ pollutants is small (as expected, given the small fraction of the global population resident in the UK). Even total European emissions are dwarfed by those of North America where per capita emissions are higher, and Asia where the number of population is very large. It is therefore easy for changes in globally averaged concentrations of air pollutants to be dominated by changes in emissions beyond Europe. The main global impact of European emissions changes may be to lead or influence similar emissions changes elsewhere in the world. Otherwise, the main impact on European emissions changes is on regional concentrations of pollutants in the immediate vicinity of Europe.

230. Where the radiative forcing caused by the pollutants is sensitive to the albedo of the underlying surface, terrestrial emissions may have slightly less effect where plumes remain over the land than if they are advected over the darker sea. Emissions from shipping and aviation may therefore be slightly more important over the sea, and emissions from shipping are increasing to become a significant fraction of total emissions for some pollutants.

Table 3.3: UK, EU and global emissions of nitrogen oxides, sulphur dioxide, particulate matter PM_{10}, non-methane volatile organic compounds and ammonia in the year 2000

Pollutant	Emission		
	Tg per annum (% of global)		
	UK	EU	Global
NO_X (as N)	0.5 (1.1%)[1]		44.8 (100%)[2]
SO_2	1.0 (1.2%)[1]	4.3 (5.2%)[3]	83.2 (100%)[2]
PM_{10}	0.16[1]		
NMVOCs	1.4[1]		
NH_3	0.29[1]		53.5 (100%)[2]

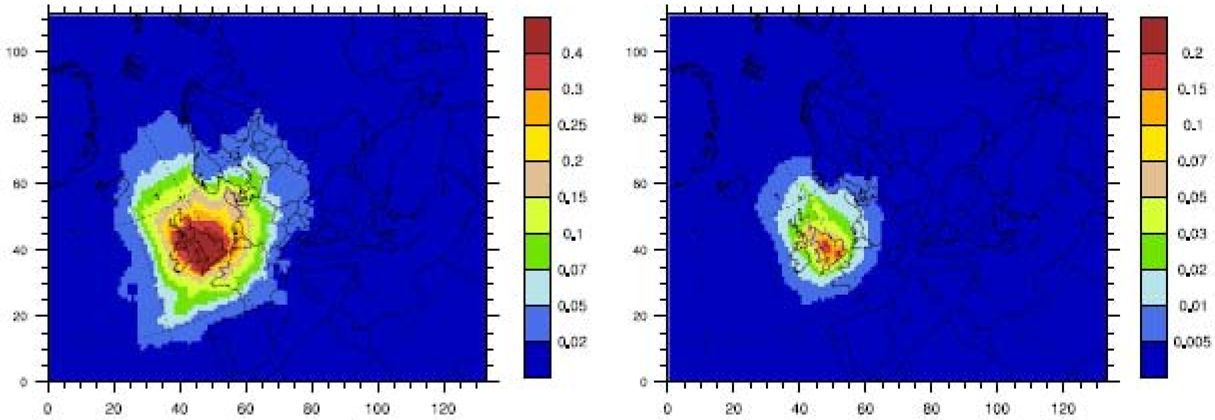
[1] Dore *et al*. (2004)

[2] Derwent *et al*. (2003)

[3] Data from EPER European Pollutant Emissions Register for the year 2001, accessed at http://eper.cec.eu.int/ on 7 October 2005.

231. The geographical extent of aerosol concentrations attributable to UK emissions of the precursor gases is illustrated in Figure 3.22.

Figure 3.22: Change (µg m^{-3}) in secondary inorganic aerosol (left) and $PM_{2.5}$ due to a 15% reduction in UK emissions (Klein *et al*., 2005)



3.3.5 Geographical scale of climate response to inhomogeneous air quality pollutant concentration distributions

232. Given the marked geographical inhomogeneity in the distribution of AQ pollutants, it is reasonable to ask if there is a local *in situ* response of temperature or other meteorological parameters to the presence of a cloud of aerosol or some other pollutant that reflects or absorbs radiation.

233. Relatively few climate model studies of this problem have been carried out. Some insight can be gained from the recent work of Jones *et al*. (2005). By running the Hadley Centre climate model three times, once with GHGs, then with GHGs and sulphate aerosols and then with GHGs and C aerosols, the effect of each aerosol component individually is obtained by subtraction. The surface temperature changes of each of the three components is shown in Figure 3.23.

234. The most striking feature of these results of relevance to the current question is the similarity in spatial variability of temperature change due to well-mixed GHGs and due to both aerosol components. Clearly, the first-order influence on temperature is global or at least hemispherically averaged forcing, and the finer-scale geographical variability is dominated by aspects of the surface and circulation not by the inhomogeneity of the sulphate or BC aerosol concentrations. This important point is quite well known in the climate modelling community, but is worth emphasising in the current context of relationships between AQ and CC. The issue is reviewed and discussed in depth by Boer and Yu (2003).

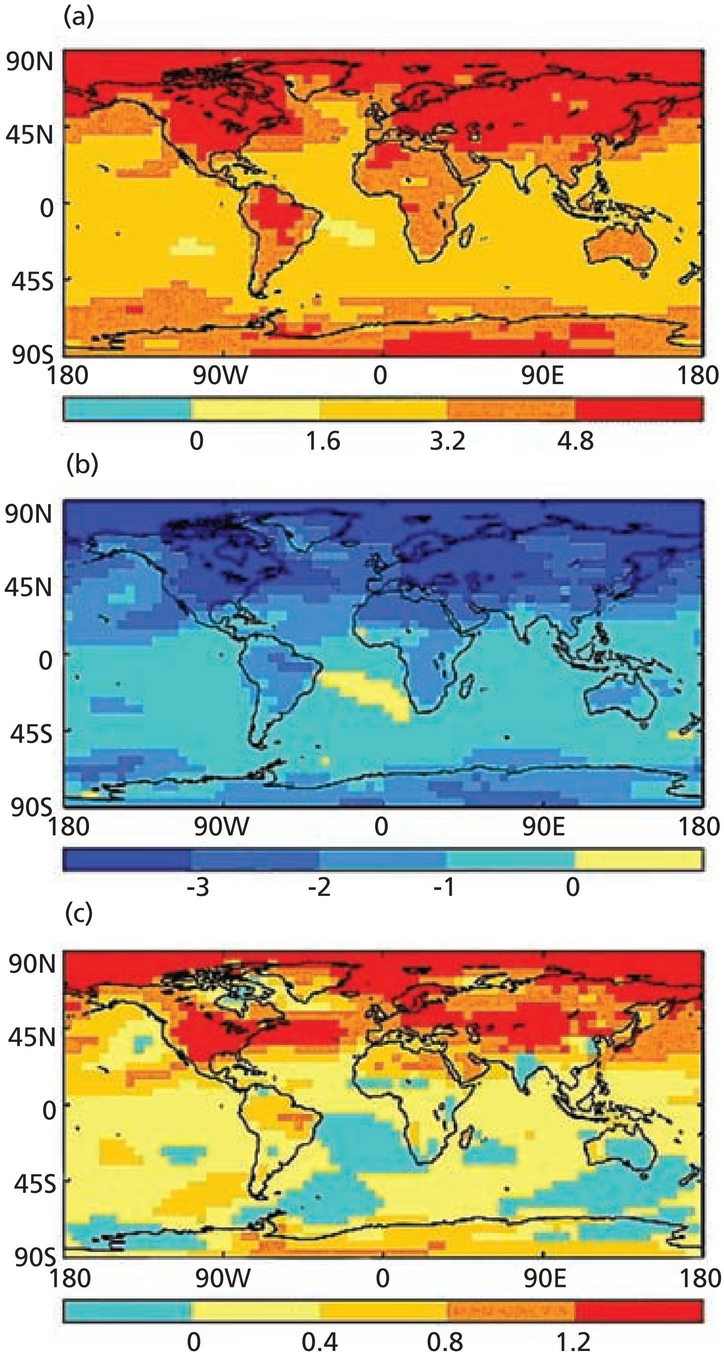
235. On closer examination, some *in situ* regional responses can be detected. For example in China, very high concentrations of BC decrease incoming shortwave radiation sufficiently to offset the warming effect of GHGs. In India the BC also has a cooling effect, but here it is not a direct influence on the radiation balance but by strengthening the summer monsoon. Rypdal *et al*. (2005) reviewed several modelling studies and came to similar conclusions.

236. Jones *et al*. (2005) found that over the 20th Century GHGs warm globally by about 1°C, which is partially offset by cooling from aerosols of about -0.3 °C. For Europe, the cooling from aerosols is larger, about -1.6 °C. However this study did not contain any temporal variations. The evolution of aerosols over Europe is quite different from that over the rest of the world, especially over the last 20 years. It is possible that the decrease in aerosols in that period would lessen their cooling effect over Europe.

237. Stott (2003) also did a Detection and Attribution study on continental scales. His results suggest aerosol cooling over Europe over the 20th Century of less than -0.3 °C. He concludes that the HadCM3 model used is more likely to over-emphasise rather than under-emphasise the aerosol cooling in Eurasia.

238. Regional climate models do not consider the effects of regional variations in air pollution. So the significant difference between projections of CC for the west of England compared with the east are primarily caused by the profound influence of the Atlantic Ocean, and not by the steep gradient in aerosol and photo-oxidant concentrations discussed above.

Figure 3.23: Modelled patterns of near-surface temperature change between the 1890s and 1990 due to (a) greenhouse gases, (b) sulphate aerosols, (c) black carbon. Note that plots have different scales. (Jones *et al*., 2005)



3.3.6 Direct effects of air quality pollutants on climate other than via radiative forcing

239. It is well known that the ability of a cloud to produce rain is influenced by the number and size of aerosol particles on which its droplets are formed. Penner *et al*. (2001) discuss some complex feedbacks between this effect and global cloud amount (see also discussion of the indirect radiative forcing of climate by

polluted cloud in Section 3.2.1.8), but the more straightforward relationship between aerosol particles and rain constitutes a direct relationship between air pollution and climate irrespective of the role of clouds in radiative forcing and climate feedback.

240. Polluted clouds having a larger number of smaller droplets are less likely to form rain than clean clouds that have a smaller number of droplets (hence larger droplets for a given total amount of water, which makes it easier for rain to form).

241. Observational evidence of links between air pollution and the size and number of droplets in cloud and drizzle is well established. Hudson and Yum (1997) and Yum and Hudson (1998) found linkages between the number of CCN and the size of cloud and drizzle droplets in marine stratocumulus cloud. Twohy *et al*. (1995) and Garrett and Hobbs (1995) compared polluted and clean clouds in the same airshed. Boers *et al*. (1998) obtain similar evidence from seasonal variations. A number of studies (e.g. Feingold *et al*., 1999; Eagen *et al*., 1974) have also suggested that a small number of giant CCN (natural or anthropogenic) can determine the extent to which the much more numerous smaller aerosol particles can influence precipitation.

242. Direct evidence of the influence of pollution on rainfall suppression has now been obtained from a few carefully conducted studies. The difficulty of these is selecting conditions where the rainfall effect can be observed separately from other effects such as the urban heat island. Quantitative assessment is therefore biased towards special situations where the effect is larger than usual. Rosenfeld (1999, 2000) shows qualitatively that pollution can suppress the formation of rainfall in convective clouds, while Rosenfeld and Woodley (2003) found evidence from satellite measurements that pollution can completely shut off precipitation from clouds that have cloud-top temperatures greater than 10°C. Borys *et al*. (2003) show that the addition of as little as 1 µg m^{-3} of sulphate aerosol to clean background can reduce orographic snowfall in the Colorado Rocky Mountains by up to 50%. Givati and Rosenfeld (2004) find empirical evidence of 15 – 25% suppression of rainfall from shallow, orographic clouds downwind of urban areas. In Europe, Millan *et al*. (2005) emphasise the sensitivity of Mediterranean rainfall to several factors including air pollution.

243. A number of studies (Beirle *et al*., 2003; Cerveny and Balling, 1998; Dessens *et al*., 2001; Gordon, 1994; Simmonds and Keay, 1997; Wilby and Tomlinson, 2000) have detected weekly cycles in weather conditions including rainfall, which can be attributed to the effects of air pollution.

3.4 Recommendations for further research

244. The analysis in this chapter has revealed significant variability in our level of understanding of processes relevant to the impact of AQ on CC and our ability to quantify the effects. We therefore conclude the chapter by highlighting a few areas where further research would have made a more confident analysis possible.

245. In reviewing the effects of emissions that influence the photochemistry of O_3 formation, it has become clear that the net effect of pollutants such as NO_X on climate is sensitive to the modelling approach adopted, in particular whether

certain reactions and processes are included or omitted. The more recent assessments have included some net impacts, especially of NO_X emissions from aviation, that are small as a result of globally averaging and summing large, uncertain effects of opposite sign. Where the positive and negative effects have different spatial variability and timescale of effect, it is necessary to continue to question and to research the methodology for calculating these and for applying the results to policy. Where very fine scale features might be important, such as aircraft flight paths, and adaptive mesh modelling techniques becoming available that are capable of resolving these, this would appear to be potentially an especially fruitful area of further research in coming years.

246. It has been widely recognised for a number of years that the indirect effects of aerosols on cloud are much less certain than the direct effects of aerosols on radiative forcing of climate, and a significant amount of detailed measurement and modelling-based research in this complicated area is ongoing. In comparing AQ research with climate research however, it is evident that there are some inconsistencies between the way internal and external mixing of different aerosol components between individual particles is handled, and especially in the extent to which the relationship between primary emissions and the number and size of particles is considered. It would be prudent to review the assumptions and approaches that prevail in current research in this area, and check if some important factors are being overlooked.

247. In addition to the large body of ongoing research into the effects of aerosol on the radiative forcing of climate, the related effects of PM on rainfall directly should be considered. Synergies between studies of pollution and rain, and the study of the effect of aerosol on cloud and the indirect forcing of climate, might provide improved insight into interactions between air pollution and climate in this area.

248. The radiative forcing of climate by absorbing aerosols remains subject to uncertainty. Further research would, in particular, help clarify the relative merits of reducing BC emissions or CO_2 emissions, for example from a source such as diesel that emits both.

249. Whilst climate research has focused on sulphate aerosols, and is moving towards consideration of total inorganic secondary aerosol as a single species (similar to the way several distinct aerosol components are lumped together in AQ management as PM_{10} or $PM_{2.5}$), it is clear that there are important emissions control policies that specifically address precursors of non-sulphate aerosol, including abatement of NO_X emissions that is often prioritised for other reasons. Ongoing research therefore needs to be encouraged, that considers non-sulphate aerosol components, including nitrate aerosol and its relationship with emissions of NO_X and ground-level concentrations of NO_2 and O_3.

250. The single pollutant identified in this chapter that has the largest number of effects is NO_X. This includes damage to human health through formation of ground-level NO_2 and O_3; CC effects through changing the build-up of CH_4 and through the formation of tropospheric O_3; human health effects and direct and indirect climate effects of particulate nitrate; acidification and eutrophication by nitrate. We note that local NO_X emissions control is driven primarily by concern over health effects of NO_2, with national emissions being controlled to

limit acidification and eutrophication, whilst ignoring the contribution of NO_X emissions to PM_{10} and its health impacts as well as its effects on climate through its role in atmospheric photochemistry and the formation of nitrate aerosol. This disconnection between multiple effects of NO_X seems unsatisfactory. Additional commonly overlooked factors are the transport of NO_X to remote regions via PAN, and its contribution to the formation of SOA. Some research to strengthen our understanding of the net effects of NO_X emissions would therefore be of interest.

251. We have noted the lack of modelling studies of the regional CC effects arising from regional distribution of pollutants, including the local effects of local radiative forcing. The current poor state of knowledge in this area has hampered our ability to answer the questions asked by Defra, so would appear to be a priority for research. The relationship between observed global dimming and regional variations in AQ also needs to be better understood.

252. According to our current understanding, for policy research into the abatement of emissions from fossil fuel combustion, it would appear sufficient to focus on the climate effects of CO_2 emissions and synergies or conflicts with the AQ effects on non-CO_2 emissions. The effect of non-CO_2 emissions on climate should be the focus of emissions control and policy research for non fossil fuel and non combustion emissions. It should also be borne in mind that this may change in future, in particular the climate effects of non-CO_2 emissions from airborne fossil fuel combustion may prove to be important over certain timescales and at regional scale.

253. Ecosystems are an important component of the global C budget, because of their uptake and emissions of CO_2 and CH_4. These C fluxes have been shown by experimental and modelling studies to be modified by S deposition, N_2 deposition and O_3, but more research is needed (a) to quantify these effects and their significance at regional and global scales and (b) to integrate them more effectively with ongoing studies of the effects of major factors such as climate, land use change and increasing CO_2 concentrations.

254. For aerosols and reactive gases, it is difficult to move from radiative forcing and similar metrics which essentially reflect the instantaneous properties of the pollutants, to proper consideration of the time-integrated effects over the 20 to 100 year timeframes into the future which are important for CC. The difference between a pollutant that is emitted today and accumulates in the atmosphere for future generations, and a pollutant that is not persistent but for which future emissions are projected to increase, is very important for questions of sustainable development, and yet is poorly reflected in most metrics and indicators. There are also important areas of scientific uncertainty that can become critical when considering effects over future time horizons. Research on how to quantify and compare multiple effects of emissions of mixtures of pollutants over all the relevant timescales should therefore continue to be pursued and prioritised. Methodologies such as Health Impact Assessment and Life Cycle Analysis could be examined, to assess the extent to which the crude methods they adopt for comparing or summing AQ and CC effects are appropriate.

Chapter 4

Impact of climate change on air quality

Key points

- A change in seasonality in Air quality (AQ) problems is anticipated in the future. This is manifested by:
    - a simulated <u>decrease</u> in the frequency of occurrence of poor AQ associated with winter stagnation in the UK
    - an <u>increase</u> in summertime photochemical smog linked to increasing temperatures and small reductions in cloud cover (and associated increases in solar radiation)
    - <u>increases</u> in summertime ozone (O_3) precursor biogenic volatile organic compound (VOC) emissions linked to simulated temperature changes.
- Improvements are needed to the supply of climate model data for AQ applications:
    - hourly resolution data for important air pollution dispersion controls which vary diurnally (e.g. atmospheric stability)
    - regional climate model data on time horizons which are most useful for policymaking (i.e. 2020 – 30 rather than just 2061 – 90)
    - regional climate model simulations which more realistically simulate the extremes of soil dryness and surface temperature during periods of summertime drought.
- Ensemble model inter-comparison exercises are essential to determine the magnitude of uncertainties associated with simulations of future climate and atmospheric composition.
- Chemistry Climate Model (CCM) and Chemical Transport Model (CTM) ensemble studies simulating the effect of climate change (CC) on tropospheric O_3 agree that the atmospheric lifetimes of O_3 and methane (CH_4) are likely to decrease by 2030. However they also highlight disagreement regarding the relative effects of key processes:
    - increases in water vapour associated with increasing temperatures and the consequent enhanced destruction/production of O_3 in low/high nitrogen oxides (NO_X) environments
    - increases in the flux of O_3 from stratosphere to troposphere.
- Continued investment is needed in atmospheric composition measurements across a range of monitoring platforms in order that CCM and CTM simulations can continue to be validated.
- The Summer of 2003 in Europe is expected to become ‘typical’ by the 2040s in terms of temperature.

- Changes in vegetation cover, either as a result of changing climate, or deliberate planting policies to mitigate CC, have the potential to modify both pollutant deposition and emissions significantly. Choices of species may be particularly important in the context of biogenic emissions, since there are very large differences between species in emissions of biogenic VOCs.
- Great uncertainties exist regarding the magnitude and relative importance of the many interactions which occur between the atmosphere and the biosphere. Differences in the ways in which these processes are simulated in models account for a large fraction of model divergence.

Box 4.1 Summary response to Question 3

Question 3: How could the likely impact of CC on the general weather patterns and emissions of air pollutants and their precursors affect atmospheric dispersion and chemistry processes in general, and UK AQ in particular? For example, might an increase in heatwaves affect air pollution episodes? Might the frequency and intensity of winter inversions decrease? If so, how will this affect AQ?

The most recently available UK Climate Impacts Programme (UKCIP) CC scenarios suggest that the winter season may become windier by the end of the current century (although with low confidence), associated with a greater Atlantic influence, while summer seasons are anticipated to be significantly hotter and somewhat sunnier, with the summer of 2003 becoming the norm as soon as the 2040s. As a result it is thought that periods of poor dispersion in winter, resulting from stagnation and temperature inversions, may become less common in the UK. Meanwhile, the weather conditions which promote summertime photochemical smog are expected to become more common. A change in the seasonal balance of UK AQ problems may therefore lie ahead.

In parallel with anticipated changes in weather conditions, the changing climate will have an impact on pollutant emissions, the most significant and complex of which are thought to be related to earth system interactions. Volatile Organic Compounds emissions from vegetation are known to rise in conditions of high temperature and sunlight and this was clearly the case in August 2003. However, the impact of this on AQ may be limited by an anticipated parallel decrease in anthropogenic NO_X emissions. The many other competing biosphere interactions lead to significant uncertainty in the net effects.

4.1 Introduction

255. It is now accepted that the chemical composition of the atmosphere is an integral part of the earth's climate system and that it is necessary to take an Earth System approach and address the many feedbacks which exist between climate, natural and anthropogenic pollutant emissions, atmospheric chemistry and deposition processes. It is also necessary to consider interactions which occur between the troposphere and the stratosphere and especially within the Upper Troposphere Lower Stratosphere (UTLS) 'exchange' region. The Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC-AR4) will include two chapters from Working Group 1 in which the significance of atmospheric composition will be discussed: 'Chapter 2 - Changes in atmospheric constituents and radiative forcing'; 'Chapter 7 - Coupling between changes in the climate system and biogeochemistry'.

256. This chapter focuses specifically upon ways in which atmospheric composition has reacted and may react in the future to changes in the climate over various timescales. In particular, the year 2030 is considered in support of policy-making; while emission scenarios to 2030 are slightly easier to envisage than for the end of the current century, signal-to-noise in terms of effects will be weaker due to greater difficulty in distinguishing between natural variability and anthropogenically forced CC. Where possible, specific comments on implications for North-west Europe are included. Despite the many feedbacks and interactions which exist, the reverse question of how atmospheric composition may affect climate is addressed in the previous chapter.

257. Climate change feedbacks on atmospheric composition can be classified into:

    a. transport processes (wind, convection, mixing properties in the atmospheric boundary layer, stratosphere-troposphere exchange)

    b. transformation controls (relative humidity, specific humidity, cloud cover and type, temperature, albedo and its effect on photolysis rates)

    c. removal processes (precipitation frequency and amount, surface properties including changes in the partial pressures of oxidised and reduced nitrogen (N) in terrestrial surfaces)

    d. emission controls (both anthropogenic and biogenic, including demography, shift in seasonal temperatures and the effect on energy consumption, plant and forest species, atmosphere-ocean interaction including ice cover variability).

258. It can be helpful to take a synoptic climatological approach to considering such feedbacks since individual synoptic weather patterns each embrace a particular collection of transport, transformation, removal and emission conditions (e.g. Comrie, 1992; Davies *et al*, 1986; McGregor and Bamzelis, 1995).

4.2 Climate change and air quality in the historical record

259. Debate continues regarding the interaction between the chemical composition of the atmosphere and the climate system especially during transitions from glacial to inter-glacial periods. Estimates of the atmospheric concentration of key trace gases during these periods has been made through collection and analysis of ice cores. It is therefore clear that important links between atmospheric chemistry and climate are far from new.

260. However, the focus in this section is on a very short recent period, namely the last fifty years, during which time AQ measurements have routinely begun to be made in the developed world.

4.2.1 The role of the climate system in controlling atmospheric chemistry at the regional-hemispheric scale

261. Dameris *et al*. (2005) and Grewe (2005) present a troposphere-stratosphere simulation of the time period 1960 – 2000 using the CCM E39/C model. The simulation includes a variety of changing boundary conditions, such as monthly mean observed sea surface temperatures, the 11-year solar cycle, the Quasi-Biennial-Oscillation (QBO), three major volcanic eruptions (affecting stratospheric aerosol loading) and emissions of carbon dioxide (CO_2), CH_4, nitrous oxide (N_2O), chlorofluorocarbons (CFCs) and NO_X (from biomass burning, traffic, ships, soils, lightning, industry, air traffic). Although the horizontal resolution of this model is rather coarse compared to regional models, the simulation can nevertheless provide useful information on the impact of large-scale processes on regional AQ. The model, however, contains relatively simple NO_X - carbon monoxide (CO) - CH_4 chemistry and so results should be viewed with some caution.

262. The general circulation in the stratosphere is dominated by ascent in the tropics and descent at higher latitudes. The tropical mid-stratosphere is an important O_3 production region while, in the troposphere, O_3 concentration is driven by O_3 influx from the stratosphere and by O_3 production via nitrogen dioxide (NO_2) photolysis.

263. The model simulations show that the 11-year sunspot cycle affects stratospheric O_3 production while, in the tropical troposphere, NO_X and O_3 concentration depend upon lightning generated NO_X. The El-Nino/La Nina system is simulated to be the most important natural climate variability in the tropics affecting lightning occurrence and therefore also O_3 concentration.

264. Ozone concentration variability in the troposphere is affected by both stratospheric and tropospheric processes. Lightning NO_X emissions, associated with convection, dominate the O_3 concentration in the upper tropical troposphere, while stratospheric O_3 and industrial precursor emissions are more important in other regions (Grewe, 2005). Inter-annual variability of O_3 caused by stratospheric dynamics is simulated to be in the order of ± 4% whereas that produced by El Nino is ± 2-3% (the latter effect being found to be higher in other studies).

265. The RETRO (REanalysis of the TROpospheric chemical composition over the past 40 years) European Union project (Schultz, 2005) is also seeking to undertake a comprehensive reanalysis of the global trends in air pollution over the past 40 years. This will also enable further assessment of the role of the changing climate in affecting historical atmospheric composition at the regional to global-scale and may then be used by others to undertake high-resolution simulations in, for example, Europe.

4.2.2 The role of weather in day-to-day and inter-annual variations in air quality at the UK and European scale

266. Inter-annual variations in weather are known to significantly impact AQ (Section 4.2.2.4). However, the impact on AQ of any trends in climate over decadal periods, over the last 50 years during which time AQ monitoring has become widespread, is likely to be small relative to the changes in pollutant emissions over this same timescale. Any 'signal' of the effect of CC on AQ is likely to be stronger in the future than in the recent measurement record.

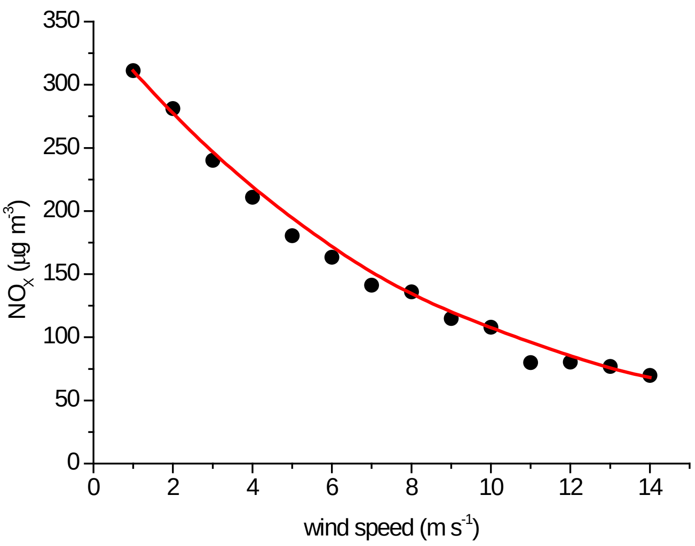
267. Nevertheless, in this section we can point to some interesting and important recent AQ episodes in Europe where weather conditions have been shown to be influential. These examples serve to highlight those meteorological parameters which, through CC, may have further impacts on AQ in the future, potentially confounding any changes associated with pollutant emission controls.

4.2.2.1 Weather – air quality relationships in average conditions

268. In addition to the significant role which weather conditions play in causing episodes of poor AQ (Sections 4.2.2.2 – 4.2.2.4), their influence is also clear in typical AQ conditions, as highlighted here in terms of wind, temperature and solar radiation effects.

269. One of the clearest examples is shown in Figure 4.1 in which the diluting effect of wind speed on NO_X concentration is demonstrated at the London Hillingdon station, close to the M4 Motorway.

Figure 4.1: Wind Speed versus nitrogen oxides concentration at the London, Hillingdon automatic urban network station



270. Further examples in Figures 4.2 and 4.3 show, respectively, the influence of wind speed on particulate matter (PM), both $PM_{2.5}$ and PM_{coarse} (PM_{10}-$PM_{2.5}$) as measured at the Marylebone Road roadside and Bloomsbury urban background sites in London (Charron and Harrison, 2005). It is clear that $PM_{2.5}$ decreases when wind speed increases due to dilution but that PM_{coarse} increases due to resuspension, thereby revealing the different sources of these PM components.

Figure 4.2: Wind Speed versus $PM_{2.5}$ mass concentration at Marylebone Road (MR) and Bloomsbury (UB), London

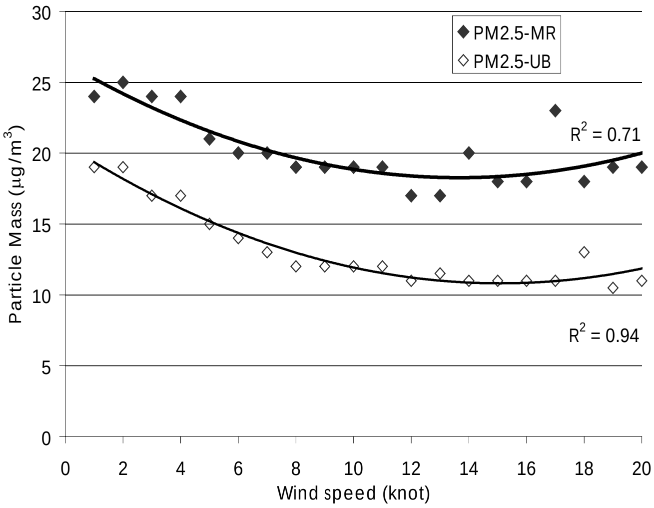
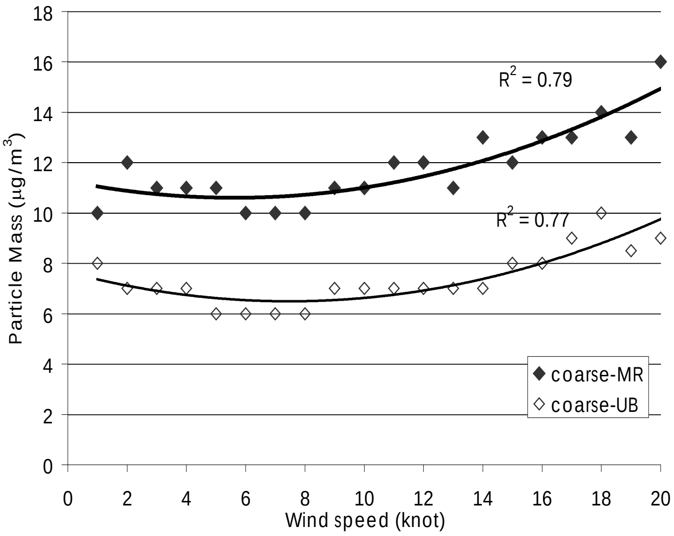
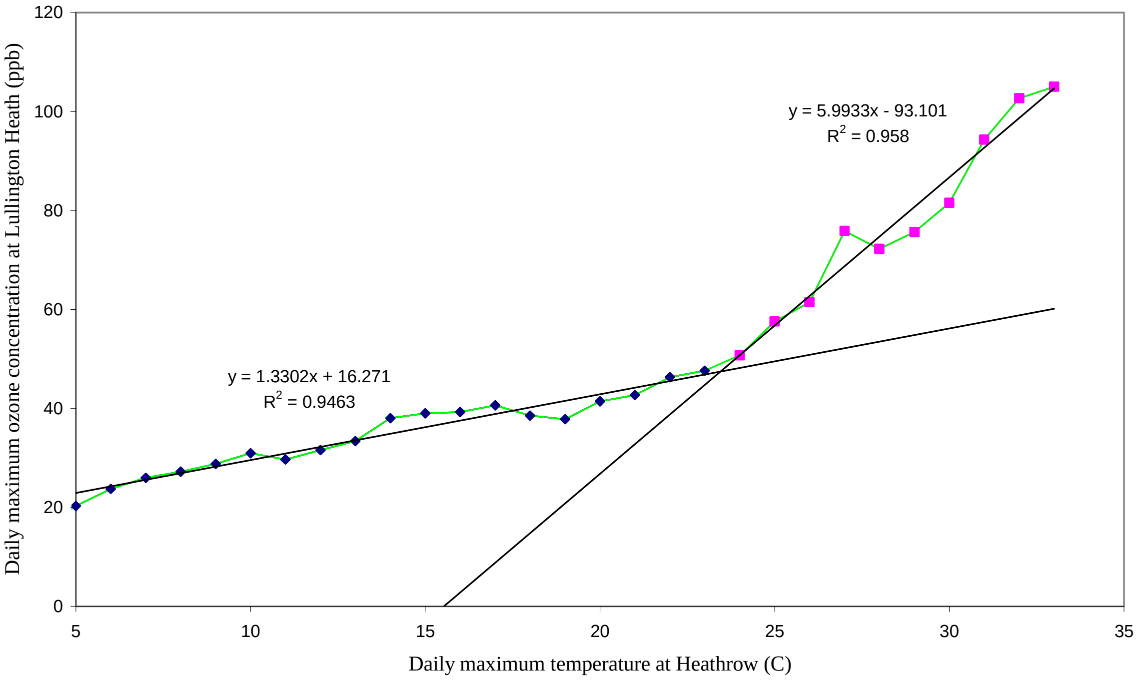


Figure 4.3: Wind Speed versus PM_{coarse} at Marylebone Road (MR) and Bloomsbury (UB), London



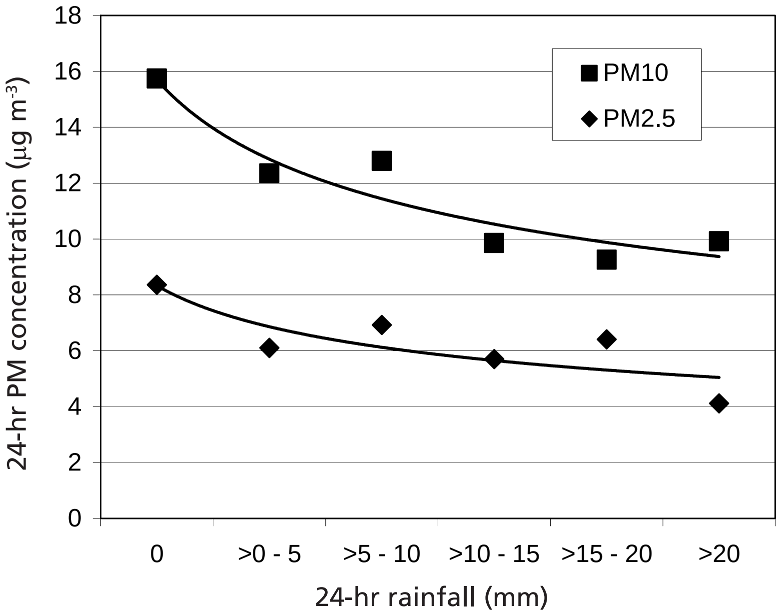
271. Anderson *et al*. (2001) demonstrated the close relationship between daily maximum temperature and daily maximum surface O_3 concentration, showing in particular a heightened sensitivity at higher temperatures (Figure 4.4). Such a finding is typical but it should be noted that air temperature is also strongly correlated with solar radiation intensity, boundary layer height and atmospheric stability and all of these factors place important controls on AQ.

Figure 4.4: Relationship between daily maximum temperature at Heathrow and daily maximum ozone concentration at rural Lullington Heath, UK, 1993 – 98 (Anderson *et al*., 2001). To convert to µg m^{-3} units, 1 ppb = 2.00 µg m^{-3} for O_3 at 20°C and 101.3 kPa



272. Figure 4.5 shows the averaged effect of precipitation in reducing the concentration of ambient PM_{10} and $PM_{2.5}$. The effect can be ascribed to the scavenging of PM out of the atmosphere into rain drops (washout), although the relationship should not be over-interpreted because of the influence of other important associated meteorological factors such as windspeed. The temporal sequencing of storms also affects washout, pollutant residence times and therefore the importance of long-range transport.

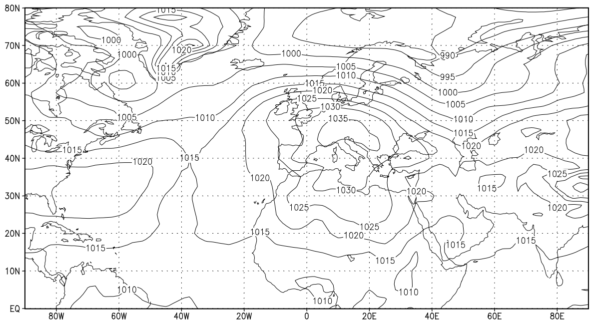
Figure 4.5 Averaged effect of rainfall on 24-hour PM_{10} and $PM_{2.5}$ concentrations measured in Edinburgh. Concentrations are median values for each rainfall category. The solid lines are for guidance only



4.2.2.2 December 1991 in London (nitrogen dioxide and particulate matter PM_{10})

273. **Poor dispersion** of air pollutants is one factor which often leads to a deterioration in AQ. Changes to dispersion efficiency are therefore one obvious way in which the climate may impact upon AQ. Key parameters are **wind speed** and **atmospheric stability**.

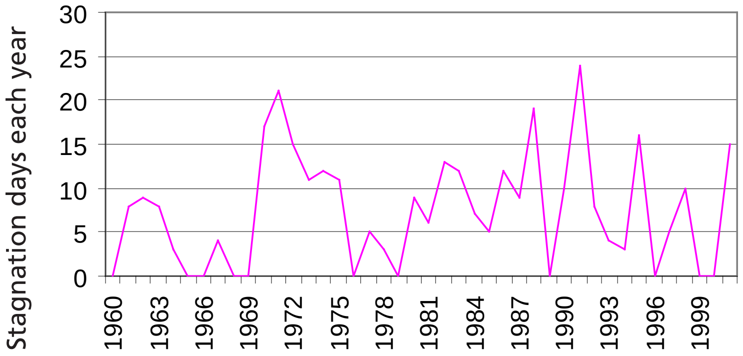
Figure 4.6: Composite sea-level pressure analysis for 12 – 15 December 1991



274. In the recent historical record, December 1991 (Figures 4.6 and 4.7) has been documented as a classic winter stagnation event in London (Derwent *et al*., 1995; Bower *et al*., 1994). Dorling *et al*. (2003) derived a stagnation index for the UK, based on National Centres for Environmental Prediction (NCEP) reanalysis data, which was able to capture the inter-annual variation in stagnation frequency (Figure 4.8) over the period 1960 – 2001, highlighting another important event in December 2001 (AQEG, 2004). Simulations of how dispersion efficiency may change under future CC are discussed in Section 4.4 of this chapter.

Figure 4.7: Nitrogen dioxide concentrations (μg m^{-3}) in London 11 – 15 December 1991

Figure 4.8: December stagnation day frequency in the UK



4.2.2.3 February/March 1996 in the UK (PM_{10})

275. The months of February and March 1996 saw some significant PM_{10} episodes across much of the UK (Figure 4.9, Table 4.1) during a period in which transport from the east and south-east from the European continent was unusually common, highlighting the impact of **transport** from polluted sources.

Figure 4.9: Number of daily 24-hour average PM_{10} exceedences of Air Quality Strategy objective summed across the UK Automatic Urban Monitoring Network by month (1996 – 2003)

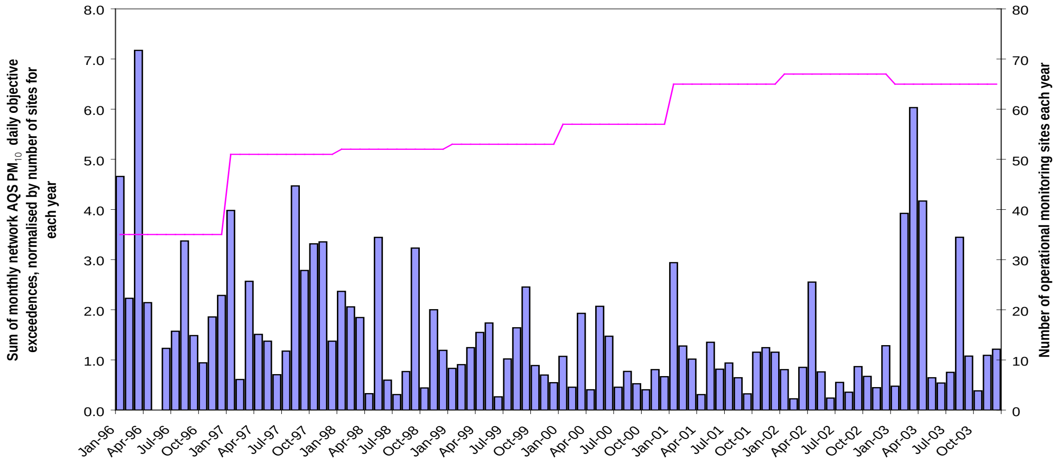


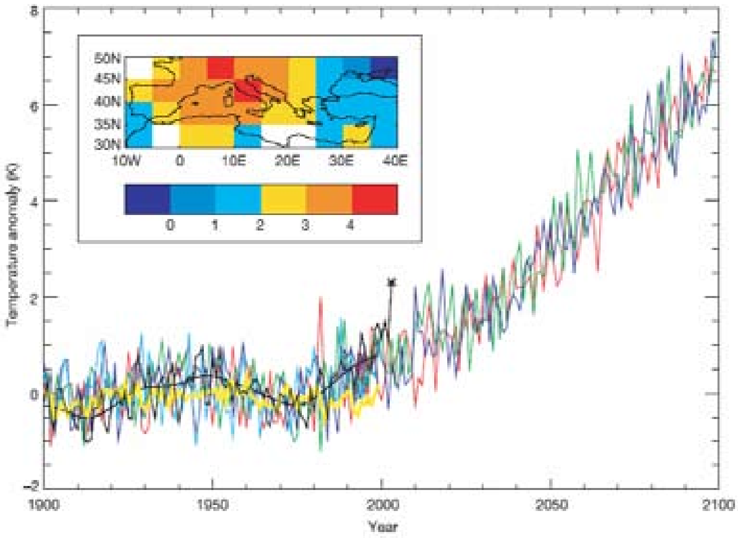
Table 4.1: Annual number of UK Air Quality exceedences normalised by the number of monitoring stations in each year (1996 – 2003)

Year	Number of exceedences
1996	29
1997	27
1998	19
1999	14
2000	11
2001	13
2002	10
2003	24

4.2.2.4 2003 in the UK and Europe (particulate matter PM_{10}, ozone)

276. Stedman (2004), Fischer *et al*. (2004), Institut de Veille Sanitaire (2003) and EEA (2003) report on the very significant mortality impacts of the poor summertime AQ in 2003 across Europe, associated with the summer heatwave and drought (Schär *et al*., 2004), demonstrating the important role of **air temperature** and **solar radiation**. In the period 1 –15 August, High Band O_3 concentrations (180-360 µg m^{-3}, 90-180 ppb) were recorded in the UK on ten separate days, in both rural and urban areas, including the highest London O_3 concentrations for over a decade (Kent, 2003). In the same report it is suggested that a trend of declining NO_X emissions, and therefore reduced O_3 titration, may also have contributed to the elevated O_3 concentrations. Enhanced natural VOC emissions (see Section 4.3.1.1) were also important during this period. Reduced dry deposition rates of O_3 may have occurred as a result of water stress on plants associated with drought conditions while reduced column O_3 during this period is likely to have been accompanied by enhanced ultraviolet radiation at the surface. Stott *et al*. (2004) show in Figure 4.10 below that the anomalous weather conditions experienced in Europe in the Summer of 2003 are likely to become common by the 2040s as a result of CC. Meanwhile, Pal *et al*. (2004) highlight a drying trend in European summers, coupled with increased vulnerability to extreme drought and flood (2002 being one of the wettest on record in central Europe).

Figure 4.10: Observed and simulated European June-August temperature anomalies relative to the 1961 – 90 mean (Stott *et al*., 2004). Shown are observed temperatures (black line, with low-pass-filtered temperatures as heavy black line), modelled temperatures from four HadCM3 simulations including both anthropogenic and natural forcings to 2000 (red, green, blue and turquoise lines), and estimated HadCM3 responses to purely natural forcings (yellow line). The observed 2003 temperature is shown as a star. Also shown (red, green and blue lines) are three simulations initialized in 1989) including changes in greenhouse gas and sulphur emissions according to the SRES A2 scenario to 2100. The inset shows observed summer 2003 temperature anomalies, in K.



277. Widespread PM_{10} episodes also occurred in the early spring of 2003 (Figures 4.11 and 4.12), associated with synoptic conditions promoting south-easterly airflows. As a result, the UK headline AQ indicator showed a sharp deterioration in 2003 (Figure 4.13), following an improving trend over previous years. Figure 4.14 shows the impact of using 2003 meteorological data relative to that for 2002 on modelled annual mean PM_{10} in London.

Figure 4.11: PM_{10} concentration data recorded at the North Kensington monitoring station in London in 2002 and 2003

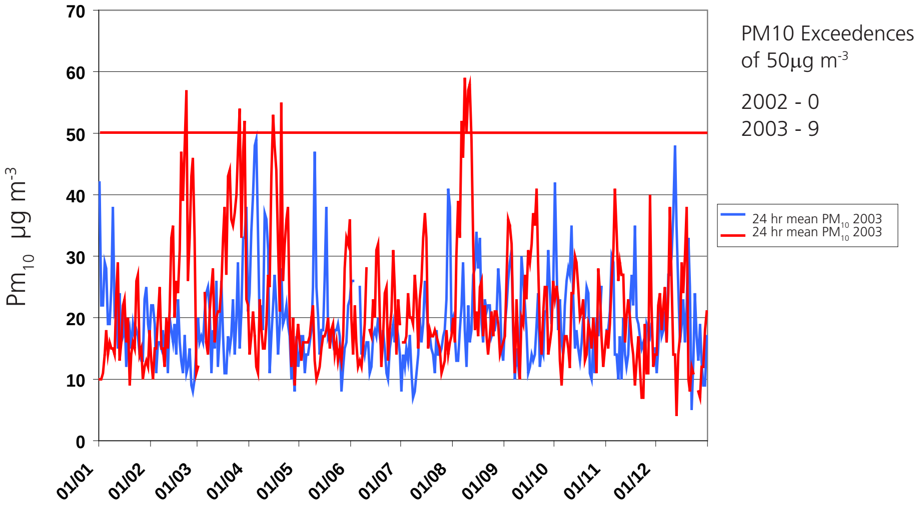
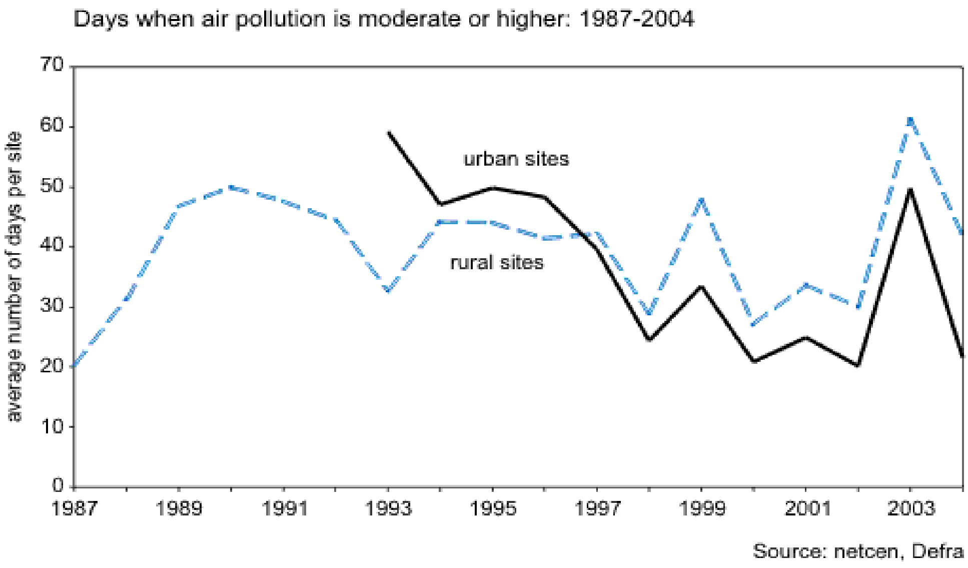


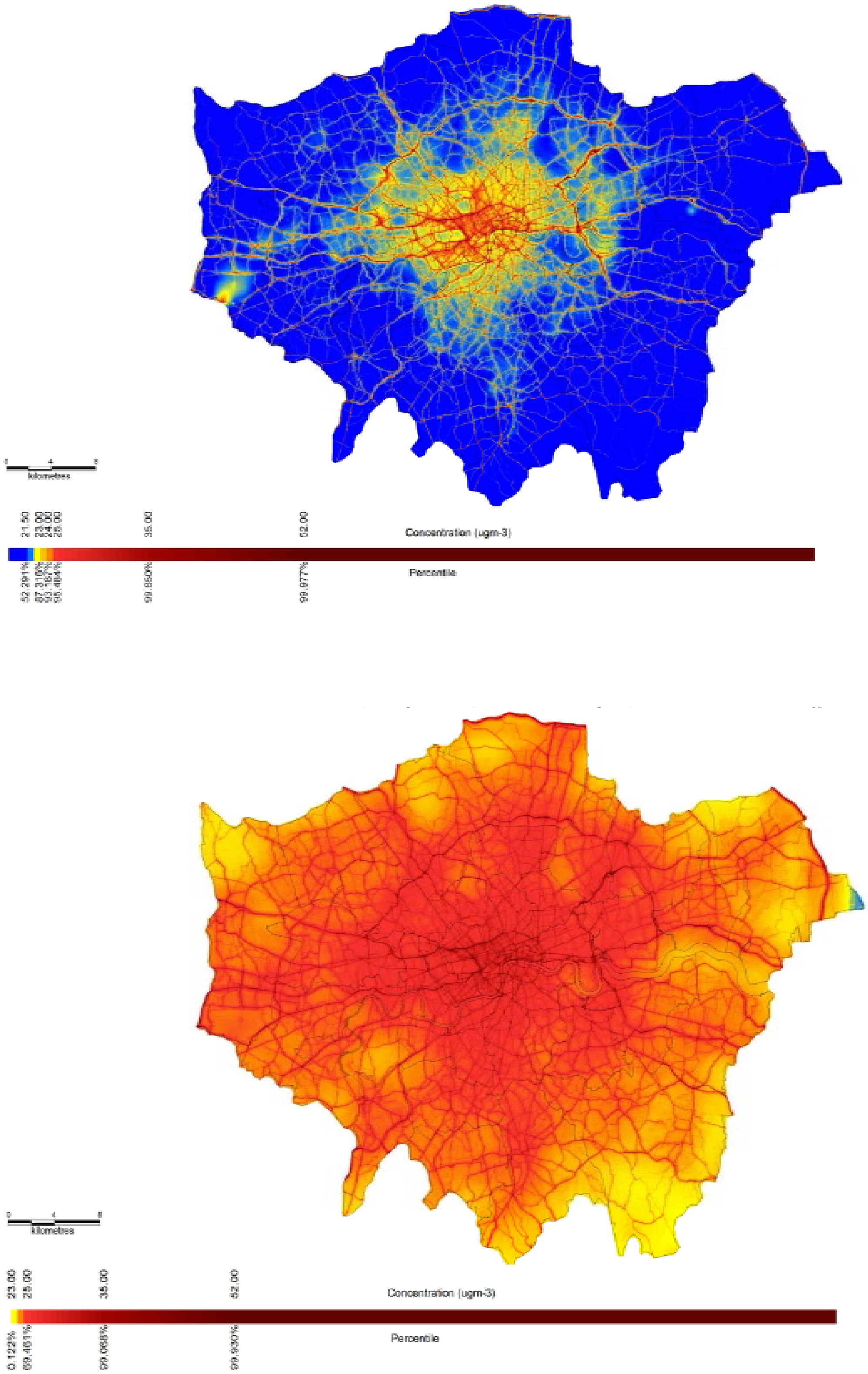
Figure 4.12: London haze, March 2003

Figure 4.13: UK Headline Air Quality Indicator 1987 – 2004



Source: netcen, Defra

Figure 4.14: Modelled 2005 Annual Mean PM_{10} concentration (µg m^{-3}) in London based on 2002 (top) and 2003 (bottom) meteorological data (Greater London Authority, personal communication)



Box 4.2: Regional-scale ozone formation: a case study

In conjunction with the Natural Environment Research Council (NERC) Tropospheric Organic Chemistry Experiment (TORCH) project, a photochemical trajectory model (PTM) was used to simulate regional-scale O_3 formation during late July and August 2003. The model is based on that of Derwent *et al*. (1996), with recent updates described by Utembe *et al*. (2005) and Johnson *et al*. (2005). It simulates the chemical development in a well-mixed boundary layer air parcel being advected along multi-day trajectories prior to arrival at a given receptor site. The air parcel picks up emissions of NO_X, CO, sulphur dioxide (SO_2), CH_4 and anthropogenic VOC (based on National Atmospheric Emissions Inventory (NAEI) and European Monitoring and Evaluation Programme (EMEP) emissions) and biogenic VOC (based on Dore *et al*., 2003a), which are processed using a detailed description of the chemical and photochemical transformations leading to the formation of O_3 and other secondary pollutants (Jenkin *et al*., 2002).

The model was used to simulate the chemical development over a 96 hour period along 150 trajectories arriving at the site of the TORCH-2003 campaign at Writtle in Essex. The trajectories corresponded to arrival times of 0000, 0600, 1200 and 1800 hr for the period 26 July – 31 August 2003. Figure 4.15 shows a comparison of the simulated O_3 concentrations at the arrival point with those observed. This demonstrates that the model broadly recreates the observations, including the generally elevated concentrations during the anticyclonic period which persisted from 3 – 12 August.

Figure 4.16 shows the change in simulated daily-average O_3 concentration throughout the campaign resulting from applying a small incremental increase (1%) to the emissions rate of both anthropogenic and biogenic Non-methane Volatile Organic Compounds (NMVOC). Because the perturbation to the system is small, this provides a reasonable measure of the relative impacts of anthropogenic and biogenic NMVOC for the conditions being simulated. The anticyclonic period generally shows the largest resultant O_3 increment, because the emissions input was greatest during this period. However, it is also clear that the biogenic emissions are calculated to make a larger relative contribution at the prevailing higher temperatures. During the anticyclonic (heatwave) period, biogenic NMVOC emissions are thus calculated to account for 33% of regional-scale O_3 formation on average, and typically 40-45% on the highest temperature days. This can be compared with a simulated contribution of about 20% during the remainder of the campaign. Although it is recognised that the magnitude of biogenic NMVOC emissions is subject to some uncertainty, these results support an important role for biogenic NMVOC oxidation in regional-scale O_3 formation under heatwave conditions.

Figure 4.15: Comparison of observed hourly mean ozone concentrations (line) with those simulated for six-hourly intervals (open circles) for the entire TORCH-2003 campaign. To convert to µg m^{-3} units, 1 ppb = 2.00 µg m^{-3} for O_3 at 20°C and 101.3 kPa

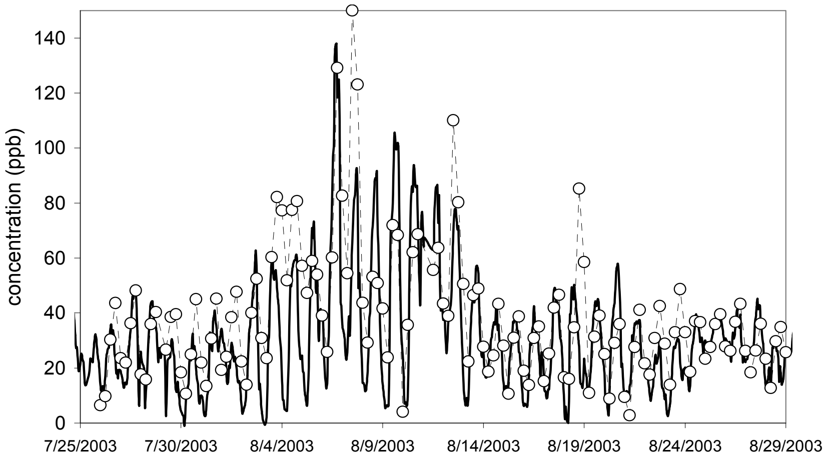
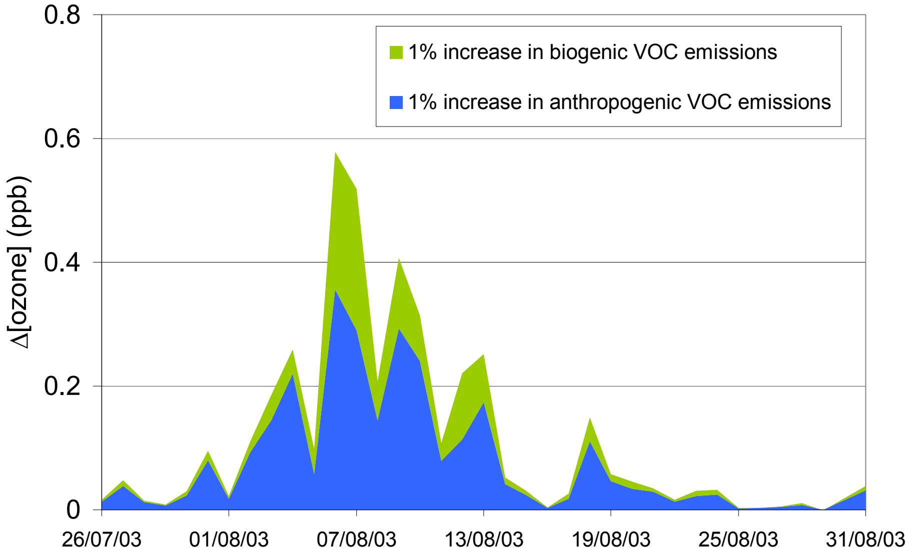


Figure 4.16: Simulated increase in ozone concentration at the arrival point (Writtle, Essex) resulting from an incremental increase of 1% in emissions of volatile organic compounds. To convert to µg m^{-3} units, 1 ppb = 2.00 µg m^{-3} for O_3 at 20°C and 101.3 kPa



278. The hot and dry summer of 2003 in Europe also saw above average wildfire activity and associated pollutant emissions, as shown in Figure 3.9. Wildfire and biomass burning emissions are discussed further in Section 4.3.1.1 of this chapter.

4.3 Interactions between climate, emissions and the biosphere

4.3.1 Weather, climate and air pollution emissions

279. The climate has an important influence upon:

- emission rates from some natural sources
- emission rates from some anthropogenic sources
- human comfort and therefore our behaviour and choices with respect to emission processes.

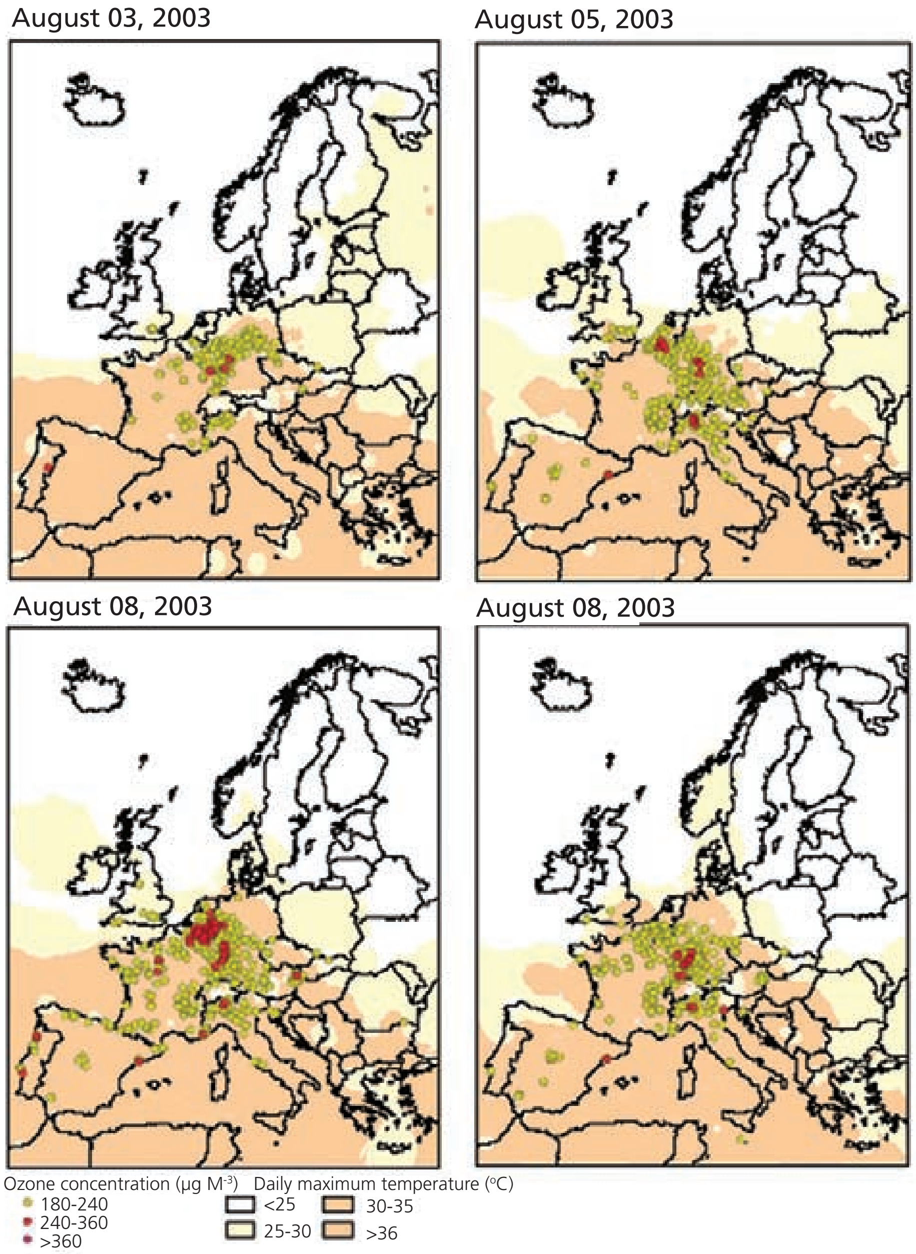
4.3.1.1 Climatic effects on natural emissions

280. Agriculture, forestry and semi-natural ecosystems are important sources of air pollutants both directly (e.g. ammonia (NH_3) emissions from livestock) or indirectly (e.g. biogenic VOC emissions from forestry and CH_4 emissions from agriculture and wetlands are linked to O_3 formation). Changing climate may increase local and national emissions both directly (e.g. increased volatilisation of NH_3 at higher temperatures) or indirectly (e.g. through changes in land cover and land management).

Volatile organic compounds

281. The TORCH Experiment (Utembe *et al*., 2005) has demonstrated that, even in the current climate, natural VOC emissions, e.g. of isoprene from poplar trees, can increase substantially in high temperature conditions such as those experienced in August 2003 in the UK (Figures 4.21 and 4.22). This led to the highest surface O_3 concentrations experienced in the UK for over ten years (Figure 4.17; Kent, 2003; see Section 4.2.2.4)

Figure 4.17: Stations reporting an hourly ozone concentration in excess of 180 µg m^{-3} during the August 2003 heatwave (EEA, 2003)



August 03, 2003

August 05, 2003

August 08, 2003

August 08, 2003

282. In terms of the global carbon (C) balance Guenther (2002) estimated the global annual emissions of reactive C compounds from terrestrial vegetation as 1.2 Pg of C, compared with a figure of 6 Pg of C in 1990 from fossil fuel and cement production. In global terms, emissions of VOC from natural (biogenic) sources are estimated to exceed those from anthropogenic sources by about an order of magnitude (e.g. Guenther *et al*., 1995), and consequently have a major impact on global atmospheric chemistry. Many hundreds of individual VOC species are emitted from biogenic sources (e.g. see Geron *et al*., 2000; Owen *et al*., 2001), with the identities and distribution depending on the type of vegetation and other factors (e.g. season). However, particularly significant contributions are generally made by 'isoprene' (a C5 conjugated dialkene) and by 'monoterpenes', a class of isomeric C10 hydrocarbons which includes species such as α pinene, β pinene and limonene. These are all highly reactive VOCs which can contribute to regional-scale photochemical O_3 formation in the presence of NO_X (e.g. Derwent *et al*., 1998; Saunders *et al*., 2003) and, particularly for the monoterpenes, can be oxidised to generate products which contribute to the generation of PM in the form of secondary organic aerosol (SOA) (e.g. Kanakidou *et al*., 2005).

283. Even in many populated regions, biogenic emissions are comparable in magnitude to anthropogenic emissions, e.g. in some parts of central and southern Europe, and in the Boreal forest in Finland (e.g. Simpson *et al*., 1999). In the UK, the NAEI currently reports an unchanging annual emission total of biogenic VOC of 178 kt. This accounted for about 7% of total UK VOC emissions in 1990, increasing to about 11% in 2000, and is projected to account for about 15% in 2020, the progressively increasing contribution being a consequence of reductions in anthropogenic emissions. It is noted, however, that estimates of biogenic emissions are subject to significant uncertainties. For example, Stewart *et al*. (2003) estimate a factor of four uncertainty in their estimate of the biogenic VOC emissions total for Great Britain, which can be compared with the uncertainty estimate of ±8% for the UK anthropogenic VOC total (AQEG, 2005).

284. In practice, however, biogenic VOC emission rates depend on temperature and (in some cases) light intensity, and therefore demonstrate significant diurnal, seasonal and inter-annual dependences (e.g. Guenther *et al*., 1993; Stewart *et al*., 2003). Isoprene emissions generally depend on temperature and light intensity, typically increasing by a factor of about 4 between 20°C and 30°C, and peaking at about 38 – 40°C (e.g. Guenther *et al*., 1993). Monoterpene emissions also depend on temperature, and are typically estimated to increase by a factor of about 2.5 with each ten degree increase in temperature (e.g. Guenther *et al*., 1993). As a result they also tend to be much greater during heatwaves, when temperatures exceed 30°C and solar intensity is high. The fractional contribution of biogenic VOC emissions under specific summertime conditions is potentially more substantial, therefore, and aggregated annual emissions would be expected to display some year-on-year variability related to the actual meteorological conditions experienced. These factors mean that seasonal and diurnal variations in biogenic VOC emissions, and the rate of these emissions under the very high temperatures that characterise O_3 episodes, and which may become more frequent under a changing climate, are of considerable importance. To illustrate this important

point, we present here (a) an analysis of measured biogenic VOC concentrations in non-episode conditions, (b) an analysis of measured biogenic concentrations during the August 2003 episode and (c) a model simulation of the contribution of biogenic VOCs to O_3 formation during this episode.

Biogenic VOC concentrations in non-episode conditions

284. Ratios of isoprene and 1,3-butadiene concentrations (Figures 4.18 and 4.19) clearly demonstrate seasonal and diurnal variations in the contribution of biogenic emissions to isoprene concentrations at London sites, superimposed on a well-defined anthropogenic contribution, which is reported to be about 40% of 1,3-butadiene emissions (e.g. Burgess and Penkett, 1993; Derwent *et al*., 1995; Reimann *et al*., 2000). The biogenic contribution is minimal during the winter months, and maximal in July and August. In winter, there is no detectable diurnal cycle, but in summer, there is a ten-fold increase in the middle of the day. Monthly mean biogenic isoprene concentrations typically maximise at about 0.25 ppb (0.71 µg m^{-3}) in the summer at London sites (Figure 4.20).

Figure 4.18: Seasonal variation of [isoprene]/[1,3-butadiene] London sites, based on 1998 and 1999 data. The displayed monthly mean data clearly indicate an underlying anthropogenic isoprene contribution equating to about 40% of 1,3-butadiene emissions, with an additional biogenic contribution which maximises in the summer months. To convert to a ratio based on µg m^{-3} units, presented figures should be multiplied by 1.26

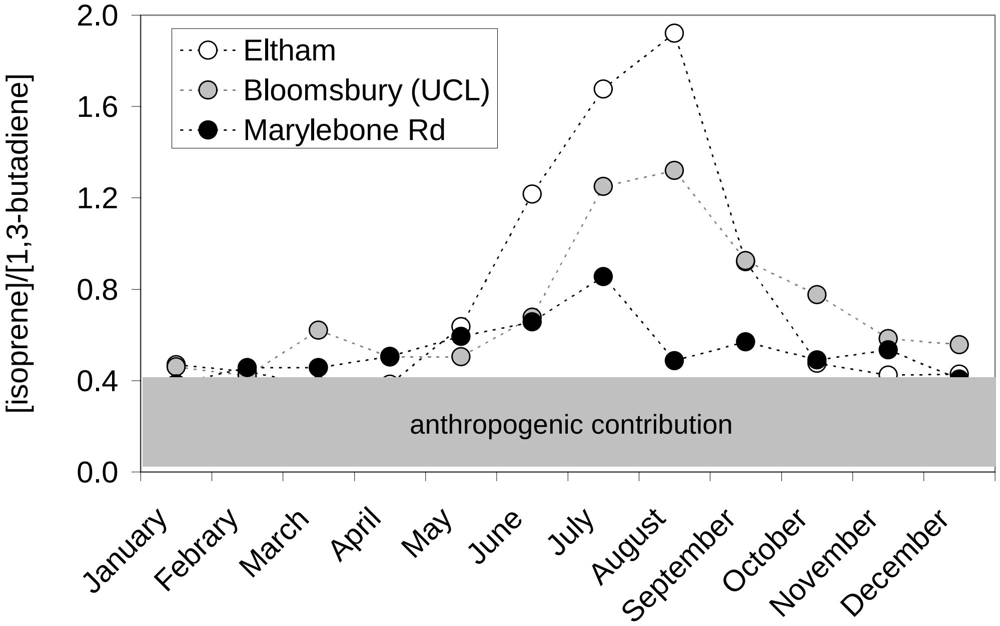


Figure 4.19: Diurnal variation of [isoprene]/[1,3-butadiene] at London Eltham in January and July, based on 1998 and 1999 data. The displayed hourly mean data indicate that the anthropogenic isoprene contribution (equating to about 40% of 1,3-butadiene emissions) accounts for all the observed isoprene in January, whereas biogenic emissions dominate during the daytime in July. To convert to a ratio based on μg m^{-3} units, presented figures should be multiplied by 1.26

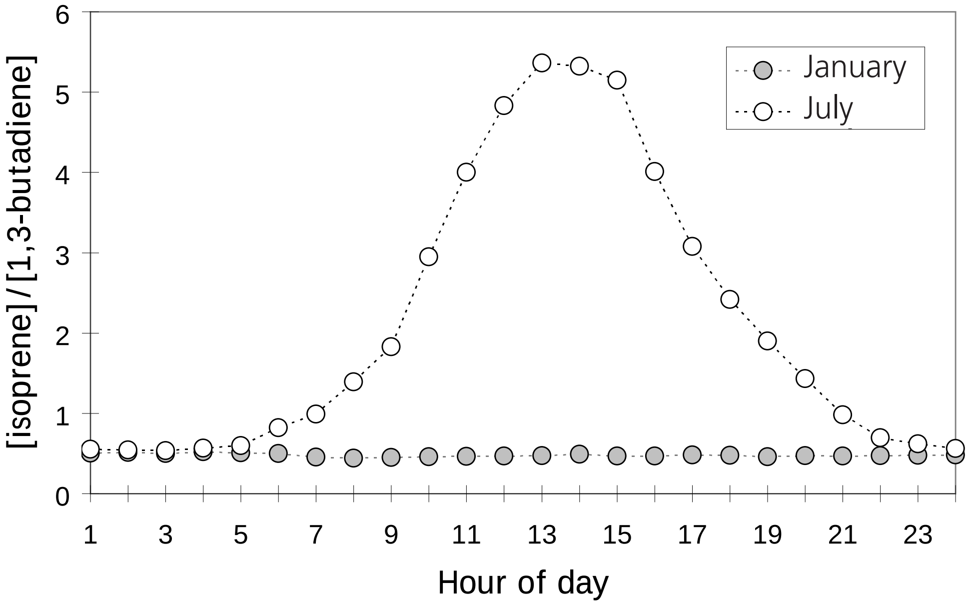
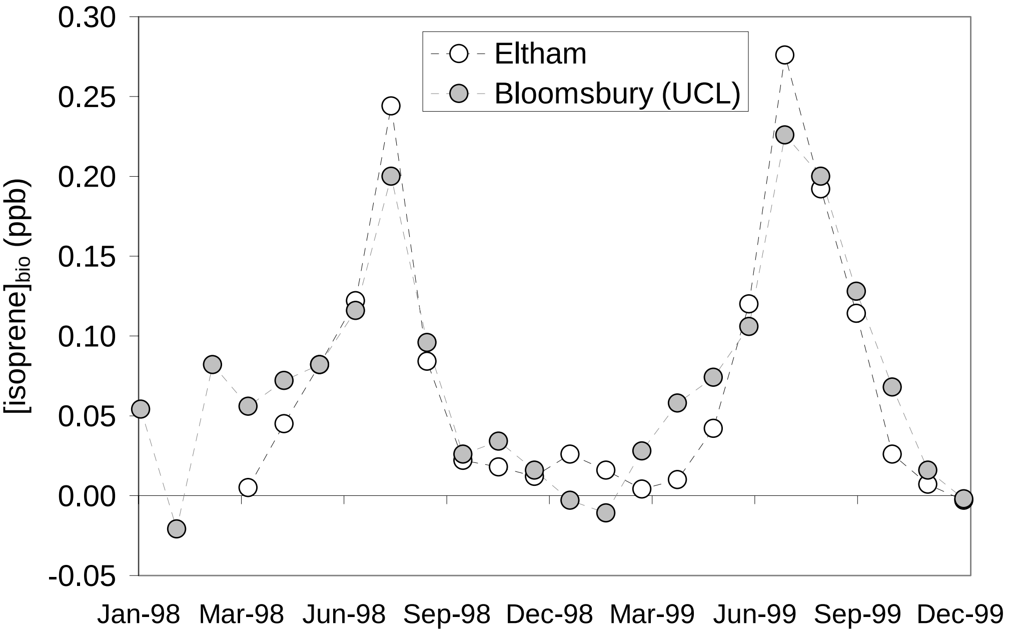


Figure 4.20: Monthly mean concentrations of biogenic isoprene at London sites in 1998 and 1999. To convert to μg m^{-3} units, 1 ppb = 2.83 μg m^{-3} for isoprene at 20°C and 101.3 kPa (assumed conditions for EC data reporting in mass concentration units). The concentrations were calculated from observed concentrations of isoprene and 1,3-butadiene, assuming that the anthropogenic isoprene contribution equates to 40% of the observed 1,3-butadiene, i.e. $[\text{isoprene}]_{\text{bio}}$ = [isoprene]-0.4[1,3-butadiene], based on ppb units



Biogenic VOC concentrations during the August 2003 episode

286. Hourly mean concentrations recorded during the August 2003 heatwave at the Automatic Urban and Rural Network (AURN) sites at Marylebone Road and Harwell, and at Writtle (Essex) where they were measured as part of the NERC TORCH project, show a clear dependence on temperature, with peak concentrations of about 1.5–2 ppb (4.25 – 5.66 μg m^{-3}) when the prevailing temperatures were in excess of 35°C (Figures 4.21 and 4.22). Under such circumstances, biogenic VOC emissions potentially make a significant contribution to regional-scale O_3 formation, and are believed to be a contributory factor to the elevated surface O_3 concentrations in August 2003, which were the highest observed at UK rural sites since the previous heatwave year of 1995. As described below, biogenic VOC emissions have been estimated to account for about 30% of O_3 in south-east England derived from regional-scale VOC oxidation in the August 2003 heatwave. It is therefore clear that model simulations of future AQ will need to take account of this important effect of temperature increasing VOC emissions (Bell and Ellis, 2004). It will also be important for national emissions inventories to take account of changes in biogenic emissions with varying climate, although this would only account for changes in mean climatic conditions, and not the frequency of extreme episodes. Such a temporally and spatially disaggregated inventory, based on relationships with meteorological episodes, was presented by Stewart *et al*. (2003).

Figure 4.21: Hourly mean concentrations of isoprene measured at Harwell and Marylebone Road during the August 2003 heatwave. The right hand panels show the data plotted as a function of temperature measured at Heathrow Airport (AURN data, courtesy of netcen). To convert to μg m^{-3} units, 1 ppb = 2.83 μg m^{-3} for isoprene at 20°C and 101.3 kPa (assumed conditions for EC data reporting in mass concentration units)

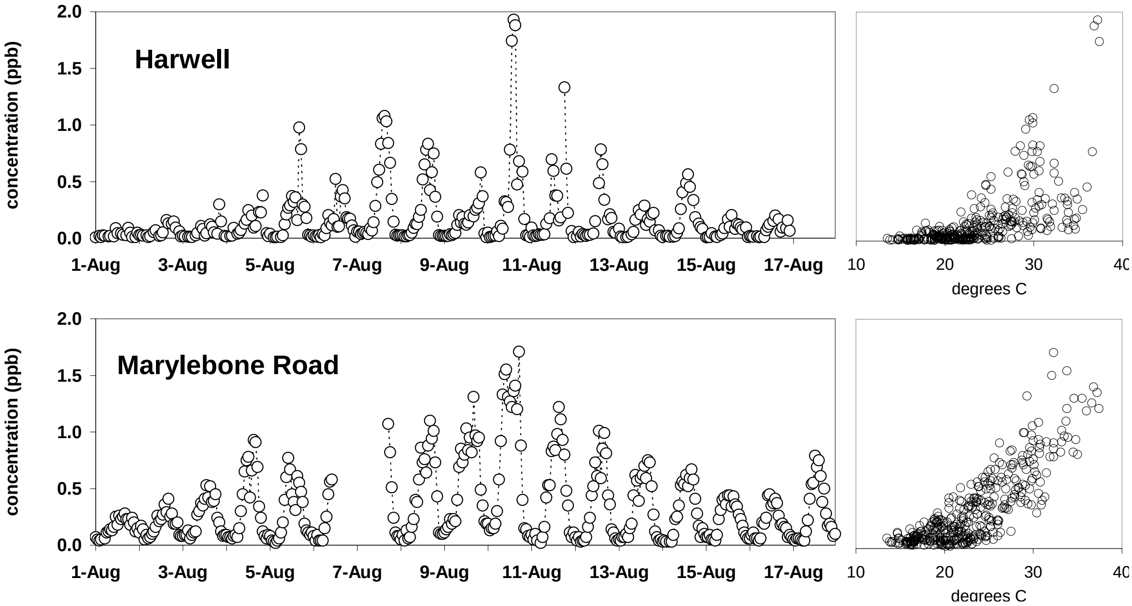
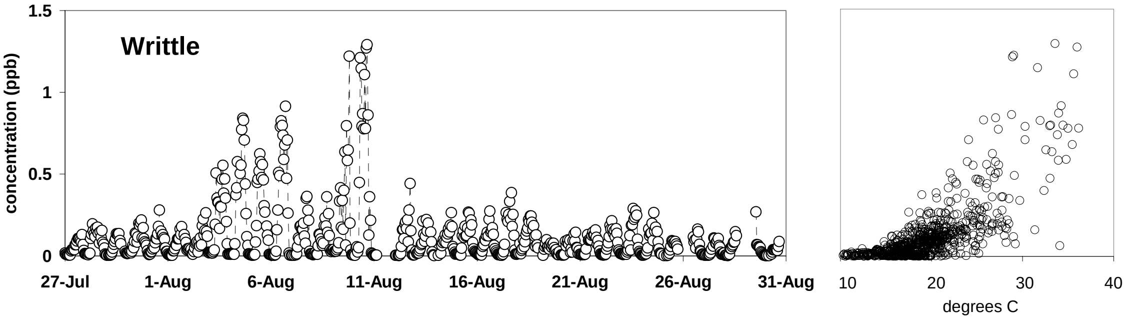


Figure 4.22: Hourly mean concentrations of isoprene measured at Writtle (Essex) during the NERC TORCH campaign in late July and August 2003. The right hand panel shows the data plotted as a function of temperature (Data courtesy of A. Lewis *et al*., University of York). To convert to µg m^{-3} units, 1 ppb = 2.83 µg m^{-3} for isoprene at 20°C and 101.3 kPa (assumed conditions for EC data reporting in mass concentration units)



287. The strong temperature dependence of biogenic VOC emissions stresses the importance of understanding the temporal nature of the emission sources in order to model O_3 episodes. This illustrates the weakness of the current biogenic VOC estimates in the NAEI which reports emissions only on annual basis. An area of improvement in the inventory would be to at least incorporate the seasonal and ideally the diurnal pattern of emissions from natural sources. Spatially resolved emissions information for the UK using land cover data on the type of vegetation would also be of benefit to modellers. Providing such information would be an ambitious undertaking given the high levels of uncertainty (and probably variability) in biogenic emissions, but will become increasingly necessary for modelling future O_3 episodes in a potentially hotter climate at a time when anthropogenic VOC emissions have been substantially reduced. The NAEI is currently investigating areas of improvement in the emission estimates for a number of natural sources of emissions.

Effects of changes in land cover

288. Since vegetation is an important source of VOCs, long-term changes in species composition, due both to effects of climate and changes in land use, will influence the size of these emissions. The detailed inventories of the VOC emission potential of individual species shows large variations between species; of the 50 plant species with the greatest estimated national biomass in the UK, only a small number (primarily spruces, pines, oaks, heathers and thistles) have a large emission potential for isoprene and/or monoterpenes. When emission potential, climate and biomass data are integrated, oak species, poplar species and Sitka spruce have been identified as the important UK emitters of isoprene, with Scots pine and Sitka spruce being dominant for monoterpenes (Stewart *et al*., 2003). These species affect different regions of the country; e.g., Sitka spruce is a dominant source in Scotland and northern England, whereas poplars are most important in East Anglia.

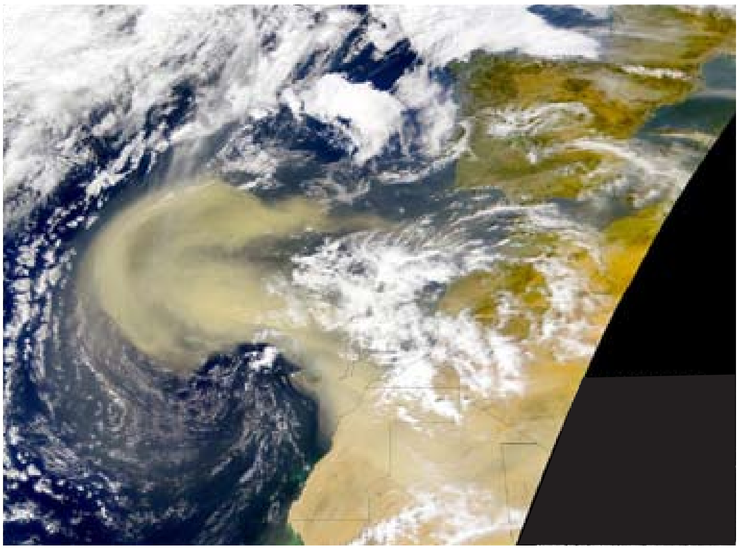
289. Therefore changes in the cover of these dominant individual species in the future may have significant impacts on biogenic emissions. In terms of forest cover, Sitka spruce is the dominant emitting species in Britain (responsible for 40% of isoprene and monoterpene fluxes; Stewart *et al*., 2003) but in a warmer and drier climate it may be replaced as the species of choice in coniferous plantations by Douglas fir or Corsican pine. In contrast, planting of poplar or willow species as energy crops may increase national VOC fluxes, as these species are high isoprene emitters; a doubling of willow biomass was estimated by Stewart *et al*. (2003) to increase national emissions by 10%. Choice of species for urban tree planting may also influence AQ, both positively through increased pollutant deposition, and negatively, through biogenic emissions leading to O_3 formation. On this basis, Donovan *et al*. (2005) identified species likely to have a positive effect on AQ in UK cities (e.g. maples, birches, larches and pines) and those likely to have a negative effect (e.g. oaks, willows and aspen). However, factors other than species choice and climate may be important. In the eastern USA, for instance, analysis of data from 250,000 re-surveyed forest plots was used to demonstrate a significant overall increase in biogenic VOC emissions which was not due to climate, but to changes in leaf area, ecological succession, species composition and plantation management (Purves *et al*., 2004), hence demonstrating that projecting future changes without considering quite subtle changes in land cover may provide very inaccurate estimates of future VOC emissions.

Dust

290. Climate also places an important control on the degree to which dust is released from the ground surface over all spatial scales; drought conditions, poor land management and sufficiently strong surface winds provoke increases in the release of surface dust. Such processes operate at the street-scale through to the so-called ‘Fen Blows’ (Figure 4.23) and up to the huge plumes associated with desert regions of the world, particularly the Sahara and China/Mongolia. Satellite-based monitoring has been central in identifying the magnitude of these regional-scale events (Figure 4.24). These events can cause short-term exceedences of PM_{10} standards in the UK.

Figure 4.23: Fen blow in Norfolk

Figure 4.24: Saharan Dust Plume, from SeaWifs



Lightning nitrogen oxides (ozone)

291. Ozone production in the tropical upper troposphere is dominated by NO_X emissions associated with lightning (Grewe, 2005). The El-Nino/La Nina system is the most important natural climate variability in the tropics affecting lightning occurrence and therefore also O_3 concentration.

Pollen

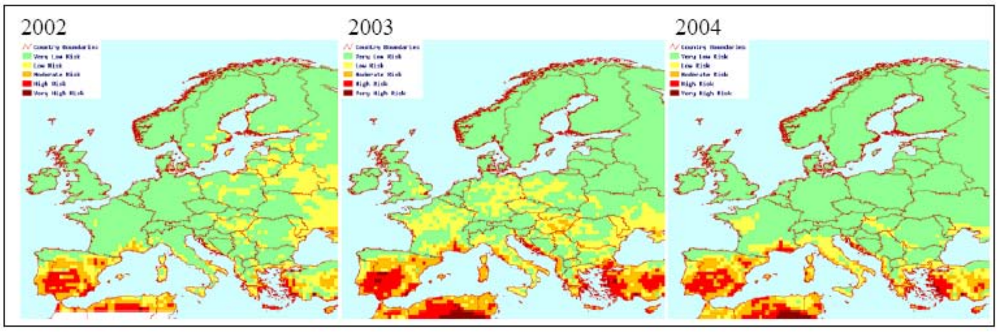
292. If we extend AQ to include the hay fever impacts of pollen, observation shows that the start of the hay fever season is strongly related to temperature and the related release of pollen and spores (Van Vliet *et al.*, 2002). The start of the season has been shown to have begun significantly earlier (~20 days) over recent decades, depending upon species. Future climate scenarios suggest that this trend will continue through the 21st Century. It should be noted, however, that grasses, one of the most important groups of species which cause hay fever, show only a minor advance in the start of the pollen season.

Biomass burning and wildfires

293. Over large regions of the globe, fires are known to contribute significantly to the emissions of gases and aerosols into the atmosphere, and large-scale forest fires may have effects on AQ not only locally, but over large regions. There is evidence that the extent and number of forest fires has increased in Europe over the period 1960 – 2000 (Fromm and Bevilacqua, 2004), although this may partly be an artefact of increasing availability of information, e.g. through remote sensing (Zhang *et al*, 2003). It is important to note that forest management may be an important contributor to this change in Europe and in North America, because of species choice and increased average stand age (Schelhaas *et al*., 2003). Ironically, fire management policies may have led to a situation where the structure and species composition of forests increases the likelihood of new fires. However, CC is also identified as a contributory factor (e.g. Gillett *et al*. (2004) in Canada; Hemp (2005) on Mt Kilimanjaro), and in particular, decreased moisture availability, that increases both the frequency and severity of serious fires, whether these are initiated by human activity or natural causes (McMorrow *et al*., 2006). More severe fires will not only increase emission rates, but also decrease the rate of regrowth.

294. Schelhaas *et al*. (2003) estimate that over the period 1950 – 2000 fires were responsible for 16% of the forest disturbance in Europe (compared with 53% from storms), and that over the period 1961 – 2000, forest fires caused the loss of 0.15% of the total forest area annually. Increased fire frequency could also affect net C balance. Jones and Cox (2005) suggest that increased forest fires in the northern hemisphere, caused by the hot and dry Eurasian summer of 2003, may have contributed to the anomalously large increase in global CO_2 concentrations in that year. Figure 4.25 shows the results of an assessment of the risk of fires during the summer of 2003, compared with 2002 and 2004. One feature of interest in this risk assessment is that, whereas the risk did not increase in areas of the Mediterranean, which have a high risk of fires in most summers, it did increase significantly in northern continental Europe and southern areas of the UK, suggesting this may be an important factor for future UK AQ.

Figure 4.25: Increased fire risk in Europe in 2003 relative to the neighbouring years (JRC, 2005)



Emissions from soils

295. There is little doubt that CC will influence emissions from soils, and the cycling and transformation of pollutants deposited to soils. Most of the key processes, e.g. nitrification, denitrification, decomposition, mineralisation and CH_4 oxidation are microbial. Increased C inputs to the soil as a result of elevated CO_2 concentrations are also relevant. The major climate-related factors of importance will be soil and litter temperature and soil water status.

296. The emissions of important radiatively active gases associated with soils (e.g. CO_2, N_2O, CH_4) will tend to increase with temperature and decrease with soil water status, although temperature is likely to be the dominant factor. Of particular importance in this context are organic soils, because of the greater C which they store. The largest proportion of the UK store of C is in the organic soils which dominate Scotland and many upland areas of northern England and Wales. Modelled soil C in the UK is negatively related to temperature, and increased soil temperatures might be expected to lead to release of C through increased CH_4 and CO_2 emissions, although other factors (e.g. changes in productivity, the C/N ratio, soil water status) will also be important.

297. Changes in land cover, and in particular increased forest planting in such soils, would also have implications for emissions from organic soils. When organic peatland soils are drained, directly or through tree planting, more C is oxidised and CO_2 is released; hence planting Sitka spruce on peat can lead to loss rather than gain of C, at least over the first one to two decades. However, other factors, such as early growth of grass and other species, decreased CH_4 emissions, and possible increased N_2O emissions, also need to be considered, making overall assessment difficult (Broadmeadow and Matthews, 2003). A further factor in terms of soil emissions is the possible effect of drier soils and increased wind speeds on dust re-suspension, especially from organic soils with low bulk density.

298. Increased temperatures will also lead to increased emissions of NH_3; however, these in turn are closely linked to changes in agricultural management practices, including those designed to reduce NH_3 emissions (see Chapter 5). The timing of manure applications is critical to the fate of the applied N; if management practice in response to earlier growing seasons was to apply manure earlier in the season, this might offset the effect of increased temperatures. Ammonia losses from slurry application increase with temperature and wind speed and soil wetness. It is also affected by the type of slurry and the application method used.

299. Nitrogen oxides (principally nitric oxide, NO) emissions from soil are also dependant on meteorology, soil type, microbial content and fertiliser application with the greatest natural control being temperature. Meteorological effects on soil NO_X emissions were investigated by Yienger and Levy (1995), who found that soil NO_X emissions were a strong function of both soil temperature and precipitation. Estimates of the effects of fertiliser application can be made assuming that 0.3% of total N fertiliser applied is released as NO (Dore *et al.*, 2003).

4.3.1.2 Climatic effects on anthropogenic emissions

300. Many direct and indirect anthropogenic emissions sources are climate sensitive. This sensitivity could act to modify UK atmospheric emissions in relation to absolute values and/or their spatial and temporal characteristics. Feedbacks can therefore be expected to have some influence on future AQ through emissions of air pollutants and future climate through emissions of greenhouse gases (GHGs).

301. This section considers some of the potential ramifications of a changing climate on selected emission source sectors, using examples from the transport and energy sectors. These sectors are useful as they involve a range of emission production processes and reflect various end-user groups.

Transport - evaporative emissions

302. Evaporation of petrol vapour used in transport occurs at various stages from the storage and distribution of fuels from the refineries to the petrol stations through to the fuelling and end use in individual road vehicles. These processes currently contribute to around 8% of all anthropogenic emissions of NMVOCs in the UK, with the vast majority of emissions occurring at the final stages of the fuel chain at petrol stations and use in the vehicle. Evaporative emissions are dependent on ambient temperature and the volatility of the fuel so are sensitive to CC.

303. Evaporative emissions of fuel vapour from petrol vehicles occurs due to the daily rise in temperature (diurnal losses) and the transfer of heat to the systems delivering fuel from the vehicle's fuel tank to the engine that occurs when the engine has warmed up (hot soak and running losses). Such emissions were particularly significant with older cars using carburettor fuel delivery systems. Emissions from modern cars are much reduced due to the fitting of C canisters for evaporative emission controls, the use of more advanced electronic fuel injection systems and reductions in the volatility of summer blends of petrol. Evaporative emission control systems are now mandatory for all new petrol cars to comply with European Directive 98/69/EC that sets limits on evaporative emissions from vehicles at the stage of type approval. Directive 98/70/EC sets maximum limits on the volatility of fuels (expressed by their Reid Vapour Pressure, RVP) that can be sold during summer months.

304. National emission inventories like the NAEI use a series of empirically-derived equations relating evaporative emissions to fuel RVP and ambient temperature. There are separate equations for each evaporative loss mechanism and for vehicles with and without evaporative emission control. Details of the methodology can be found in the UK's Greenhouse Gas Inventory report (e.g., Baggott *et al*., 2004). Emissions are calculated on a monthly basis using monthly average temperature data and fuel RVP and summed over the year. Evaporative emissions from the car fleet in the UK are projected to decline as more modern cars penetrate the fleet, but the equations show a significant degree of sensitivity to ambient temperature conditions. It is estimated that a 3°C increase in UK annual mean temperature would lead to an increase in the annual rate of evaporative emissions of NMVOCs from the UK vehicle fleet of about 20 – 25%. However, this increase is relative to a progressively declining contribution that evaporative emissions from vehicles make to total projected UK emissions of NMVOCs such that the increase in total UK NMVOC emissions would be no more than around 0.2%.

305. Equations relating evaporative emissions to temperature and RVP during fuel distribution are also used in the inventory. Larger petrol stations have to use vapour recovery systems to control emissions during refuelling and this is taken into account. Less detailed analysis on the effects of changes in ambient temperature has been carried out, but indications are that emissions from refuelling are less sensitive to temperature changes than emissions from the vehicles.

Energy consumption

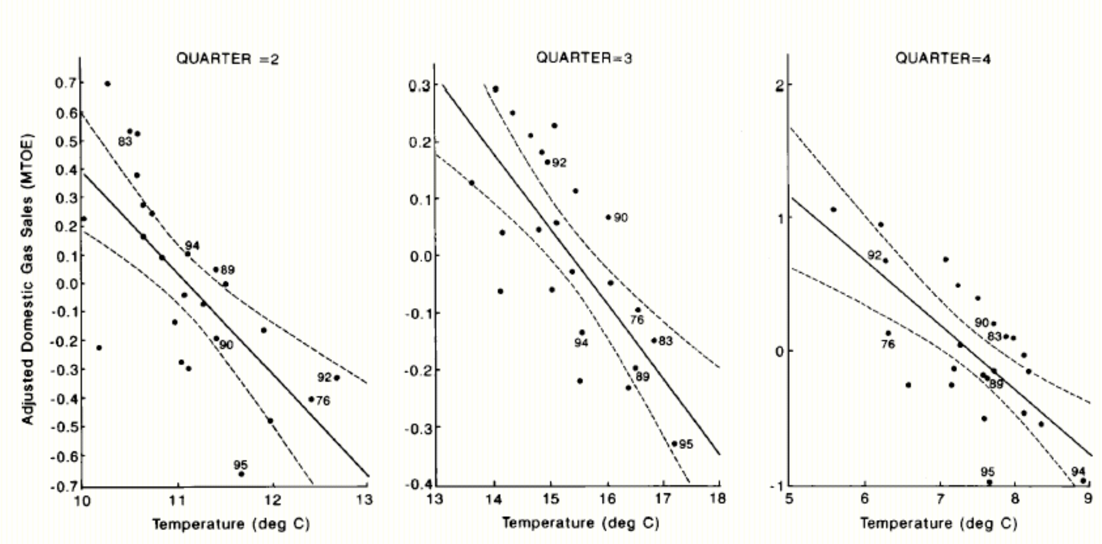
306. Energy consumption varies between different sectors of the UK economy with buildings being associated with around half of all energy usage (Levermore *et al*., 2004). The period 1973 – 96 saw an increase in UK final energy demand from the commercial sector that was three times greater than that in the domestic sector. The drivers of this change have been related back to various non-climate related factors such as increasing office floorspace but there is also evidence for a climate influenced trend towards increased air conditioning of the working environment. The resultant energy demand is primarily for electricity and varies in relation to office type.

307. Climate-activity relationships are not well understood at present (Subak *et al*., 2000) but there is a growing body of research and associated literature that attempts to assess the influences of climate variables on different sectors, such as energy consumption patterns. The approaches that have been used include the analysis of past trends as historical analogues for future change and the development of models based on standard climate scenarios.

308. Central England Temperature records have been used to assess the influence of the November 1994 to October 1995 unusually warm period on the economy of the UK relative to 1972 – 95 (Subak *et al*., 2000). As might be expected, strong relationships were found between temperature and energy demand for gas and electricity (particularly the former which is predominantly used for space heating in domestic premises – Figure 4.26). There were no significant relationships found for power stations or the iron and steel industry which implies that emissions were not significantly affected during this period. Changes in the relationships between temperature and electricity consumption were found between the hot UK summers of 1976 and 1995. Despite predicted savings of £60m for the third quarter of 1995 as a result of expected temperature-related reductions in electricity consumption, actual consumption data showed this period was associated with an added cost of £34m. Whilst there are a number of possible explanations, it has been suggested that this is due at least in part to increased use of air conditioning and refrigeration (Subak *et al*., 2000). If true, this is likely to have some impact on future power generation related emissions, despite the lack of an observed relationship in this particular analysis.

309. In relation to future energy requirements, two main climatic impacts are anticipated in relation to the UK building stock. Firstly warmer winters will result in lower energy demands for space heating and secondly hotter summers will lead to an increase in the use of mechanical ventilation and air conditioning. The reduction in heating energy is likely to be more than offset by the increased energy demand for cooling. This will tend to reduce demand for gas but increase demand for electricity (CIBSE, 2005).

Figure 4.26: The relationship between gas sales and temperature 1972 – 95 (Subak *et al.*, 2000)



310. Hadley Centre Coupled Ocean Atmosphere Global Climate Model (HadCM3) outputs (scenarios A2 and B2) have been used to generate Test Reference Years and Design Summer Years as the basis of an assessment of CC impacts on the performance of buildings in the UK in 1980, 2025, 2050 and 2080 (Levermore *et al.*, 2004). Models were developed based on a standard heavy, medium and light multiple storey office building in different UK locations associated with different climate model output grid boxes (London, Manchester and Edinburgh) to assess the impact on internal human comfort against accepted overheating criteria. Findings suggest that average office premises in the south of England (East of England grid box) are unlikely to provide acceptable working conditions by 2025 without refurbishment, air conditioning or adaptive strategies for the occupants. Once standard air conditioning is introduced the energy demand effectively doubles (Levermore *et al.*, 2004). This has clear implications for future energy requirements and CO_2 emissions in the East of England. Between the 1980 reference period and 2080, it was estimated that CO_2 emissions associated with gas usage would be reduced by around a quarter and CO_2 emissions associated with electricity usage would be doubled. This does not consider any feedbacks associated with the limiting effects of local and regional air pollution controls (EEA, 2004) or specific design and adaptation strategies. The West of England box shows similar patterns to the East of England. The North West and Scotland boxes show increasing hours over the 25°C threshold but the only failure of the benchmark criteria is for the NW in 2080.

311. CIBSE (2005) considered a range of dwellings, offices and schools and showed that for most buildings it should be possible to provide satisfactory conditions without a large increase in energy requirements (i.e. through the application of passive design measures such as natural ventilation). The increased use of passive ventilation acts to reduce energy demand but may potentially increase exposure to outdoor pollutants.

4.3.2 Climate-biosphere interactions

312. A number of studies have considered the impact of CC on future concentrations of O_3 and deposition of N and sulphur (S) from the perspective of changes in climate and atmospheric chemistry (e.g. Langner *et al*., 2005). However, these results need to be considered in the context of other factors influencing ecosystem processes.

4.3.2.1 Impacts of air pollutants on ecosystems

313. The regional impacts of air pollutants on ecosystems, primarily the impacts of O_3 acid deposition and N deposition, may be modified by a range of climatic factors, both directly and indirectly. For example:

- Increases in atmospheric CO_2 concentrations and increased frequency of summer droughts have been shown to reduce the stomatal uptake and impacts of O_3 on crop production and tree growth, although they may lead to increased atmospheric O_3 concentrations.
- Adverse effects of N deposition may be enhanced, e.g. by increased temperatures leading to enhanced soil microbial activity, increasing N availability and nitrate leaching, and by an increased likelihood of insect pest outbreaks. For example, Emmet *et al*. (2004) investigated changes in net N mineralisation across an environmental gradient of European shrublands, and found a strong climate effect, with the effects of soil moisture decreasing mineralisation being stronger than the effect of soil temperature in increasing it.
- Changes in rainfall patterns, soil temperature and base cation deposition may change the impacts of acid deposition on sensitive soils and waters. For example, increased frequency of drought events may alter the frequency of acidification/high sulphate episodes in sensitive waters draining peat soils, because of the oxidation of S stored in the peat (e.g. Clark *et al*., 2005).
- Warming of arctic ecosystems, in particular, may increase the global circulation and bioaccumulation of persistent toxic substances such as mercury and polychlorinated biphenyls (PCBs), hence increasing their impacts on sensitive organisms at the top of the food chain, and increasing human uptake.

314. The implication of these and many other effects of CC is that the environmental risk assessment tools which are currently used to inform policy development in relation to these impacts at both national and European levels may need to be modified (e.g. EEA, 2004). These include the use of critical levels and critical loads, the application of models of O_3 flux to sites of damage within the leaf (Ashmore, 2005), and dynamic models to predict the timescale of ecosystem recovery in response to reductions in emissions of SO_2, NO_X, and NH_3.

315. Detailed consideration of these issues is outside the scope of this report. However, Defra has recently initiated a review of the report of the National Expert Group on Transboundary Air Pollution (NEGTAP) on acidification, eutrophication and ground-level O_3 in the UK (NEGTAP, 2001), which will consider the implications of CC for assessment of the impacts of air pollution on ecosystems in the UK in more detail.

4.3.2.2 Deposition of pollutants to ecosystems

316. Deposition to vegetated surfaces such as forests is an important loss process for a number of air pollutants, including O_3. Changes in processes that act to increase or decrease deposition to vegetation can have significant impacts on both O_3 transport and ground-level concentrations. Rates of deposition to vegetation are directly influenced by environmental variables and land cover, and so are sensitive, directly and indirectly, to the effects of CC. These interactions are explored further below.

Changes in phenology

317. There is evidence from the UK Phenology Network that for a range of species warmer winters and springs have lead to earlier budburst and growth over recent decades; models of budburst which have been developed and tested using these data suggest that future CC scenarios will lead to a trend towards even earlier budburst. Trends in phenology (Sparks and Menzel, 2002) across Europe since the 1950s demonstrate the same phenomenon. Warmer springs may also lead to earlier planting of many crops, as long as the risk of damage from early frost events is not thereby increased; Scottish data would suggest that the number of ground frost days has declined by approximately 25 days over the last 45 years (Barnett *et al*., 2006). These changes will influence the seasonal patterns of deposition for pollutants with a high deposition velocity to land surfaces, both because of the earlier development of higher leaf area indices and because of the earlier increase in stomatal activity. The increase in global background O_3 concentrations will also lead to greater exposure in the spring period (Coyle *et al*., 2003), hence both phenological changes and O_3 concentration changes will lead to greater deposition earlier in the year.

318. However, the evidence for impacts of CC on autumn senescence and leaf fall is less clear, because this is controlled by a wider range of factors which may have contrasting influences (e.g. increased summer drought may accelerate senescence, while warmer autumns are likely to delay senescence. Hence, the overall growing season or leaf area duration of many species is likely to increase, especially when the effect of increased CO_2 concentration in increasing leaf area is also considered. This in turn is likely to increase the annual surface deposition for aerosols and gaseous pollutants.

Temperature, moisture and radiation effects on deposition to plant surfaces

319. Most models treat deposition velocity to leaf surfaces as a fixed term. However, there is increased evidence that this is not the case, and that deposition of O_3 in particular, is a temperature or light-dependent process. Fowler *et al*. (2001) interpreted four years of data in southern Scotland as implying a process of thermal decomposition of O_3 at the leaf surface with an apparent activation energy of about 36 kJ mole^{-1}. However, Kurpius and Goldstein (2003) interpreted a similar exponential increase of non-stomatal flux with temperature in coniferous forests as indicating an increase in loss of O_3 through reactions with increased biogenic terpene emissions. This interpretation is supported by a recent forest thinning experiment (Goldstein *et al*., 2004), which showed an increase in monoterpene emissions that was associated with increased O_3 deposition, despite

the reduced leaf area. These two interpretations have very different implications: if this is a simple temperature-dependent physical destruction, then the implication is that O_3 removal would be increased and transport distances decreased, but if the hypothesised chemical reactions are involved, there are complex implications for atmospheric chemistry both within the forests and downwind.

320. In contrast, deposition of the more soluble gases SO_2 and NH_3 is strongly influenced by the presence of surface moisture. Hence, greater deposition rates are expected in wetter winters, but lower deposition rates in drier summers.

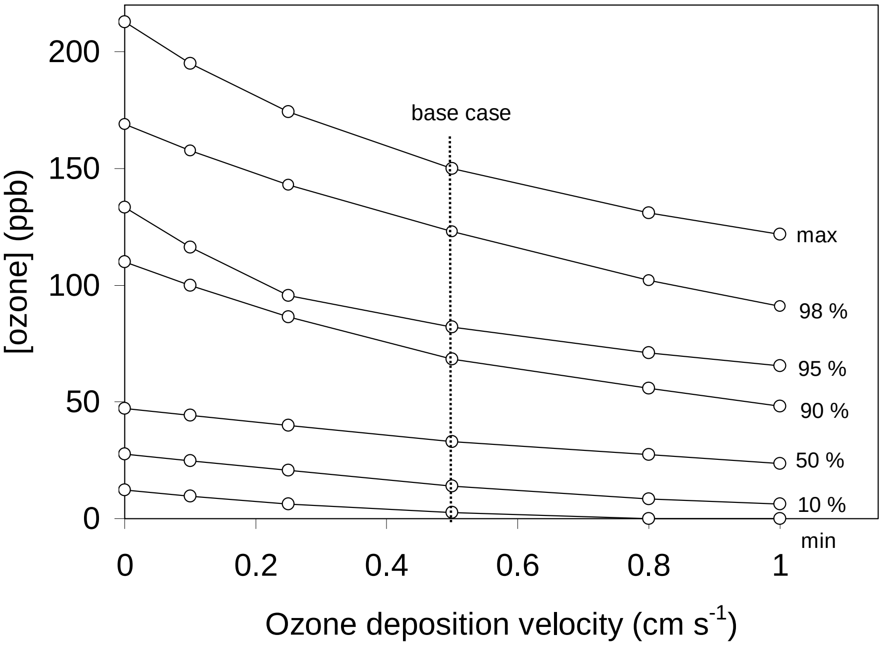
Uptake through the stomata

321. Ozone uptake through the stomata is directly relevant to its impacts on vegetation, and also is the major process controlling O_3 deposition on summer days when concentrations are highest. A new version of the EMEP model now includes a more detailed mechanistic model of stomatal responses to key environmental variables, and provides good simulation of O_3 deposition (Tuovinen *et al*., 2004). New critical levels of O_3 have now been developed, based on cumulative flux above a threshold (Ashmore *et al*., 2004).

322. Stomata respond directly to elevated CO_2 concentration, vapour pressure deficit, temperature and soil moisture deficit. As a broad generalisation, drier summers with higher CO_2 concentration will lower stomatal deposition and hence lead to lower deposition and greater transport distances, and a reduced impact on vegetation of O_3 in particular. In the absence of other limiting factors, plants growing in higher CO_2 concentrations are able to maintain a higher leaf area index, with implications both for increased pollutant deposition rates and for increased biogenic VOC emissions.

323. Emberson *et al*. (2000) demonstrated that O_3 deposition was not necessarily greatest on the days with highest O_3 concentration, in particular because of the effect of vapour pressure deficit in causing stomatal closure on hot days. The effect of climatic factors in a hot summer such as 2003 in southern Europe is illustrated by Vitale *et al*. (2005) who modelled canopy O_3 uptake for Holm oak (*Quercus ilex*) in Italy. Both eddy covariance measurements and modelling of the effect of different parameters on stomatal conductance showed that O_3 uptake by the canopy was substantially reduced in mid-summer, when O_3 concentrations were highest, but increased significantly in the early autumn, when soil moisture increased and vapour pressure deficit decreased.

Figure 4.27: Simulated trend in ozone distribution statistics for the August 2003 episode at Writtle (Essex) as a function of applied ozone deposition velocity. To convert to μg m^{-3} units, 1 ppb = 2.00 μg m^{-3} for O_3 at 20°C and 101.3 KPa

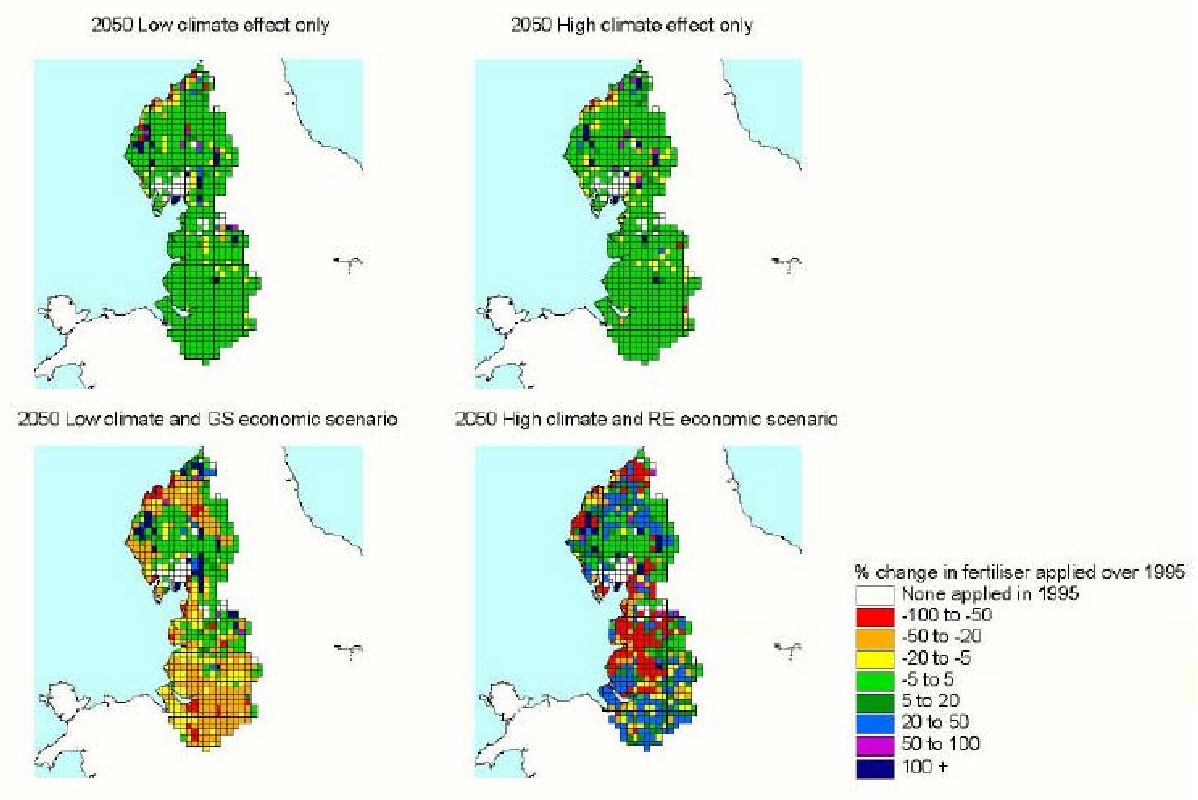


324. It should be noted that while these effects may reduce O_3 flux and deposition to vegetation, this reduced deposition may in turn lead to increased atmospheric concentrations of O_3 and hence the potential for greater adverse effects on human health. An illustration of the effect of variation in deposition velocity on the modelled O_3 concentrations during the August 2003 episode (Figure 4.27), using the model described in Box 4.2, shows that the reduction of the deposition velocity from 0.5 cm s^{-1} to 0.25 cm s^{-1} results in a general shift of the O_3 distribution to higher concentrations, with the peak concentration increasing by approximately 24 ppb (48 μg m^{-3}) (16%) and the mean concentration increasing by approximately 9 ppb (18 μg m^{-3}) (23%).

4.3.2.3 Changes in land cover and land use

325. Changes in land cover and land use may arise for a variety of reasons. Unmanaged ecosystems may change both in terms of species composition and broad land cover through natural successional processes and through the effects of CC. Planned changes in land cover may likewise reflect both policy drivers that are not associated with CC (e.g. changes in the Common Agricultural Policy, CAP) and those that relate to mitigation of its impacts (e.g. increased use of biofuels; tree planting to offset C emissions). Both of these factors have implications for pollutant impacts, pollutant deposition and the cycling and fate of pollutants such as N and S, as well as wider environmental implications.

Figure 4.28: Modelled changes in fertiliser application relative to 1995 based on UKCIP98 scenarios (Holman and Loveland, 2001)



326. The potential for changes in agriculture in the UK have been examined in detail in two areas of the UK. Agricultural model outputs based on UKCIP98 scenarios for the North West and East Anglia in the 2020s and 2050s have suggested that agriculture has a limited sensitivity to CC impacts and is rather more dependant on the nature of socio-economic change considered (Holman and Loveland, 2001). Another explanation is that the agricultural sector has already exhibited considerable adaptation to CC (Subak *et al*., 2000). Despite these factors, Holman and Loveland (2001) still show some increase under most scenarios for arable and grass yields, the former increasing faster initially and levelling off and the latter showing the highest increase in the 2050s. Estimates were also made regarding the anticipated changes in fertiliser use in the North West region, which have implications for fertiliser related soil emissions of NH_3, NO_X and N_2O.

4.4 Climate change and air quality in the future

327. It is clear that fully coupled chemistry-climate models are needed in order to address all important inter-connected processes. Such studies are beginning to be undertaken, particularly within Atmospheric Composition Change: European Network of Excellence (ACCENT) in support of the IPCC Fourth Assessment Report process, and these are reported in Section 4.4.3. Such approaches are very demanding on IT resources and, as a result, can only provide information at relatively low spatial resolution. However, it is also instructive to first consider the simulated behaviour and changes to key meteorological variables through the 21st century based on climate model simulations which are not fully coupled (Section 4.4.1), including higher resolution regional-scale climate modelling, and to consider what their impact on local-regional AQ might be (Section 4.4.2).

4.4.1 How will key meteorological conditions change in the future?

328. Most UK climate impacts research is based on the UKCIP climate scenarios (UKCIP98 and UKCIP02). These are based on the Hadley Centre Regional Climate Model (HadRM3) integrations using a nested (dynamical downscaling) approach in which global models (the Hadley Centre Coupled Ocean Atmosphere Global Climate Model (HadCM3) and the Hadley Centre Global Atmosphere Climate Model (HadAM3)) are used to provide boundary conditions. The grid resolution of HadRM3 is 50 km. This section summarises the main findings from the UKCIP02 scenarios of relevance to AQ studies. The findings are also compared with new results from a recent 25 km resolution HadRM3 run (Johnson *et al.*, 2005), undertaken in order to generate the hourly resolution output data needed for AQ studies and described more fully in Section 4.4.2. It is important to recognise that (a) considerable uncertainty in the magnitude (and for some variables the sign) of future changes remains; (b) future projections are very model dependent as a result of varying model design and forcing; (c) model inter-comparisons and ensemble approaches are crucial in quantifying uncertainty.

329. An alternative to dynamical downscaling is statistical downscaling in which global climate model output is downscaled to local conditions via statistical relationships. This section also summarises the state of the art in statistical downscaling.

4.4.1.1 Dynamical downscaling

330. It is important to comment upon the limitations of regional climate modelling by considering the degree to which HadRM3 is able to realistically simulate <u>current</u> UK and European climate. Moberg and Jones (2004) summarise the performance of the HadRM3 model with respect to daily maximum and minimum temperature. Their main finding is that HadRM3 simulates positive biases in present day maximum surface air temperature in summer, the model being sensitive <u>in continental Europe</u> to the degree of spring/summer drought/dryness, with a consequent tendency to simulate temperatures which are higher than observed if and when soils dry out in summer. It is felt, however, that this is also a feature of the driving global models HadCM3 and HadAM3, tempered by global model gridsquares over the UK containing at least some sea cover. Rowell and Jones (2006) have subsequently argued that <u>projected</u> enhanced summer dryness in Great Britain, based on simulations using HadAM3, is in fact more controlled by larger-scale (lower confidence) changes in circulation (more subsidence and less Atlantic influence) than by soil moisture effects.

331. On this basis, AQEG note that some caution is therefore appropriate before using the UKCIP climate impact scenarios and the HadRM3 model output for driving a regional-scale AQ model or to use in AQ assessment. Excessive temperatures and any associated additional soil dryness may greatly affect the rate of O_3 production and the surface uptake of O_3 which controls its lifetime in the boundary layer and hence its transport distance. Excessive soil dryness will also lead to exaggerated natural emissions of wind-blown dusts. AQEG recommend that Defra consider carefully the use of the UKCIP climate impact scenarios for AQ and CC policy purposes. AQEG also recommend that end users (such as the AQ community) should be considered when creating the UKCIP scenarios and that information should be provided with the data to advise the end users on any processing required to remove extreme values. For AQ studies, scenarios that focus more on the period up to 2030 are required.

332. Anderson *et al*. (2001) used daily HadCM3 output, without any dynamical downscaling, to consider the possible implications of CC on AQ and the results are reported in Section 4.4.2.

333. With regard to climate model uncertainty generally, Rowell (2006) and Déqué *et al*. (in press) also report on an inter-comparison between outputs from nine separate European Regional Climate Models (RCMs) undertaken within the Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects (PRUDENCE) project. An ensemble approach was adopted with RCMs driven by two different global climate models and using multiple emission scenarios. In addition, HadRM3 was forced with three different realisations of HadAM3 in order to address the significance of natural climate variability. The main findings arising from the PRUDENCE ensembles are that the greatest uncertainty for temperature lies in the simulation of the global model. Uncertainty in the precipitation simulation is more significant for the RCMs.

334. Tables 4.2 and 4.3 taken from Hulme *et al*. (2002) summarise the UKCIP02 simulations of changes in key atmospheric variables known to affect AQ. Of particular relevance to AQ applications is the low confidence in the performance of the model simulations of wind. These simulations of changes to wind climatology by the 2080s are shown in Figure 4.29.

Figure 4.29: Percentage change in mean annual and seasonal wind speed in the UK by the 2080s, relative to 1961 – 90, Hulme *et al*. (2002)

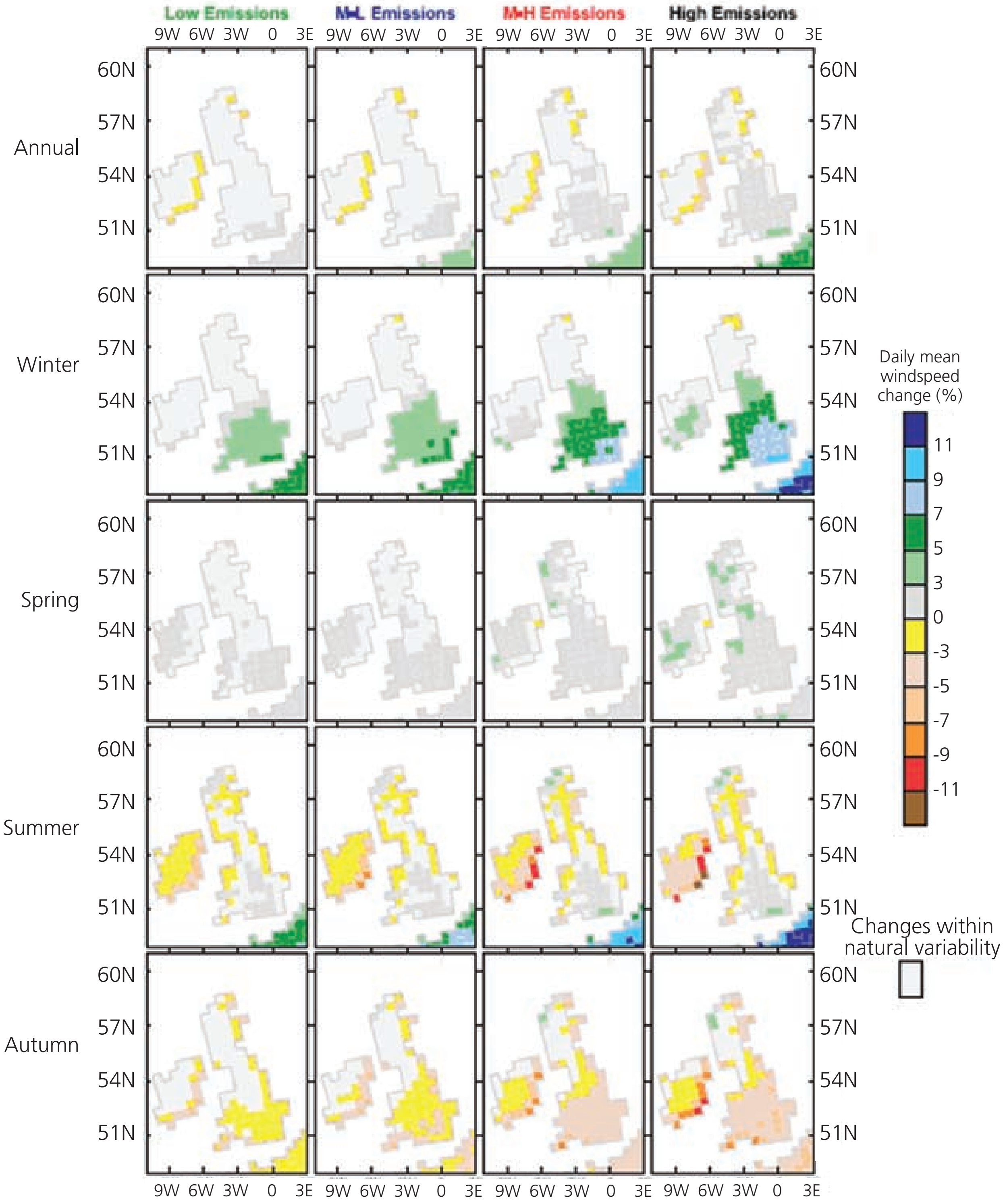


Table 4.2: Summary statements of the changes in average seasonal UK climate for the UKCIP02 climate change scenarios for which we can attach some confidence. Relative confidence levels H = high; M = medium; L = low. The qualitative consistency of these statements with the UKCIP98 scenarios is indicated in the last column by: √√ = highly consistent; √ = some consistency; X = some differences; XX = Inconsistent; n/a = little or no analysis in UKCIP98 (Hulme *et al.*, 2002)

Variable	UKCIP02 Scenarios	Relative Confidence Level	Consistency with UKCIP98
Temperature	Annual warming by the 2080s of between 1° and 5°C depending on region and scenario	H	✗
	Greater summer warming in the southeast than in the northwest	H	✓✓
	Greater night-time than day-time warming in winter	L	✓
	Greater warming in summer and autumn than in winter and spring	L	✓
	Greater day-time than night-time warming in summer	L	✓
Precipitation	Generally wetter winters for the whole UK	H	✓✓
	Substantially drier summers for the whole UK	M	✗
Seasonality	Precipitation: greater contrast between summer (drier) and winter (wetter) seasons	H	✓✓
	Temperature: summers warm more than winters	L	✗
Variability	Years as warm as 1999 become very common	H	✓✓
	Summers as dry as 1995 become very common	M	✓✓
	Winter and spring precipitation becomes more variable	L	✓
	Summer and autumn temperature become more variable	L	✓
Cloud Cover	Reduction in summer and autumn cloud, especially in the south, and an increase in radiation	L	✓
	Small increase in winter cloud cover	L	✓
Humidity	Specific humidity increases throughout the year	H	✓✓
	Relative humidity decreases in summer	M	✓
Snowfall	Totals decrease significantly everywhere	H	n/a
	Large parts of the country experience long runs of snowless winters	M	n/a
Soil moisture	Decreases in summer and autumn in the southeast	H	n/a
	Increases in winter and spring in the northwest	M	n/a
Storm tracks	Winter depressions become more frequent, including the deepest ones	L	n/a
North Atlantic Oscillation	The NAO tends to become more positive in the future – more wet, windy, mild winters	L	n/a

Table 4.3: Summary statements of the change in daily weather extremes for the UKCIP02 climate change scenarios. Relative confidence levels: H = high; M = medium; L = low. The relative consistency of these statements with the UKCIP98 scenarios is indicated in the last column by: √√ = highly consistent; √ = some consistency; X = some differences; XX = Inconsistent; n/a = little or no analysis in UKCIP98 (Hulme *et al.*, 2002)

Variable	UKCIP02 Scenarios	Relative Confidence Level	Consistency with UKCIP98
Precipitation intensity	Increases in winter	H	✓
Temperature extremes	Number of very hot days increases, especially in summer and autumn	H	n/a
	Number of very cold days decreases, especially in winter	H	n/a
Thermal growing season length	Increases everywhere, with the largest increases in the southeast	H	✓
Heating 'degree-days'	Decrease everywhere	H	✓✓
Cooling 'degree-days'	Increase everywhere	H	✓✓

335. The UKCIP scenarios were not conducted with AQ applications particularly in mind and hence relevant information on boundary layer depth and diurnal variability was not included. For comparison, more recent 25 km resolution HadRM3 simulations (Johnson *et al.*, 2005) are presented in Table 4.4 below, including variables of particular relevance to AQ applications. It should be noted, however, that this latter study only considered four individual years during each of the control and scenario integrations, raising questions as to whether natural climatic variability has been fully accounted for. Furthermore, not all the changes are consistent with recent observed climate changes such as have been observed in Scotland where winter cloud cover has been increasing (Barnett *et al.*, 2006).

336. In summary, the simulated changes would suggest that while AQ might be expected to improve in the winter months as a result of the simulated increase in winter wind speed (albeit with low confidence) and precipitation (fewer poor dispersion conditions), summer season AQ is more likely to deteriorate in response to lower wind speeds and slightly less cloud cover (and consequent increased solar radiation). Such a change in the seasonality of poor AQ is also synchronous with anticipated changes to the likely seasonality of pollutant emissions noted in Section 3 of this chapter.

337. It would be instructive to reproduce, using HadRM3 output, the approach of Anderson *et al*. (2001), using HadCM3, in which the changing frequency of combined low wind speed and high (low) temperature conditions is analysed to determine likely frequency changes in summer (winter) season AQ episodes (although deficiencies in the ability of HadRM3 to realistically simulate summer dryness need to be kept in mind). Doyle and Dorling (2005) report on a stagnation definition methodology which could also be easily adapted to climate model output.

Table 4.4: Changes in UK climate as simulated in a 25 km resolution HadRM3 climate model integration (Johnson *et al*., 2005)

Parameter	Future change
Wind speed	Summer – lower Winter – higher
Wind direction	Summer – similar but slightly more northerly with less westerly Winter – slightly more westerly than easterly
Heat flux	Summer – slightly higher Winter – no obvious change
Boundary layer depth	Summer – more depths greater than 1500m Winter – no obvious change
Cloud cover	Summer – slightly less Winter – no obvious change
Incoming solar radiation	Summer – slightly greater Winter – no obvious change
Temperature	Summer – significantly higher with heat wave events much more frequent Winter – significantly higher
Precipitation	Summer & winter – more occurrences of no precipitation
Pressure (mean sea level)	Summer – high pressure more prevalent Winter – low pressure more prevalent

338. Urban heat island effects will be superimposed on top of more general changes to climate parameters (Wilby, 2003; LCCP, 2002). Increases in solar radiation and decreases in cloud cover in summer may favour heat island intensification, compounding the effect of heatwaves on human health. Based on HadCM3 climate model output using two different emission projections, Wilby (2003) showed that urban heat island intensity is projected to increase in London, based on statistical relationships with synoptic-scale weather variables. However an enhanced heat island may intensify the strength of the urban-rural country breeze circulation which may help to disperse urban air pollution.

4.4.1.2 Statistical Downscaling

339. Global and regional climate models do not accurately simulate all variables of interest at the local scale. This has led to the development of statistical approaches in which coarser resolution variables are used as predictors for local conditions; statistical models can be developed between these coarser resolution variables and station observational data (Goodess *et al*., in press). An example would be to develop statistical models of the relationship between gridpoint geostrophic wind speed (e.g. using reanalysis data) and station wind conditions. Such a model can then be used in conjunction with climate model gridpoint data with the assumption that stationarity in the relationship between predictor and predictand is maintained. Wilby *et al*. (2002) describe such a statistical downscaling model SDSM system. The approach suggests, based on output from the HadCM3 General Circulation Model (GCM), that no significant trend in annual mean windspeed is expected through the 21st Century, in contrast to the

low-confidence increase in winter wind speed simulated in the UKCIP scenarios (Table 4.2). Furthermore, Pryor *et al*. (2005) show, using empirical downscaling, that some state-of-the art climate models even simulate a decrease in wind speed in northern Europe by the end of this century.

340. Guidance on the use of both dynamical and statistical downscaling approaches is provided by the IPCC (http://ipcc-ddc.cru.uea.ac.uk/guidelines/index.html).

4.4.2 Offline assessments of future climate change impacts on air quality

341. While the studies summarised in Section 4.4.1 considered how the UK and European climate may change in the future, a few studies have specifically considered how future CC may impact local AQ, without considering coupled chemistry-climate feedbacks. All these studies also contain the significant uncertainties which arise from choice of climate model and parameterisations within AQ models.

342. HadCM3 daily 'Central England' gridpoint meteorological conditions were analysed by Anderson *et al*. (2001) through December 2099 and based on the IPCC IS92a (business as usual) scenario, to consider the changing frequency of episodes of cold still winter weather and of episodes of hot sunny summer days. It was observed that the number of days with both low windspeeds and low minimum temperatures (combining to create poor dispersion) decline through the 21st Century as winters become milder and windier (Table 4.5).

Table 4.5: The number of days with at least one hour in which the windspeed is less than 2 m s^{-1} and the minimum temperature is in the range shown for each decade up to 2100 (Anderson *et al*., 2001)

Decade	Number of days in the range from -15°C to -10°C	Number of days in the range from -10°C to -5°C	Number of days in the range from -5°C to 0°C
1990 – 1999	0	1	32
2000 – 2009	0	2	17
2010 – 2019	0	1	38
2020 – 2029	1	3	43
2030 – 2039	1	3	11
2040 – 2049	0	2	30
2050 – 2059	0	1	20
2060 – 2069	0	1	30
2070 – 2079	0	0	26
2080 – 2089	0	1	24
2090 – 2099	0	0	17

343. By studying the joint distribution of elevated temperatures and low windspeed conditions (conducive to photochemical episodes) it was shown that these conditions became significantly more common in the second half of the 21st Century (Table 4.6).

Table 4.6: The number of days with at least one hour in which the windspeed is less than 2 m s^{-1} and the maximum temperature is in the range shown for each decade up to 2100 (Anderson *et al*., 2001)

Decade	Number of days in the range from 25°C to 30°C	Number of days in the range from 30°C to 35°C	Number of days in the range from 35°C to 40°C
1990 – 1999	1	0	0
2000 – 2009	1	0	0
2010 – 2019	3	0	0
2020 – 2029	3	0	0
2030 – 2039	5	0	0
2040 – 2049	8	1	0
2050 – 2059	9	2	0
2060 – 2069	8	2	0
2070 – 2079	6	1	1
2080 – 2089	14	2	0
2090 – 2099	15	5	2

344. Using the same definition of stagnation as used in the stagnation climatology discussed in Section 4.2.2.1, Dorling *et al*. (2003) undertook an analysis of future stagnation frequency based on output from the HadCM3/HadAM3/HadRM3 climate model suite. Two future Special Report on Emissions Scenarios (SRES) were considered for the period 2070 –2100, 'Business as Usual' and 'Mitigation'. Results showed that winter stagnation frequency over the UK was lower compared to the 1960 – 90 control climate but that it was lowest in the future 'Business as Usual' scenario, as shown in Table 4.7. Miranda *et al*. (2005) addressed possible changes to photochemical air pollution over Portugal by the year 2050 using a dynamical downscaling approach. Output from the Melbourne University GCM was used to provide boundary conditions for the MM5 Mesoscale Meteorological Model which in turn was coupled to the CAMx Chemical Transport Model. The study focused upon periods of consecutive days when the surface air temperature was ≥ 25°C in the 2050s compared to the 1990s. Future national emission scenarios were developed, at national scale, as part of this work. Both NO and O_3 concentrations were shown to increase by the 2050s.

345. Using output from the Goddard Institute for Space Studies (GISS) Global Climate Model to provide boundary conditions for the MM5 Mesoscale Meteorological Model and Community Multiscale AQ model running at 36 km resolution, Knowlton *et al*. (2004) were able to simulate the effect of CC on surface O_3 concentrations in the New York Metropolitan area. Results showed that without considering the effect of emission changes or population growth, CC alone was simulated to produce a 4.5% increase in O_3-related acute mortality by the 2050s.

Table 4.7: Winter stagnation frequency in the UK as simulated in the HadCM3 climate model for the control climate and for two future special report emission scenarios. (Dorling *et al.*, 2003)

Percentage days	December	January	February	Winter	Year
1960 – 90 control climate	11.0	14.6	15.5	13.7	9.4
2070 – 2100 'business as usual'	7.7	5.5	8.1	7.1	6.3
2070 – 2100 'mitigation'	11.3	8.0	12.0	10.4	7.8

346. The global CTM MOZART-2 (Model of O_3 and Related chemical Tracers version 2) was driven with meteorology from the National Centre for Atmospheric Research (NCAR) coupled Climate Systems Model (CSM) forced by the IPCC A1 Scenario (Murazaki and Hess, 2006). Chemical emissions were held constant at 1990 levels. In keeping with other studies, background O_3 was simulated to decrease in the 2090s (due to the rise in water vapour) with increases in O_3 in the polluted eastern United States (associated with higher temperatures altering the ratio of NO_X to peroxyacetyl nitrate (PAN)). It is possible, however, that since only one future decade was considered, normal inter-decadal variability may mask more robust changes in important meteorological parameters.

347. MATCH, a regional chemistry-transport-deposition model, was used by Langner *et al*. (2005) in conjunction with two 10-year CC experiments produced with the Rossby Centre Regional Atmospheric Climate Model version 1 (RCA1). The RCA1 model was forced by boundary conditions from two different climate models using the IPCC IS92a (business as usual) emission scenario. A strong increase in surface O_3 was observed as a function of CC in southern and central Europe, in conjunction with a decrease in northern Europe. The changes are sufficiently large to be able to extract clear signals from the inter-annual variability.

348. Hogrefe *et al*. (2004) describe a study using a modelling system consisting of the NASA GISS Atmosphere-Ocean Global Climate Model, MM5 and CMAQ. Future emissions of GHGs and O_3 precursors were based on the IPCC A2 scenario (high CO_2 growth). Five summers in each of the 2020's, 2050's and 2080's were analysed. Results indicated that summertime average daily maximum 8-hour O_3 concentrations increase by 2.7, 4.2 and 5.0 ppb (5.4, 8.4 and 10.0 µg m^{-3}) respectively as a result of regional CC alone with respect to five summers in the 1990s. Concerning the 2050s, changes to the large-scale circulation boundary conditions were found to be the biggest contributor to changes in predicted summertime average daily maximum 8-hour O_3 concentrations (5.0 ppb, 10 µg m^{-3}), followed by the effects of regional CC (4.2 ppb, 8.4 µg m^{-3}) and the effects of increased anthropogenic emissions (1.3 ppb, 2.6 µg m^{-3}). However, when changes in the fourth highest summertime 8-hour O_3 concentrations were considered, changes in regional climate are the most important contributor to simulated concentration changes (7.6 ppb, 15.2 µg m^{-3}). Thus, while previous studies have pointed out the potentially important contribution of growing global emissions and intercontinental transport to O_3 AQ in the USA for future decades, the results presented imply that it may be equally important to consider the effects of a changing climate when planning for the future attainment of regional-scale AQ standards.

349. One of the greatest limitations so far in considering the impact of CC on AQ has been the lack of availability of hourly climate model output (or at least a diurnal cycle of some sort) making studies of changes to atmospheric dispersion difficult. This gap is beginning to be addressed, for example through a Defra-funded UK Meteorological Office (UKMO) - Cambridge Environmental Research Consultants (CERC) collaboration (Johnson *et al*., 2005). The Hadley Centre coupled atmosphere-ocean climate model, HadCM3 (Gordon *et al*., 2000), was used to simulate CC over the period 1861 –1990 (driven by observed concentrations of GHGs and estimates of sulphate aerosols), and to make a prediction for the period 1990 – 2100 driven by the IPCC SRES A2 (Nakićenović *et al*., 2000). The horizontal resolution of the atmosphere of HadCM3 is 2.5 degrees latitude by 3.75 degrees longitude, corresponding to approximately 300 km over the UK. This relatively coarse resolution (in common with other global coupled models) limits the simulation of current climatic features, such as the Atlantic storm tracks, which have an important influence over the UK.

350. In order to improve this, the HadCM3 predicted changes in sea surface temperatures and sea ice extent were used as input into a global atmosphere-only model, HadAM3H (Hudson and Jones, 2002a), having twice the horizontal resolution of the global coupled model; this gave a better representation of the storm tracks and other features. The HadAM3H model was run to simulate two 30-year periods, 1961 – 90 (the most recent reference period of the World Meteorological Organisation (WMO), representing recent climate) and 2071 – 2100.

351. The global simulations and predictions from the two HadAM3H model runs were downscaled to approximately 25 km resolution (0.22 x 0.22 degrees) using the regional climate model HadRM3H (Hudson and Jones, 2002b) giving high resolution results for the two periods 1961 – 90 and 2071 – 2100. HadRM3H has the same physical and dynamical formulation as the driving global model (HadAM3H) except where resolution dependent parameter changes were required for stability, or where implied by the nature of the model's physical parameterisations.

352. Datasets containing hourly data for London and Glasgow were produced from the regional climate simulation model for the years 1971, 1976, 1981 and 1986 representing the current climate, and for 2071, 2076, 2081 and 2086, representing the future climate. Four years is not many over which to sample the climate, but by spacing the years an attempt has been made to sample variability on decadal time scales as well as year to year variability.

353. Table 4.8 presents the simulated changes to key meteorological variables and the resulting potential influence on AQ. The most significant outcome appears to be a likely change in the seasonality of poor AQ occurrence with more episodes in summer due to O_3 and fewer episodes in winter.

Table 4.8: Simulated changes in meteorological parameters and potential resulting changes in UK air quality, based on a 25km resolution HadRM3 integration (Johnson *et al*., 2005)

Parameter	Future change	Influence on air quality
Wind speed	Summer – lower	Less dispersion, so possibly higher air pollution levels due to local emissions
	Winter – higher	Greater dispersion, so possibly lower air pollution levels due to local air pollution
Wind direction	Summer – similar but slightly more northern with less westerly	Little effect
	Winter – slightly more westerly than easterly	Possibly lower air pollution due to less pollution sources to west of UK
Heat flux	Summer – slightly higher	Slight changes in local pollution impacts – higher concentrations from elevated sources but lower impact from surface sources
	Winter – no obvious change	None
Boundary layer depth	Summer – more depths greater than 1500m	Possibly lower air pollution due to larger dilution and mixing (but very small effect)
	Winter – no obvious change	None
Cloud cover	Summer – slightly less	Possibly lower local pollution due to greater turbulence, but turbulence may influence plume grounding. Greater sun light may increase photochemical reactions leading to higher O_3
	Winter – no obvious change	None
Incoming solar radiation	Summer – slightly greater	Possibly lower local pollution due to greater turbulence, but turbulence may influence plume grounding. Greater sun light may increase photochemical reactions leading to higher O_3
	Winter – no obvious change	None
Temperature	Summer – significantly higher with heat wave events much more frequent	Likely to produce conditions conducive to high O_3 pollution episodes
	Winter – significantly higher	Unclear
Precipitation	Summer and winter – more dry days	Possibly higher pollution as precipitation tends to clean the atmosphere of pollutants
Pressure (mean sea level)	Summer – high pressure more prevalent	Possibly higher pollution due to anticyclonic conditions circulating pollutants from continental Europe. Also high pressure systems are usually associated with high O_3 concentrations
	Winter – low pressure more prevalent	Possibly lower pollution due to more turbulent conditions.

4.4.3 Coupled chemistry-climate modelling

354. The most significant meteorological variables for AQ directly affected by CC are temperature and specific humidity. Climate models suggest that the relative humidity of the atmosphere will remain roughly constant in future. Since a warmer atmosphere can hold more water vapour, this implies that the specific humidity will increase, as will the vapour pressure deficit, which controls stomatal

behaviour. Warmer temperatures can increase the reaction rates producing O_3 and reduce the amount of NO_X that becomes locked away in the organic compound PAN. Increased water vapour will increase the destruction of O_3. Which of these effects dominates depends on the environment. Throughout most of the troposphere the water vapour effect leads to a net decrease in O_3 with CC (Johnson *et al*., 2001). However close to the surface over polluted regions, (which is the region of most interest) some CCMs show an increase in O_3 pollution with CC (e.g. Murazaki and Hess, 2006) due to a decrease in PAN formation.

355. Although water vapour and temperature increases have opposite effects on O_3, they both increase the oxidising capacity of the atmosphere by increasing the rate of production of the hydroxyl radical (OH), the 'detergent' of the atmosphere. Therefore in a warmer, wetter climate, pollutants will be oxidised faster. This will decrease the concentrations of primary pollutants (such as NO_X, SO_2) near to sources, but increase the concentrations of secondary pollutants (such as nitric acid (HNO_3) and sulphuric acid (H_2SO_4)) near the source. The oxidised pollutants tend to be more soluble than the primary pollutants, and hence more easily removed. On the global-scale therefore, a future increase in oxidising capacity will in general tend to decrease the abundance of most pollutants in the atmosphere although some specific chemical species may increase. However, the decreased transport distances implied by this effect may modify the UK budgets for NO_X and SO_2 described by NEGTAP (2001), resulting in a greater proportion of UK emissions being deposited within the country.

356. Circulation patterns in a future climate, for instance the number and strength of summer high pressures systems, will vary as the pattern of surface temperature varies. Mickley *et al*. (2004) found over the USA that while the transport changes would have little effect on the mean levels of pollution, they would increase the severity of extreme episodes. Collins *et al*. (2003), Zeng and Pyle (2003) and Sudo *et al*. (2003) showed that O_3 transport from the stratosphere to the troposphere in a future climate would tend to increase. In the absence of other changes this will lead to increased surface O_3 concentrations. However in the Collins *et al*. (2003) study, the extra O_3 destruction in the warmer climate outweighed the increased stratospheric input.

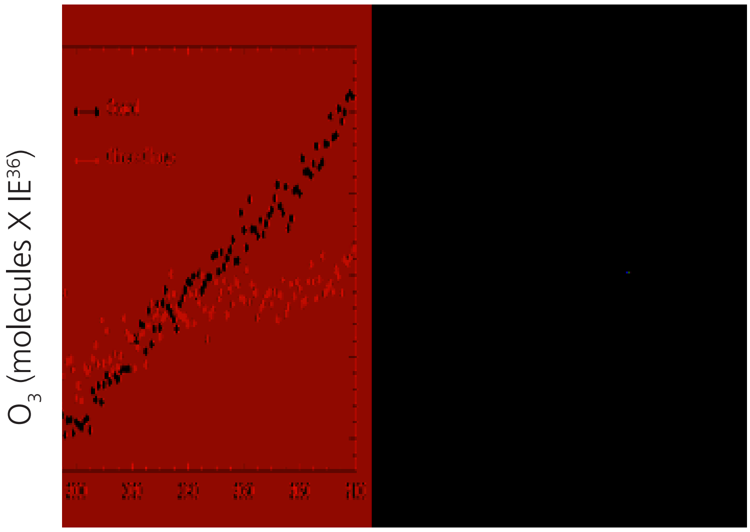
357. Langner *et al*. (2005) simulated the effects of a 2.6°C climate warming and found decreases in nitrate and sulphate deposition over Central Europe due to decreases in precipitation. They also found less removal of total reactive nitrogen oxides (NO_y) species by precipitation, leading to greater surface O_3 abundances.

358. The combined effect of all these meteorological and biogenic processes on AQ is very uncertain. No atmospheric chemistry models simulate all the possible climate effects. Some of the predicted climate changes are robust (temperature, water vapour), others vary considerably between models (precipitation, soil moisture). Recent studies that have tried to incorporate as many effects as possible are described below.

359. State-of-the-art coupled chemistry-climate modelling, including work at the Hadley Centre, has highlighted the importance of:

- feedbacks between the climate and atmospheric composition (especially concerning water vapour, CH_4, O_3 and aerosols (with a strong focus on black carbon))
- changes in the stratosphere and to the exchange of air between stratosphere and troposphere.

Figure 4.30: Trend in July global ozone burden based on STOCHEM simulations (Johnson *et al*., 2001)



360. Stevenson *et al*. (2005) used the IS92a SRES and compared results for the 2020's for a fixed climate and for a projected climate from HadCM3 (Johns *et al*., 2003) with a global mean surface warming of approximately 1°C and investigated the impact of changes in:

- temperature (on reaction rates and changes in isoprene emissions)
- humidity (on the $O^1D + H_2O$ reaction)
- convection (affecting mixing and lightning NO_X emissions)
- large-scale circulation (e.g. stratosphere-troposphere exchange (STE))
- precipitation (wet removal processes).

361. The largest influence appears to be changes in humidity (Figure 4.30), directly related to temperature change (Figure 4.31), reducing O_3 lifetime, together with enhanced oxidants leading to OH production reducing the CH_4 lifetime and increasing aerosol production (Johnson *et al*., 2001); the overall climate-chemistry feedback is, in this model simulation, dominantly negative (Stevenson *et al*., 2005). However, inter-annual changes in O_3 were seen to be as large as the overall emission/climate related changes caused by 2030 (Figure 4.32), indicating that cause and effect remains difficult to identify on this policy-relevant timescale.

362. Other model studies, such as that of Zeng and Pyle (2003), found less sensitivity to water vapour changes and more sensitivity to CC induced increases in mid-latitude STE of O_3 (associated with higher O_3 concentrations in the lower stratosphere resulting from colder temperatures). The contrasts in sensitivity are partly related to the resolution and parameterisation of stratospheric processes.

363. Stevenson *et al*. (2006) describe results of a model inter-comparison of 26 differently formulated CTMs (meteorology not influenced by the chemical fields) and CCMs (where the chemical fields enter the radiation calculations of the driving GCM and directly influence the dynamics) organised under the auspices of ACCENT, the results of which are feeding into the IPCC Fourth Assessment Report process (Section 7.3 'Global Atmospheric Chemistry and Climate Change' and 7.4 'Air Quality and Climate Change'). These experiments are based on new 'optimistic', 'likely' and 'pessimistic' International Institute for Applied Systems Analysis (IIASA) emission scenarios summarised in Table 4.9. Ten of these models are also used to simulate the effect of CC on atmospheric chemistry, based on the S2 experiment (Table 4.9), between 2000 and 2030 (the 'intermediate' future of interest to policy makers). Such a study helps to quantify the uncertainties associated with future projections.

Figure 4.31: Surface temperature change in K from 1990 – 2020 (Stevenson *et al*., 2005)

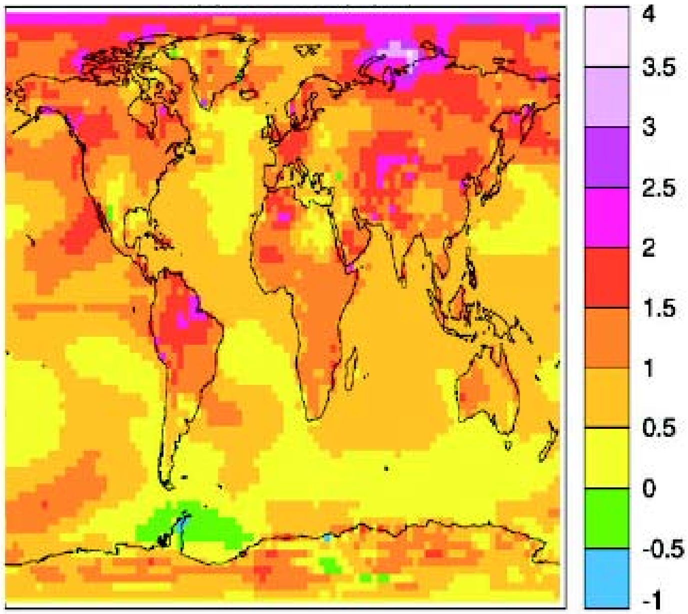


Figure 4.32: Surface ozone change (ppb) due to climate change between the 1990s and the 2020s simulated with the STOCHEM model (Stevenson *et al.*, 2005). To convert to μg m^{-3} units, 1 ppb = 2.00 μg m^{-3} for O_3 at 20°C and 101.3 kPa

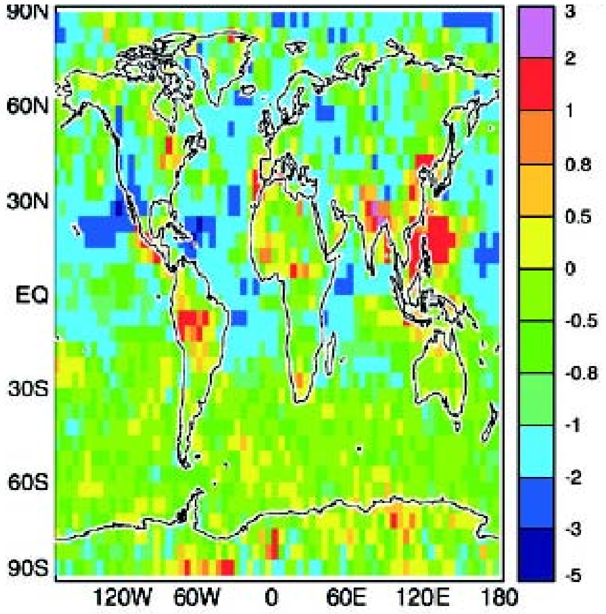
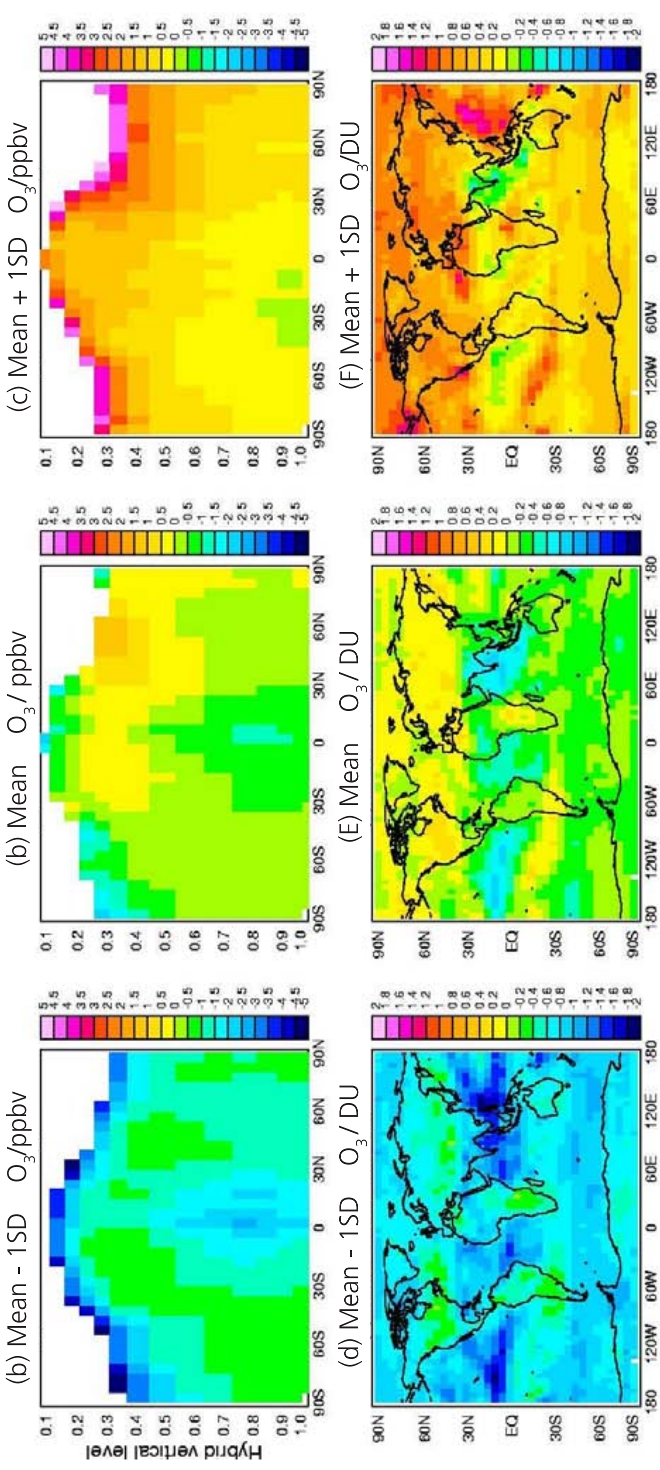


Table 4.9: ACCENT Chemical Transport Model and Chemistry Climate Model intercomparison experiments (Stevenson *et al.*, 2006)

Code	Name	Meteorology	Emissions	Reference
S1	Y2000	2000/ 1995 — 2004	2000 (EDGAR3.2)	Olivier *et al.* (2001)
S2	CLE	2000/ 1995 — 2004	2030 IIASA CLE	Dentener *et al.* (2004)
S3	MFR	2000/ 1995 — 2004	2030 IIASA MFR	Dentener *et al.* (2004)
S4	A2	2000/ 1995 — 2004	2030 SRES A2	Nakićenović *et al.* (2000)
S5	CLE-ΔC	2025 — 2034	2030 IIASA CLE	Stevenson *et al.* (2005)

Figure 4.33: Influence of climate change on ozone – average of 10 models participating in the ACCENT collaboration. (b) and (e) are the ensemble mean response while other panels show results one standard deviation above/below the mean (Stevenson *et al.*, 2006). To convert to µg m^{-3} units, 1 ppb = 2.00 µg m^{-3} for O_3 at 20°C and 101.3 kPa



364. The intercomparison involved a wide range of model output, including daily column NO_2 and formaldehyde (HCHO) data to compare with Global Ozone Monitoring Experiment (GOME) measurements; hourly surface O_3 output for detailed analyses of future O_3 AQ impacts on health and vegetation; and deposition fluxes of the main species responsible for acidification and eutrophication. Analysis suggests that model response of O_3 to CC is quite divergent (Figure 4.33), especially in the Tropics. However changes in humidity, STE and lightning NO_X are of most importance, especially with respect to O_3.

365. Natural and anthropogenic emissions will change in response to CC. None of the models included such anthropogenic emission responses while some incorporated natural emission responses (e.g. biogenic isoprene and lightning NO_X).

366. Significant challenges remain, especially in realistically simulating interaction between the atmosphere and the biosphere. Coupled modelling is essential in order to capture at least some of the feedback complexity, including any changes to the relative importance of deposition processes. It is vital to encourage ensemble climate modelling approaches in which simulations from a variety of models can be inter-compared; the IPCC process and ACCENT model intercomparison are fundamentally important here.

4.5 Recommendations

367. Improvements are needed to the supply of climate model data for AQ applications, specifically:

- hourly resolution data are required for important air pollution dispersion controls which vary diurnally (e.g. atmospheric stability)
- regional climate model data should be provided on time horizons which are most useful for policymaking (i.e. 2020 – 30 rather than just 2061 – 90)
- dynamically and statistically downscaled simulations are needed which more realistically simulate the extremes of soil dryness and surface temperature during periods of summertime drought
- climate model meta-information is needed which highlights to end-users how modelled extremes should be interpreted
- research on tropospheric chemistry and climate should be more focussed on changes at ground-level, and at the regional-scale. Emphasis should be given to chemical species relevant to AQ.

368. Ensemble model inter-comparison exercises are essential to determine the magnitude of uncertainties associated with simulations of future climate and atmospheric composition.

369. Continued investment is needed in atmospheric composition measurements across a range of monitoring platforms in order that CCM and CTM simulations can continue to be validated.

Chapter 5

Mitigation measures for air pollution and climate change

Key points

General points

- Over the past 20-30 years most attention has been focussed on the mitigation of air quality (AQ) impacts mainly through legislation and changes to technology. In mitigating these impacts, little or no consideration has been given to the impacts (beneficial or detrimental) on climate. These two policy areas have largely developed separately from one another.
- Several different types of mitigation measure can be broadly identified and categorised. These include:
  - **Conservation**: reducing the use of resources through energy conservation.
  - **Efficiency**: carrying out the same activity, but doing so more efficiently, thus reducing resource use and emissions of AQ and climate-active pollutants.
  - **Abatement:** the application of a technological approach to reducing emissions.
  - **Fuel switching**: substituting a lower emission fuel for a higher emission fuel.
  - **Demand management**: implementation of policies or measures which serve to control or influence the demand for a product or service.
  - **Behavioural change**: changing the habits of individuals or organisations in such a way as to reduce emissions e.g. travelling by train instead of by air.
- These measures can be brought about in many different ways including through legislation, fiscal instruments, voluntary agreements and ongoing technological change.
- Overall, UK emission projections show that significant reductions in the emissions of AQ pollutants is likely from 2002 – 20 e.g. nitrogen oxides (NO_X) 45%, sulphur dioxide (SO_2) 64%, volatile organic compounds (VOC) 26% and particulate matter (PM_{10}) 19%. Less of a reduction is predicted for ammonia (NH_3) (10%). By contrast UK emissions of carbon dioxide (CO_2) over the same period are predicted to decline by around 4%.
- UK emission projections suggest that by 2020 there will be a much larger number of sectors that control the majority of emissions compared with 2002, because emissions from many of the larger emitters in 2002 will have been controlled.
- Comparing AQ and climate change (CC) impacts and different synergies and trade-offs is problematic because there is no common metric available for comparison.

- It is important to consider fuel cycle or life cycle emissions. Many of the options that are likely to be important in the longer-term (e.g. hydrogen (H_2) and biofuels) result in a shift from emissions at the point of use to emissions related to fuel production.
- There are inherent methodological difficulties in identifying the impact of measures on emissions of pollutants of concern from an AQ perspective and those that have impacts, directly or indirectly, on climate. The assessment of the impact that particular measures might have on emissions depends on many factors e.g. the base year considered.
- AQEG has already highlighted the importance of adopting a holistic approach to the control of nitrogen dioxide (NO_2) and PM. A holistic approach is important when considering the combined issue of CC and AQ.

Win-wins and trade-offs

- Table 5.1 summarises examples of win-wins and trade-offs between AQ and CC. The points below are of a more specific nature.
- Small changes in CO_2 emissions (increases or decreases of a few percent) are important, particularly in the context of the UK's commitments to reduce greenhouse gas (GHG) emissions. The sometimes small disbenefit of some AQ abatement technologies is therefore important.
- Many 'end-of-pipe' AQ controls result in relatively small increases in CO_2 emissions through reduced efficiencies. Examples include flue gas desulphurisation (FGD) on power stations (~3% increase in CO_2) and some forms of abatement for exhaust emissions from road vehicles (< 5% increase in CO_2).
- There are numerous measures that can be identified which use electricity. These measures are dependent on how the electricity is generated (fuel mix assumptions and abatement measures). Examples include: energy-efficient domestic appliances, the use of electricity for transport and the modal switch from short-haul flights to high-speed electrified rail.
- There is a well-developed system for the control of emissions of local AQ pollutants in the UK and Europe, which is increasingly setting more stringent limits on the amounts of AQ pollutants that can be emitted. The development, or increased use of new sources of energy such as energy crops or biofuels for road transport, would need to comply with existing or planned legislation controlling these emissions. However, the increased use of some fuels could lead to increases in climate-active and AQ emissions that cannot easily be controlled e.g. NH_3 or nitrous oxide (N_2O) emissions if the production of biomass requires increased fertiliser inputs. There is a less developed system to control the emissions of these soil emissions.

- Refinery emissions of CO_2 increase as a result of meeting fuel sulphur (S) limits. Sulphur-free (< 10 ppm S) petrol and diesel leads to increased refinery CO_2 emissions of 5-10%. However, in the longer-term, these emissions could be offset by improvements to petrol engine efficiencies. This is because new control technologies that are effective at controlling NO_X in lean-burn petrol vehicles require sulphur-free fuel. It seems likely however, that future diesel engines (in the 2010 – 15 time frame) will be associated with increased fuel consumption and CO_2 emissions over baseline Euro IV vehicles (i.e. vehicles produced to Europe-wide standards with regard to emissions) due to the application of new pollution control technologies such as four-way catalysts, lean NO_X traps and particulate filters.

- Diesel fuel is generally considered to have GHG benefits over petrol. This is mostly because diesel emits lower quantities of CO_2 than petrol. However, the overall benefits of diesel in this respect are less apparent when other factors are accounted for. For example, diesel cars tend to have larger engines than equivalent petrol cars, thus reducing their CO_2 benefits. Furthermore, the refinery processes used to produce diesel are increasing in energy intensity to meet increased diesel fuel demand and fuel compositional requirements. Some emerging emissions control technologies for diesel vehicles can also result in increased fuel penalties, which would reduce their CO_2 benefit compared with petrol. Finally, recent modelling work indicates that black carbon (BC) emissions associated with diesel vehicles contribute to warming effects, although the magnitude of these effects is uncertain. These issues suggest that it is important to consider emissions and effects beyond those associated with tailpipe emissions, and this applies equally to other fuel cycles.

- Emissions of GHGs and AQ pollutants from energy production from the agricultural sector are likely to become more important in the longer-term. This is because of the attractiveness of using non-fossil carbon (C) sources as a fuel for electricity generation, heat and transport sources. These emissions can arise from the growth of biomass (e.g. NH_3, N_2O and isoprene), depending on the species and fertiliser regime; from fuel production and distribution; as well as from end-use emissions. These effects need to assessed alongside the benefits of reduced CO_2 emissions from their use.

- Measures that result in an increase in N_2O emissions could significantly reduce the benefits due to reductions in CO_2 because N_2O is a much more powerful GHG than CO_2. For example, the use of selective catalytic reduction (SCR) to reduce emissions of NO_X from road vehicles (enabling engines to operate at a higher efficiency), could lead to increases in N_2O emissions – and may more than offset the CO_2 advantage of increased engine efficiencies. Some biofuels that rely on high fertiliser inputs may also result in increased emissions of N_2O, depending on previous land use, which could reduce their overall GHG benefit compared with conventional fuels.

- The measures that most clearly benefit CC and AQ are those which result in the reduction in the demand for a product or service or those that enable the same activity to be carried out more efficiently. For these measures there is generally a commensurate percentage reduction in both climate-active and AQ emissions. These reductions can be brought about in several ways including demand management and improvements in technology. These types of measures exist across the different sectors e.g. transport, energy and agriculture. Examples include energy conservation measures (e.g. insulation and more energy efficient appliances) and the reduction in road traffic by demand management.

- There is a lack of published information that considers emissions of climate-active and AQ pollutants together for different policies and measures.
- Improvements in the efficiency of processes and services, which can reduce AQ and climate-active emissions, can also encourage the increased use of them too, which can offset potential benefits. For example, aircraft fuel consumption and emissions have decreased over the past 20 years through technological improvements, but these have been offset by increased demand. The area of behavioural change is therefore an important one, but one that is difficult to quantify.
- Table 5.1 aims to highlight examples of how CC and AQ mitigation measures interact. The Table is not intended to represent a comprehensive treatment of all possible interactions but to indicate the types of measure that would benefit both issues or may result in a trade-off in one (or both) issues. This table can usefully be compared with Table 3.1, which links the emissions of different pollutants to their impacts on climate. Table 5.1 also highlights the appropriate section in Chapter 5 where these issues are discussed.

Table 5.1: Examples of broad categories of measure for climate change and air quality mitigation and their effects

Measure	Effect
Mitigation measures that could reduce emissions of air quality and climate-active pollutants	
Power generation	
Fuel switching to lower carbon or renewables (e.g. coal to natural gas)	Reduction in CO_2, SO_2, NO_X (especially if used with abatement) [§ 5.4.1.2]
Combined heat and power (CHP)	Reduction in AQ and climate-active pollutants if used to replace conventional electricity generation. [§ 5.4.1.3]
Transport	
Use of certain new technologies and fuels (e.g. hybrid vehicles)	Reduces point of use and fuel chain emissions of CO_2 and AQ pollutants; H_2 from renewable sources or derived from natural gas and used in a fuel-cell vehicle; lean-burn petrol vehicles with lean NO_X traps. [§ 5.5.1]
Low emission zones	Only if newer (more efficient) vehicles replace older (less efficient) vehicles. [§ 5.5.1.3]
Efficiency improvements	
More efficient domestic appliances/ industrial processes; improvements in technology	Often a proportionate reduction in climate-active and AQ pollutants; benefits of improved efficiencies can be reduced through encouraging increased demand in same (or other) products. [§ 5.4.2]
Demand management	
Road-user charging	[§ 5.5.1.3] ↓
Conservation	
Home insulation	

Measure	Effect
Climate mitigation measures that could increase emissions of air quality pollutants	
Increased aircraft fuel efficiency	Trade-off: reduction in CO_2 but increase in NO_X [§ 5.5.2]
Fuel-switching (transport)	Increased use of diesel in place of petrol (increased NO_X, PM) [§ 5.5.1.2]
Use of biofuels under certain conditions	
General	Use of nitrogen-based fertilisers could increase NH_3 emissions; emissions of N_2O potentially important for some fuels [§ 5.5.1.2 and 5.6]
Transport fuels	Potentially increased emissions at point of use if used neat or if mixed with petrol/diesel fuels in high proportions. Increased fuel production emissions of AQ pollutants. [§ 5.5.1.2]
Domestic use	Could result in increased AQ pollutants (PM) e.g. if used in place of electricity or natural gas
Waste management	Incineration (including CHP) instead of landfill. Reduced methane (CH_4) but increases in AQ pollutants. [§ 5.7.1]
Forests as a sink for carbon	Potential to increase emissions of biogenic hydrocarbons; other AQ emissions if used for fuels. [§ 5.6.3]
Air quality mitigation measures that could increase emissions of climate-active pollutants	
Power generation	
Flue gas desulphurisation (FGD)	Reduced generation efficiency hence increased CO_2 per unit electricity generated. Formation of CO_2 through use of limestone in wet scrubbing. [§ 5.4.1.1]
Transport	
Abatement of AQ emissions	For diesel vehicles: use of particle filters; four-way catalysts; lean-NO_X traps; potential to increase N_2O (e.g. selective catalytic reduction) [§ 5.5.1.1]
Reduced sulphur in fuel	Increased refinery CO_2 emissions. However, could reduce point of use emissions of CO_2 (e.g. lean NO_X trap fitted to a petrol vehicle). [§ 5.5.1.1]
Measures that could result in increased AQ and climate-active pollutant emissions	
Increased demand for products/ services	Aircraft – increased fuel efficiency has been exceeded by increased demand [§ 5.5.2]
Transport modal shifts	Increased use of short-haul flights at the expense of rail [§ 5.5.1.4]
Increased use of coal for electricity generation	If used in place of renewables, nuclear or natural gas
Use of biofuels under certain circumstances?	Significant increase in N_2O if nitrogen-based fertilisers used; transportation emissions over long distances (if imported); increased AQ emissions if used in high proportions at point of use; fuel-chain emissions increase particularly if significant use of fossil fuels [§ 5.4.1.5 and 5.5.1.2]

Box 5.1: Summary response to Questions 4 and 5

Question 4: What current or potential air pollution mitigation measures are likely to be detrimental/beneficial to UK CC and vice versa? In particular, which mitigation techniques are likely to produce win/win for both AQ and CC and which will result in unavoidable trade-offs? Priority should be given to considering the energy, transport, and agricultural sectors along with any others deemed to be appropriate.

The clearest synergies are related to the reduced use of resources. There are many examples of these synergies. These include energy efficiency measures (e.g. improved domestic appliances and loft insulation). In the energy sector, fuel switching has historically been an important influence on the emission of AQ or climate-active pollutants and this will continue to be important in the future. The switch to low C (or no C) fuels with appropriative abatement is an important synergy. Some abatement measures, such as FGD, can lead to decreases in plant efficiency and hence increased emissions of CO_2 i.e. a trade-off. In a similar way to road transport biofuels (see below), the increased use of bio-energy has the potential to result in significant reductions in fossil C emissions. However, there are likely to be important trade-offs and these require further research to determine their impact. The way electricity is generated is an important consideration. There are many sectors that use electricity that have the potential to reduce electricity consumption, as in the case of domestic appliances. There are others that could switch to electricity use in place of the direct combustion of a fossil fuel. Examples include electricity used to power trains, ships in port, or aircraft while at stand.

Question 5: In the case of road transport, for different potential mitigation options (e.g. low-emission vehicles) and fuels (e.g. water diesel emulsion, biofuels, diesel fitted with particle traps, H_2 etc.) what are the main trade-off and synergies with regard to emissions that impact on CC and local and regional AQ for the UK? It would be helpful to consider the effect of coupling the technical measure with different traffic management procedures (such as Low Emission Zones (LEZ) and Congestion Charging Zones (CCZ)).

Several end-of-pipe emission control technologies, such as particle filters, while reducing emissions of AQ pollutants lead to small increases (in the region of 1-5%) increase in CO_2 emissions. Some of these technologies also result in the increased emission of other pollutants including N_2O, NH_3 and NO_2. In the case of conventional fuels (petrol and diesel) as used in cars, emissions of BC from diesel vehicles may well result in their impact on climate warming being worse than petrol, despite the inherent efficiency of diesel engines. The clearest benefits to both issues are brought about by a reduction in road transport demand. This can be achieved in a wide variety of ways such as through congestion charging and behavioural change. The impact of emerging road transport fuels such as H_2 or biofuels is difficult to assess and depends on many factors and assumptions. In the case of H_2, its impact depends critically on how it is manufactured and used and the resulting impacts (trade-offs or synergies) vary accordingly. While the use of biofuels offers clear benefits in reducing fossil C emissions, their impact on AQ pollutants is much less clear. Of particular concern is the potential increase in emissions that are difficult to control may result from land use changes, depending on the species and cropping systems and on previous land use. These include emissions of NH_3, N_2O and isoprene. Important trade-offs and synergies are related to transport modes used. A clear trade-off is the increase in short-haul flights at the expense of high speed rail. The opposite (synergy) is also true.

For both questions 4 and 5, it is clear that a consideration of emissions over the fuel or life-cycle is important, and particularly so in the longer-term because of the increased likelihood of emissions being displaced from the point of use (as in the case of biofuels). In general, it is likely that emissions related to land-use changes will become more important in the future. This is because of the attractiveness of using non-fossil C fuels and the fact that many of the emissions associated with these changes are important species (e.g. N_2O for CC, NH_3 for AQ) and can be difficult to control. Furthermore, the issue of the timeframe considered is also important because of ongoing technological change: benefits of synergies identified in the near-term could be different in the longer-term. Finally, there are inherent difficulties in weighing-up the relative importance of impacts to AQ or CC issues.

5.1 Introduction

5.1.1 Aims and scope

370. This chapter focuses on, and its scope is defined by, the two questions posed by Defra shown in Box 5.1. In attempting to answer these questions, several issues become apparent as outlined below. First, much of the information related to potential measures for AQ or CC tends to consider emissions changes rather than impacts. The impact of a particular measure often depends on the environment into which the emission is released e.g. measures resulting in reduced VOC emissions and the effect on tropospheric ozone (O_3) concentrations would be different in 2002 compared with 2030 – 50. These impacts are considered in more detail in Chapter 3. This chapter focuses on the emissions of key pollutants that are known to have AQ and/or CC impacts. These pollutants include NO_X, SO_2, carbon monoxide (CO), VOCs, PM_{10}, $PM_{2.5}$, NH_3, CH_4, N_2O and CO_2.

371. Second, there is an inherent difficulty in assessing the combined impacts of releases of AQ pollutants and climate-active pollutants. Comparisons made between different measures or technologies tend to be relative and also tend to reflect a snapshot in time. An example is the comparison between petrol and diesel fuel, and the increased use of diesel in future. The relative merits of these fuels are constantly changing over time, driven by changes to technology and vehicle emissions legislation, making it difficult to draw firm conclusions for many of the comparisons that can be made between them. It is important therefore to be clear about the comparisons being made.

372. Many of the measures identified in this chapter have a transitory benefit or disbenefit. For example, LEZ that restrict certain (older) vehicle technologies are likely only to have a benefit over a relatively short period of time. This characteristic of different measures makes a quantitative assessment difficult, and possibly misleading. Measures that exhibit these characteristics have been identified where possible. A related issue is the timing of a measure. Some measures might benefit AQ in the near-term, whereas others might be of benefit much later (2030 – 50), when AQ issues may have diminished in terms of their importance. Again, where appropriate this characteristic is identified.

373. The chapter primarily focuses on measures and changes in emissions for the UK, although some consideration is also given to European measures and emissions. To assist in the identification of important measures, the National Atmospheric Emissions Inventory (NAEI) emissions in 2002 and 2020 (the latest year for which

the NAEI considers projections for key pollutants) for detailed emission sectors have been analysed quantitatively. This approach is useful because it directly relates to either existing or proposed measures that will affect UK emissions. For some emerging technologies that could displace existing technologies (e.g. H_2 as a road fuel) there is great uncertainty over the impacts, in part because of the large number of potential ways in which H_2 can be produced. For these types of technologies it is generally only possible to highlight broad patterns of potential impact.

374. Where possible, findings in the literature are used to assess measures and quantitative information given, if available. Often, however, it is necessary to make assumptions or use informed judgement to highlight a particular finding. For example, particle filters used in Heavy Goods Vehicles (HGVs) are known to reduce both particle mass and number and there are measurements that demonstrate this; no measurements exist for their effect on BC emissions. However, given the known characteristics of diesel fuel combustion, it is reasonable to assume that BC emissions would also be reduced.

375. Frequently, comparisons made between the emissions of AQ pollutants for different measures only consider emissions at the point of use e.g. tailpipe emissions from road vehicles. These comparisons are usually sufficient for issues such as urban AQ, where point of use emissions dominate. However, for many comparisons and assessments (particularly for GHG emissions) it is necessary to consider emissions other than those released at the point of use. It becomes necessary therefore to consider emissions over the *fuel cycle* or *life cycle* for different measures. Fuel cycle emissions include all emissions that result from the extraction of the primary fuel through its processing, transport and final use. Life cycle emissions typically consider a much wider range of sources e.g. the emissions due to the manufacture of the infrastructure associated with the particular use of a fuel, product or service.

376. Full life cycle assessments are difficult to do and usually involve intensive research and analysis to cover a single fuel or product. But these will become more necessary as we switch from conventional fuels (e.g. petroleum-based petrol and diesel) to alternative fuels, biofuels from sustainable sources and fuels like H_2 where there are many different production methods. The impact of extracting fuel (e.g. oil and gas), growing the crops (biofuels), processing, refining, transporting, storage and use are important not only for CO_2, but also other air pollutants that affect regional air pollution and CC (e.g. NO_X, VOCs, NH_3, CH_4, N_2O). It is beyond the scope of this report to consider fuel or life cycle emissions in detail, but where they are believed to be important they are highlighted.

377. There is a difference between CC and AQ impacts in terms of the importance of where emissions are released. For AQ impacts, the location point of emissions is important. This aspect of the release of emissions has many different aspects. For example, a ground-level release of an AQ pollutant leads to higher local concentrations than an elevated release of the same amount of material.

Furthermore, the release of an emission into an already polluted area such as a city could be seen as more important than a release of the same emission in a rural location. For AQ, the density of emissions in a region is an important characteristic, which is much less relevant for CC impacts. These effects are potentially important because many measures that might be considered in the future could shift the location of an emission source. One example is the use of CHP in cities, which could shift emissions from rural power stations to urban areas, despite reducing emissions overall. Although this issue has been identified, it is not considered in the main parts of this chapter.

378. There is a vast range of existing or potential measures that could be considered in this chapter across all sectors. The approach adopted therefore is to consider the major sectors separately (energy, transport, agriculture and other). Each sector has then been further broken down into different types of measure: fuel-switching, abatement, demand management and other. Often, measures to reduce emissions of AQ and climate-active pollutants tend to be thought of in terms of 'sectors' or 'technologies'. However, such a categorisation is too restrictive for these impacts. In general, several broad categories of measures can be identified:

- **Conservation**: reducing the use of resources through energy conservation.
- **Efficiency**: carrying out the same activity, but doing so more efficiently, thus reducing resource use and emissions of AQ and climate-active pollutants.
- **Abatement**: the application of a technological approach to reducing emissions.
- **Fuel switching**: substituting a lower emission fuel for a higher emission fuel.
- **Demand management**: implementation of policies or measures which serve to control or influence the demand for a product or service.
- **Behavioural change**: changing the habits of individuals or organisations in such a way as to reduce emissions e.g. travelling by train instead of by air.

379. The latter category potentially includes a vast number of measures that could be effective, but are difficult to quantify. All these measures can be brought about in many different ways including: legislation, fiscal instruments, voluntary agreements and ongoing technological change.

380. The focus of the chapter is on existing or planned measures for the near-term i.e. those measures that have already been adopted or are almost certainly going to be adopted. Measures for the longer-term, such as H_2 fuel cells, are considered in much less detail. For these measures it is generally only possible to identify key themes or pointers. Some important measures are considered as specific examples to highlight potential issues. For these examples, quantified data from the literature have been used where possible. This report does not consider the economic aspects of mitigation, or other important considerations such as ease of implementation or security of supply.

5.1.2 Background to existing policies for air quality and climate change

381. There is a long history of air pollution control in the UK and Europe. Over the past 20 - 30 years national and European legislation has become increasingly sophisticated in the control of AQ pollutants. These policies have recognised that air pollution impacts are wide-ranging e.g. effects on human health, damage to crops and materials etc. At the same time it has increasingly been recognised that many of these impacts are transboundary (e.g. photochemical pollution) and require international cooperation to understand, control and mitigate these impacts. More recently, the growing concern over CC has resulted in the development of policies to mitigate these impacts.

382. However, these two main policy areas have more or less developed independently from one another. Although it has been recognised that these two areas are interconnected, policies in one area have generally not considered impacts in the other. Chapter 1 discusses the evolution of these two policy areas in more detail.

5.1.3 What constitutes a win-win or a trade-off for air quality and climate change?

383. Part of the aim of this chapter is to identify measures that might result in a 'win' for AQ and a 'win' for CC. In addition, AQEG has also been asked to consider where potential trade-offs exist e.g. where a measure might benefit one issue but is detrimental to another. It is important therefore to define what is meant by these concepts.

384. At a basic level, a measure that results in a 'win' for AQ and a 'win' for CC would be one that reduces the emissions of all pollutants that are important to both issues. Since emissions of most AQ pollutants are expected to decline considerably over the next 20 - 30 years, measures that are effective in the near-term are more likely to reduce absolute emissions of pollutants more than measures in the longer-term. Determining a win-win or win-lose measure therefore requires a reference case with which it can be compared to ensure some kind of consistency in the comparisons being made.

385. The difficulty in comparing AQ and climate impacts are summarised in Box 5.2 where the comparison is considered in terms of 'game-theory'.

Box 5.2: Comparison of air quality and climate change – game theory considerations

It is apparent from the discussion of CC and AQ that measures to address one aspect may or may not have benefits for addressing another. The situation is even more difficult because there is no common scale or metric for comparing the effects of CC and AQ. Even for CC there is debate over which metric to use; the metric preferred in this report is the global warming potential (GWP) rather than radiative forcing. Some simple concepts from game theory are used to illustrate the conflicts that arise when comparing strategies for addressing CC and AQ (Binmore, 1992). A specific example of a game relating to power generation is considered for which control of sulphur is the aim of the AQ player, but the climate player sees a potential disadvantage because of the reduction in the cooling effect of sulphate aerosol.

It is assumed that there are two strategies for dealing with particulate, Business as Usual and Tighter Air Quality Regulation to deal with AQ emissions, and two strategies for dealing with CC, Business as Usual and Energy Conservation to reduce GHG emissions.

Relative to the base case of Business as Usual the AQ player would see a positive advantage in Tighter Air Quality Regulation (β), without addressing GHG emissions. The player would also see a positive benefit in Energy Conservation (α) taken to control GHG emissions but also benefiting AQ. Tighter Air Quality Regulation for AQ and Energy Conservation together would produce the greatest benefit. These options can be summarised in a matrix showing outcomes for AQ:

Table 5.2: Outcomes for air quality under various options

		Options for addressing climate change	
		Business as Usual	Energy Conservation
Options for addressing air quality	Business as Usual	V_1	$V_1 + \alpha$
	Tighter Air Quality Regulation	$V_1 + \beta$	$V_1 + \alpha + \beta$

The entries in the table represent outcomes which for the AQ player could be represented as life years gained using a relationship between PM_{10} and human health. The AQ player would prefer the strategy which involved the implementation of AQ regulation and encouraging energy conservation.

Relative to the base case of Business as Usual the CC player would see a disadvantage in Tighter Air Quality Regulation ($-\delta$) from controlling particulate which in the short-term offsets global warming. However there would be a positive benefit in Energy Conservation (γ) taken to reduce GHGs. Tighter Air Quality Regulation for AQ and Energy Conservation together may or may not produce a net benefit depending on the size of the terms γ and δ. These outcomes can be summarised in a matrix showing outcomes for CC:

Table 5.3: Outcomes for climate change under various options

		Options for addressing climate change	
		Business as Usual	Energy Conservation
Options for addressing air quality	Business as Usual	V_2	$V_2 + \gamma$
	Tighter Air Quality Regulation	$V_2 - \delta$	$V_2 + \gamma - \delta$

The interpretation of the outcomes, which are entries in this matrix, are less clear for CC. Ideally they would be lives lost which would permit direct comparison with the outcomes used by the AQ player. In practice they are more likely to be GWP, or radiative forcing.

The science reviewed in this report would give an indication of the relative size and magnitude of the terms in each of the outcome matrices but does not give them in the same units, so direct comparison could not be made without further assumptions. This would not matter if both players favoured the same option (a win-win situation). However in this case the best outcome for the AQ player would be the option in the bottom right-hand corner of Table 5.2, Tighter Air Quality Regulation and Energy Conservation. The best outcome for the CC player would be the option in the top right-hand corner of Table 5.3, Business as Usual for AQ and Energy Conservation for GHG emissions.

This simple example illustrates that the selection of a win-win situation for both players is not always possible and even in simple situations can be rather complicated. In this case without bringing the outcomes for AQ and climate onto a common scale it is not possible to assess the greatest overall outcome from the various 'win-lose' situations. However, the results given in this report go a long way towards assigning magnitudes to the α, β and γ etc. entries. This simple example illustrates how further considerations are required before preferred options in many 'win-lose' situations can be fully evaluated. However this would also bring in policy considerations which are outside the scope of this report.

5.2 UK emissions by major source sector in 2002 and 2020

5.2.1 UK projections and emissions by sector

386. This section briefly reviews UK emissions of different pollutants for 2002 and 2020 and highlights the principal sectors for each pollutant and the changes in total UK emissions from 2002 – 20. By considering the factors driving the emissions changes over this period, some insight can be gained into current or planned measures that affect the emissions of different pollutants. The detailed consideration of emissions change by sector provides one method of identifying potentially important influences on the emissions of AQ and GHGs.

387. There are several factors that drive reductions (or increases) in the emissions of different pollutants. In many sectors these changes in emissions are driven by legislation specifically aimed at reducing the emissions of certain pollutants. Emissions can change due to technology developments, increased efficiency and abatement measures. Emissions can also change because of a change in activity; e.g., the increased use of natural gas at the expense of coal for power generation, the switch from petrol to diesel in the transport sector, or through fiscal measures that encourage a certain behaviour. For some sectors, emissions can decrease despite an increase in activity, as is the case in power generation. However, this is not true for all pollutants, particularly CO_2.

388. An overview of the total emissions of different pollutants for 2002 and 2020 is shown in Table 5.4. The Table shows that emissions of NO_X and SO_2 are predicted to decline significantly over this period (by 45% and 64% respectively). Less significant reductions are predicted for PM_{10}, VOCs and NH_3 (19%, 26% and 10% respectively). By contrast, CO_2 emissions are predicted to decrease by a smaller amount over the same period. An updated version of CO_2 projections from the DTI (2004), which take account of certain measures related to the Climate Change Programme show that CO_2 emissions decrease by 4.0% from 2002 to 2020 from 148.7 to 142.7 MtC which is on top of a 7.5% decrease between 1990 and 2002.

Table 5.4: Total UK emissions for key pollutants for 2002 and 2020 derived from the NAEI. Carbon dioxide projections are from the DTI

Pollutant	2002 emission (kt yr^{-1})	2020 emission (kt yr^{-1})	% change (2002-2020)
NO_X	1581	869	-45
SO_2	1003	360	-64
VOC	1186	883	-26
PM_{10}	161	142	-19
NH_3	301	270	-10
CO_2 as carbon	148700	142700	-4

389. This report uses emission inventory information from a wide variety of sources. Climate models tend to use as their input different emission inventories to those used for regional or local AQ issues. An overview of the different inventories used is given in Annex 3.

390. Data have been extracted from the NAEI to provide a summary of the emissions of key pollutants in 2002 and 2020. Emission projections were available for NO_X, SO_2, PM_{10}, VOC, NH_3 and CO_2. Note, that there are no projections available for CO, CH_4 and N_2O. However, emission projections were available from Entec (2004) for CH_4 and N_2O, and these have been considered.

391. Table 5.5 shows the UK emissions of NO_X in 2002 and 2020 by source sector. For 2020, sectors were chosen that represent at least 75% of the total UK emission of NO_X. The shaded cells shown in Table 5. 5 (and Tables 5. 6 to 5.9) highlight the sectors that make up at least 75% of total UK emissions in 2002. In Table 5.5, it is seen that 19 sectors account for 75% of the total emissions in 2020, whereas in 2002 only 10 sectors are required. These data suggest that for NO_X in 2002 relatively few sectors control the majority of total emissions, and also suggest that measures applied to relatively few sectors could be effective in controlling total UK NO_X emissions. By 2020 however, there is a much broader range of sectors that define 75% of total NO_X emissions. Therefore, to further control NO_X emissions in 2020 (and beyond) would potentially require a broader range of measures. Of particular note are significant reductions in the emissions of NO_X from coal use in power stations (decrease of 89%) and reductions in exhaust emissions from HGVs and cars (65% and 85% decrease respectively).

Table 5.5: Emissions of nitrogen oxides in 2002 and 2020 derived from the NAEI. The shaded cells highlight the sectors that make up at least 75% of total UK emissions in 2002

Sector	Fuel	2002 (kt)	% of total (2002)	2020 (kt)	% of total (2020)	% change (2002 – 20)
Power stations	Coal	287.1	18%	32.0	4%	-89
HGVs	DERV	284.3	18%	98.7	11%	-65
Cars	Petrol	274.3	17%	41.6	5%	-85
Domestic	Natural gas	62.3	4%	60.5	7%	-3
LGVs	DERV	57.3	4%	36.7	4%	-36
Off-shore (own use gas)	Natural gas	53.3	3%	26.2	3%	-51
Other industry (off road)	Gas oil	51.4	3%	37.2	4%	-28
Buses & coaches	DERV	45.7	3%	14.4	2%	-68
Other industry (combustion)	Natural gas	45.4	3%	54.9	6%	21
Power stations	Natural gas	41.5	3%	35.8	4%	-14
Cars	DERV	38.5	2%	74.3	9%	93
Power stations	Landfill gas	33.0	2%	23.0	3%	-30
Cement (Non-decarbonising)		31.6	2%	35.5	4%	12
Coastal	Gas oil	29.2	2%	26.2	3%	-10
Agriculture (power units)	Gas oil	14.8	1%	14.1	2%	-5
Shipping (Naval)	Gas oil	13.9	1%	16.6	2%	20
Refineries (combustion)	Coke	11.7	1%	11.7	1%	0
Autogenerators	Coal	11.0	1%	6.2	1%	-44
Miscellaneous	Natural gas	10.3	1%	12.7	1%	24
Other		184.8	12%	211.0	24.3%	14
Total		1581.4	100%	869.1	100%	-45%

392. Table 5.6 shows the UK emissions by sector for 2002 and 2020 for SO_2. In 2002, four sectors contribute over 75% of total UK emissions, most notably coal use in power stations which contributes 65% of the total. By 2020, there is expected to be a large reduction in total SO_2 emissions of 64%. Furthermore, by 2020 18 sectors are required to describe 75% of the total emissions.

Table 5.6: Emissions of sulphur dioxide in 2002 and 2020 derived from the NAEI. The shaded cells highlight the sectors that make up at least 75% of total UK emissions in 2002

Sector	Fuel	2002 (kt)	% of total (2002)	2020 (kt)	% of total (2020)	% change (2002 – 20)
Power stations	Coal	656.1	65%	65.0	18%	-90
Refineries (Combustion)	Coke	38.6	4%	41.9	12%	8
Autogenerators	Coal	30.1	3%	16.9	5%	-44
Other industry (combustion)	Coal	28.8	3%	17.7	5%	-39
Refineries (combustion)	Fuel oil	26.9	3%	14.2	4%	-47
Cement (Non-decarbonising)		23.1	2%	34.4	10%	49
Power stations	Fuel oil	21.7	2%	0.0	0%	-100
Domestic	Coal	17.1	2%	2.6	1%	-85
Other industry (Combustion)	Fuel oil	11.0	1%	13.2	4%	20
Domestic	Anthracite	10.8	1%	1.9	1%	-83
Coastal	Gas oil	9.9	1%	8.9	2%	-10
Iron and Steel (Sinter Plant)	Coke	9.4	1%	10.9	3%	16
Iron and Steel (Blast Furnaces)		8.6	1%	12.7	4%	47
Brick manufacture (Fletton)		7.9	1%	13.1	4%	66
Chemical industry		7.3	1%	11.0	3%	51
Other industry (Combustion)	Gas oil	6.3	1%	3.7	1%	-41
Domestic	SSF	6.3	1%	1.0	0%	-84
Shipping (Naval)	Gas oil	4.7	0%	5.7	2%	20
Other		77.7	8%	85.0	24%	9
Total		1002.5	100%	359.7	100%	-64

393. UK emissions of VOCs, which exclude CH_4, are expected to decline by 26% from 2002 to 2020. As Table 5.7 shows, a large number (27) of sectors are required to make up at least 75% of total emissions in 2002, which highlights the range of different source types for these pollutants. A comparable number (32) sectors contribute at least 75% of the emissions in 2020. In 2002, petrol use in cars is the most important sector. However, by 2020 emissions from this sector decline by 84% and the chemical industry becomes the most important source of VOCs. In Table 5.7, there is no weighting given to the ozone-forming potential (POCP) of individual VOCs. Ranking by POCP might be quite different from that shown in Table 5.7.

Table 5.7: Emissions of volatile organic compounds in 2002 and 2020 derived from the NAEI. The shaded cells highlight the sectors that make up at least 75% of total UK emissions in 2002

Sector	Fuel/comment	2002 (kt)	% of total (2002)	2020 (kt)	% of total (2020)	% change (2002 – 20)
Cars	Petrol	153.2	13%	24.4	3%	-84
Offshore loading	Crude oil	67.7	6%	28.8	3%	-57
Gas leakage		64.0	5%	38.3	4%	-40
Onshore loading	Crude oil	57.7	5%	37.2	4%	-35
Chemical industry	Chemicals and manmade fibres	50.5	4%	76.1	9%	51
Spirit manufacture: maturation	Whisky in storage	46.2	4%	46.2	5%	0
Other solvent use	Non-fuel solvent	46.0	4%	38.2	4%	-17
Petrol stations (vehicle refuelling)	Petrol (unleaded)	35.0	3%	29.3	3%	-16
Domestic (house and garden)	Petrol	29.2	2%	5.5	1%	-81
Non-aerosol products (automotive products)	Car care products	28.3	2%	37.4	4%	32
Industrial adhesives	Adhesives and sealants	25.9	2%	32.5	4%	25
Aerosols (cosmetics and toiletries)	Aerosols	25.7	2%	29.2	3%	14
HGVs	DERV	24.5	2%	13.1	1%	-47
Decorative paint (retail decorative)	Retail decorative coatings	24.2	2%	15.5	2%	-36
Decorative paint (trade decorative)	Trade decorative coatings	24.0	2%	12.6	1%	-48
Refineries (process)	Non-fuel processes	23.6	2%	23.6	3%	0
Offshore Oil & Gas (Venting)	Non-fuel combustion	20.3	2%	11.8	1%	-42
Industrial coatings (metal and plastic)	Metal and plastic coatings	18.7	2%	24.3	3%	30
Aerosols (carcare products)	Aerosols	17.8	2%	24.4	3%	37
Other industry (off-road)	Petrol	14.8	1%	13.1	1%	-12
Surface cleaning (trichloroethylene)	Cleaning solvent	14.3	1%	2.1	0%	-85
Domestic	Coal	14.0	1%	2.1	0%	-85
Non-aerosol products (cosmetics and toiletries)	Cosmetics and toiletries	13.5	1%	14.8	2%	9
Surface cleaning (hydrocarbons)	Cleaning solvent	13.4	1%	10.0	1%	-25
Mopeds & motorcycles	Petrol	12.4	1%	3.0	0%	-76

Sector	Fuel/comment	2002 (kt)	% of total (2002)	2020 (kt)	% of total (2020)	% change (2002 – 20)
Non-aerosol products (paint thinner)	Population	12.1	1%	13.9	2%	15
Offshore flaring	Non-fuel combustion	12.1	1%	7.7	1%	-37
Non-aerosol products (household products)	Household products	11.6	1%	13.3	2%	15
Industrial coatings (wood)	Wood coatings	10.4	1%	11.0	1%	5
Other food (animal feed manufacture)	Animal feeds	10.0	1%	10.0	1%	0
Aerosols (household products)	Aerosols	9.4	1%	10.7	1%	14
Domestic	Natural gas	8.5	1%	8.3	1%	-3
Other		246.5	21%	215.1	24%	-13
Total		1186	100%	883	100%	-26

394. UK emissions by sector for 2002 and 2020 for PM_{10} are shown in Table 5.8. Like emissions of VOCs, there are a wide range of sources of PM_{10} and 20 sectors are required to explain at least 75% of total emissions in 2002. Emissions from quarrying in 2002 and 2020 are the single most important sector, though its ranking is partly due to the detailed extent by which emissions from other energy, transport and industry sources are disaggregated (e.g. power station emissions by fuel use, road transport by vehicle type etc.). Emissions from the quarrying sector have recently been reviewed by the NAEI in more detail and the estimate for 2002 was reduced by over 50% (to 8.9 kt) making it now the third-ranking source. However, the results from the review have not yet filtered through to revisions in the emission projections, but this is in progress.

395. Emissions from important fossil fuel use sectors decline considerably from 2002 – 20 e.g. domestic coal by 85% and power station coal use by 95%. The decline in coal-related emissions is due to a combination of fuel switching (to natural gas) and the use of emission-reduction technologies.

396. No UK emissions inventory exists explicitly for BC. The NAEI produces an inventory for black smoke (BS). This is a particulate mass emissions inventory weighted by the blackness of the collected particles, but the inventory relies on an old set of BS emission factors (expressed in g BS per unit of fuel consumed) relating to now obsolete sources or fuel quality that may not be applicable to current and future emission sources and fuel types. No projected emissions of BS are available. However, it is likely that total percentage reductions in BC will be greater than for PM_{10}. This is because of the contribution made by sectors such as quarrying, where emissions of PM_{10} are important, but not BC. Emissions of BC are mostly related to fossil fuel combustion, which as shown in Table 5.8, declines considerably from 2002 – 20. Moreover, PM from diesel combustion is blacker than PM from coal combustion, so changes in diesel PM emissions will have a larger weighting in projections of BC than say changes in coal combustion PM emissions. There is a need for a BC inventory to be developed. This could be one

related to the PM inventory with a (possibly) time-varying 'blackness'-weighting applied or alternatively expressed as a speciated-PM inventory, speciated according to the elemental C content of the PM.

Table 5.8: Emissions of PM_{10} in 2002 and 2020 derived from the NAEI. The shaded cells highlight the sectors that make up at least 75% of total UK emissions in 2002

Sector	Fuel/comment	2002 (kt)	% of total (2002)	2020 (kt)	% of total (2020)	% change (2002 – 20)
Quarrying[1]	Total aggregate	20.6	13%	30.7	22%	49
LGVs	DERV	12.2	8%	6.6	5%	-46
Domestic	Coal	10.4	6%	1.6	1%	-85
Power Stations	Coal	7.8	5%	0.4	0%	-95
HGVs	DERV	7.8	5%	1.3	1%	-83
Domestic	Wood	7.1	4%	11.7	8%	64
Broilers	Housed livestock	6.2	4%	6.7	5%	8
Cars	Brake & tyre wear	5.9	4%	7.5	5%	26
Cars	DERV	5.8	4%	4.5	3%	-23
Other industry (off-road)	Gas oil	4.9	3%	2.8	2%	-43
Construction		4.6	3%	6.7	5%	44
Other industry (Part B processes)		4.6	3%	7.6	5%	66
Domestic	Natural gas	4.2	3%	1.0	1%	-76
Other industry (Combustion)	Coal	3.8	2%	0.9	1%	-76
Domestic	Anthtracite	2.9	2%	0.5	0%	-83
Agriculture	Arable farming	2.4	2%	2.5	2%	3
Poultry	Housed livestock	2.4	1%	2.3	2%	-4
Brick manufacture (non Fletton)	Non-Fletton bricks	2.3	1%	2.9	2%	25
Agriculture	Straw	2.2	1%	2.4	2%	9
Domestic	SSF	2.2	1%	0.4	0%	-84
Iron and Steel (Sinter Plant)	Iron production	2.1	1%	2.8	2%	32
Cars	Petrol	1.9	1%	0.7	1%	-62
Other industry (Combustion)	Natural gas	1.7	1%	0.5	0%	-70
Agriculture (power units)	Gas oil	1.7	1%	1.6	1%	-5
HGVs	Brake & tyre wear	1.5	1%	1.8	1%	18
Other		31.2	19%	33.7	24%	8
Total		161	100%	142	100%	-19

[1] Note that the 2002 figures for quarrying are from the 2002 version of the NAEI. The 2003 version has revised the PM_{10} estimate down to 8.9kt, but these changes have not yet filtered through to amendments in the projected emissions from quarries.

397. UK emissions of NH_3 are expected to decline by 10% from 2002 – 20. Only four sectors are required to contribute to at least 75% of total emissions both in 2002 and 2020, as shown in Table 5.9. Emissions of NH_3 are dominated by animal wastes from the agricultural sector.

Table 5.9: Emissions of ammonia in 2002 and 2020 derived from the NAEI. The shaded cells highlight the sectors that make up at least 75% of total UK emissions in 2002

Sector	Fuel	2002 (kt)	% of total (2002)	2020 (kt)	% of total (2020)	% change (2002 – 20)
Cattle (wastes)	Manure & excreta	133.6	44%	109.8	41%	-18
Agricultural soils		36.9	12%	34.2	13%	-7
Poultry (wastes)	Manure & excreta	35.0	12%	43.2	16%	24
Pigs (wastes)	Manure & excreta	26.1	9%	23.7	9%	-9
Other		69.0	23%	58.8	22%	-15
Total		301	100%	270	100%	-10

398. UK emissions of CO_2 in 2002 are dominated by the combustion of coal, natural gas, petrol and diesel. The NAEI produces the historic time-series of emissions of CO_2 broken down by sector using fuel consumption data provided by DTI from published energy statistics. These show that eight main sectors in 2002 account for at least 7% of total UK emissions. However, the UK's official CO_2 emission projections are produced by the DTI itself, but to a less detailed level of disaggregation. This makes it difficult to compare the detailed NAEI figures for 2002 with the DTI figures for 2020 on a consistent basis. Table 5.9 shows the CO_2 emissions for 2002 and 2020 at the level of sector detail produced by the DTI from the latest energy projections taking into account UK Climate Change Policy. The same energy projections are the source of the NAEI emission projections for other pollutants from energy, industry and non road transport sources.

Table 5.10: Emissions of carbon dioxide (as carbon) in 2002 and 2020 derived by DTI

Sector	2002 (MtC)	2020 (MtC)	% change (2002 – 20)
Agriculture	0.47	0.51	8
Business	25.65	25.66	0
Energy Supply	57.10	44.05	-23
Industrial Process	3.25	7.01	115
Public	3.25	3.08	-5
Residential	23.69	20.85	-12
Transport	35.03	41.37	18
Waste Management	0.28	0.18	-36
Total	148.72	142.71	-4%

399. In the power generation sector, there is a 50% decline in coal CO_2 emissions from 2002 –20 and a 39% increase in CO_2 emissions derived from natural gas combustion, driven by fuel switching from coal to natural gas, based on the NAEI. Compared with the 50% reduction in CO_2 from coal use in power stations, the emissions reduction in other pollutants for this sector are much greater (NO_X 89%, SO_2 90%, and PM_{10} 95%), which suggests that other abatement strategies effectively reduce the AQ pollutants. The rise in CO_2 emissions from the transport sector between 2002 and 2020 offsets half the reduction in CO_2 emissions from the power generation sector.

400. There are no detailed emission breakdowns for CH_4, N_2O and CO for 2020 and Tables 5.13 to 5.15 therefore only consider 2002. However, a report by Entec (2004) has recently considered projections of CH_4 and N_2O for different sectors.

401. Emissions of CH_4 in 2002 were dominated by a wide range of sources from different sectors. Important sectors include landfill, agriculture and fossil fuel sources (CH_4 from deep-mined coal and from gas leakage in the natural gas distribution system). Entec (2004) show that CH_4 emissions are expected to decline by 36% from 2196 to 1411 kt from 2001 – 20. The decreases in CH_4 derive from many factors, including: an increase in the burning of renewable energy sources, particularly landfill gas, sewage gas and poultry litter; the progressive uptake of more advanced 'Euro' emission standards for petrol cars; and an expected decrease in the quantity of coal produced and the replacement of cast-iron gas pipes with polyethylene in the gas distribution network. Reductions in oil and gas production and numbers of cows and sheep also contribute to the decline.

Table 5.11: UK methane emissions in 2002

Sector	Fuel	2002 (kt)	% of total (2002)
Landfill		420.0	20%
Non-dairy cattle (enteric)		349.1	17%
Gas leakage	Natural gas supply	338.6	16%
Dairy cattle (enteric)		270.0	13%
Deep mined coal	Coal produced	220.7	11%
Other		499.9	24%
Total		2098.3	100%

402. Most of the emissions of N_2O in the UK derive from fertiliser use (57% of the total), as shown in Table 5.12. Entec (2004) suggest that total UK emissions of N_2O of 137 kt will not change from 2001 – 20. However, there are expected to be changes within certain sectors. For example, from 2001 – 20 emissions from the transport sector are projected to increase by 6.2 kt, whereas emissions from agricultural soils are expected to decrease by 10.7 kt (Entec, 2004).

Table 5.12: UK nitrous oxide emissions in 2002

Sector	Fuel	2002 (kt)	% of total (2002)
Agricultural soils	Fertiliser	75.1	57%
Cars	Petrol	10.9	8%
Agricultural soils	Crops	10.1	8%
Nitric acid production	Acid production	7.8	6%
Other		28.4	21%
Total		132.3	100%

403. Emissions of CO are dominated by road transport. This was responsible for 59% of UK CO emissions in 2002, with 50% coming from petrol cars alone. This is in spite of the fact that the majority of cars in the fleet are fitted with catalytic converters. Emissions of CO have not been projected for sectors other than road transport. Emissions from this sector are declining rapidly and by 2020 are predicted to be 80% lower than 2002 levels due to the further penetration of new vehicles meeting tighter emission regulations.

Table 5.13: UK carbon monoxide emissions in 2002

Sector	Fuel	2002 (kt)	% of total (2002)
Cars	Petrol	1609.1	50%
Other industry (off-road)	Petrol	282.9	9%
Iron and steel (sinter plant)	Coke	250.9	8%
LGVs	Petrol	97.8	3%
Domestic (House and garden)	Petrol	94.1	3%
mopeds & motorcycles	Petrol	91.0	3%
Domestic	Wood	89.3	3%
Other		722.7	22%
Total		3237.7	100%

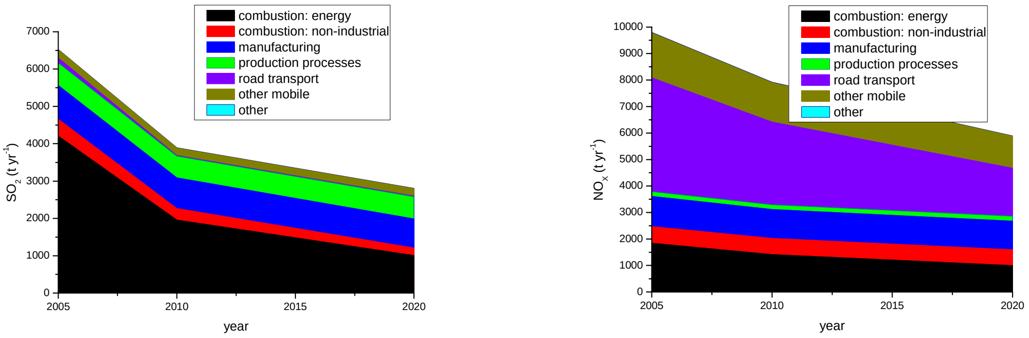
5.3 European emission projections

5.3.1 2000 – 20

404. The International Institute for Applied Systems Analysis (IIASA) have compiled European emission projections for NO_X, SO_2, non-methane volatile organic compounds (NMVOCs), PM_{10} and NH_3 using the Regional Air Pollution and Information and Simulation (RAINS) model (http://www.iiasa.ac.at/web-apps/tap/RainsWeb/). The RAINS model provides two scenarios for the energy sector – with climate policies and without climate policies. The comparisons in the following text are for the RAINS scenario *with* CC policies.

405. For the EU25 as a whole and for all pollutants, a decline in emissions is expected in the years up until 2020. However the decline is more striking for SO_2 in which a 57% reduction is forecast between 2005 and 2020 than for NH_3 in which only a 4% reduction is forecast over the same time period.

Figure 5.1. Projected EU25 emissions according to IIASA estimates a) sulphur dioxide, b) nitrogen oxides, c) particulate matter PM_{10}, d) non-methane volatile organic compounds and e) ammonia

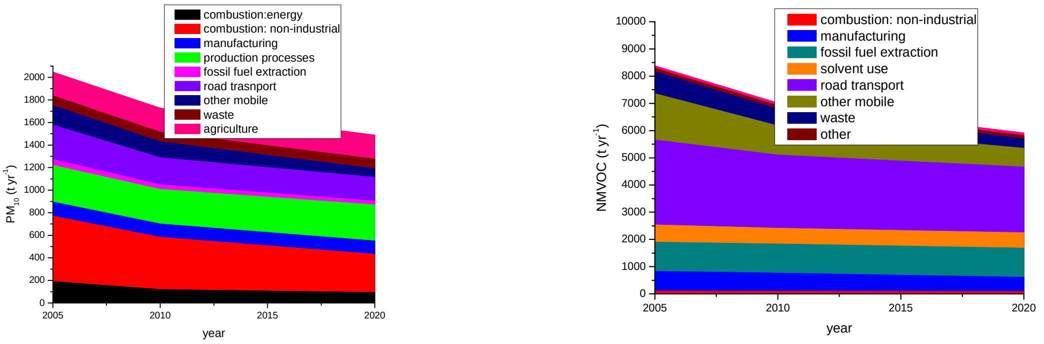


a) Sulphur dioxide

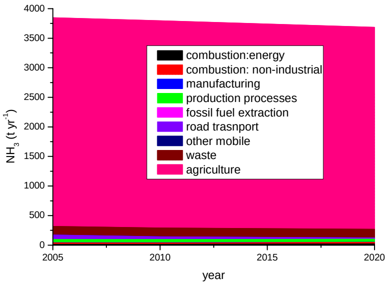
b) Nitrogen oxides

c) Particulate Matter PM_{10}

d) Non-methane volatile organic compounds



e) Ammonia



406. For SO_2, the majority of the reduction is expected in the power station and combustion sector in which switching to lower sulphur fuels is the main driver (see Figure 5.1a). Nitrogen oxide emissions for the EU25 are predicted to decline by approximately 40% between 2005 and 2020. The main reasons for the forecasted decline are due to NO_X abatement systems such as SCR being fitted to power stations and tighter regulations applying to road vehicles (See Figure 5.1b). For PM_{10} (Figure 5.1c), the majority of the decline is expected to come from the non-industrial combustion sector primarily as a result of switching to cleaner fuels such as natural gas. Power stations and transport are also expected to show a decline.

407. For NMVOCs, whilst a decline of 29% is predicted overall between 2005 and 2020, some sectors such as production processes show an increase in emissions over this period. Large decreases in emissions are expected in the transport and waste treatment sectors (Figure 5.1d).

408. For NH_3, decreases are expected in the road transport and agricultural sectors. However, emissions from power stations and combustion in manufacturing are forecast to increase slightly (Figure 5.1e).

5.3.2 2020 and beyond

409. The NAEI does not make UK emission forecasts beyond 2020 due to projected activity statistics only being available up until this date. The exception is for road transport for which emission projections are calculated to 2025. In addition there are large uncertainties associated with emission projections that far into the future. The RAINS model does however produce forecasts for the UK for NO_X and SO_2 up to 2030. Between 2020 and 2030 RAINS forecasts an increase in NO_X emissions of 6.2% and for SO_2 an increase of 0.5%. Applying this percentage increase to the UK's own emission projections would lead to NO_X and SO_2 emissions in 2030 of 923 kt and 362 kt respectively. For NO_X emissions, the increase can primarily be attributed to an increase in activity in the power station and transport sectors outweighing any emission reductions achieved in earlier years. For SO_2, little change in emissions is expected between 2020 and 2030. A slight increase in emissions is expected in the industrial sector but a decline is expected in the domestic sector.

5.4 Measures for the energy sector

5.4.1 Power generation

5.4.1.1 Abatement

410. The abatement of emissions from power generation most commonly refers to methods to reduce emissions of SO_2 and NO_X. In the case of SO_2, abatement is achieved through FGD. A typical FGD plant consumes about 2% of the electrical power output of the power station to which it is fitted, mainly to drive large fans which blow the flue gases through the FGD system (EHMS, 2004). Carbon dioxide is also formed through wet scrubbing with limestone through the reaction $CaCO_3 + SO_2 = CaSO_3 + CO_2$. Assuming a typical sulphur content of 1.6% for UK coal, this would lead to an additional 1% CO_2 i.e. a total of approximately 3%. Therefore FGD results in a trade-off where CO_2 emissions increase. There might also be a small CO_2 penalty for controlling NO_X emissions in some abatement approaches used.

411. There is increasing interest in CO_2 capture and storage from large point sources as a way of reducing future CO_2 emissions. In the UK, storage could be in depleted (or near depleted) oil or gas reservoirs, saline aquifers and unmineable coal seams (DTI, 2003). In fact, pumping CO_2 into oil reservoirs that are almost depleted could be an effective way of recovering oil and sequesting CO_2. There are several methods to capture CO_2 such as post combustion capture, pre combustion capture and oxyfuel combustion (DTI, 2003). The preferred post-combustion technique at present is to scrub the flue gas with a chemical solvent. The flue gas

needs to be cooled and, for coal and oil-fired plant, treated to remove reactive impurities. These impurities include SO_2, NO_X and PM. This process therefore requires that AQ pollutants are removed to operate efficiently and could be considered as a win-win.

412. With current processes a large amount of energy is needed to regenerate the solvent and to compress the CO_2 for transport, which significantly reduces the net electricity output and efficiency of the plant. Recent work has suggested that CO_2 can be removed with an efficiency of 85-95% with power plants requiring 10-40% more energy[1] (Metz *et al*., 2005a). Although the reduced efficiency would not lead to a net increase on CO_2 emissions it would be expected that other AQ and climate-active emissions would increase along the fuel chain simply because of the loss in overall efficiency at the power plant. The more inefficient use of finite fossil fuel resources might also be an important issue to be considered.

5.4.1.2 Fuel switching

413. Fuel switching is an important issue for this sector. This is because power generation represents the largest single source of CO_2 in the UK and is also a significant source of other key pollutants including NO_X, SO_2 and CH_4 (through fuel-chain mined coal or CH_4 leakage). The electricity generating sector has changed markedly over the past 30 years. In 1970, conventional thermal power stations produced 88% of the electricity supplied (DUKES, 2004). Output from these stations rose, peaked in 1990 before falling back due to the use of other fuels and technologies. First, there was the development of nuclear generation, which supplied only 10% of total electricity in 1970 but by 1997 accounted for 27%. Second, there was the growth of combined cycle gas turbine stations (CCGTs) which overtook nuclear in 1997 and in 2002 supplied 37.5%, falling back to 34% in 2003 because of high gas prices. Indeed, the decrease in natural gas use due to high gas prices illustrates another important set of effects related to economic factors.

414. Given the direct and indirect importance of emissions from electricity generation in the UK, projections by fuel type are summarised in Table 5.14. The Table shows that significant changes in the electricity generating mix are expected by 2020. Coal use is expected to decline by 52% from 2000 – 20 and will only account for 15% of electricity generation in 2020. The use of gas in power generation, which was the single largest sector in 2000 at 37% of the total is expected to increase considerably by 77% from 2000 – 20 and will account for 59% of the electricity generating mix in 2020. Also important is the increased use of renewables, which only accounted for 3% of the total in 2000, but will account for 15% of the total in 2020, and the decreased use of nuclear (from 23% of the total in 2000 to 7% in 2020). Overall, there is a shift from high-C to low (or no) C fuels. Despite an

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[1] The range reflects the use of different power plant. For natural gas combined cycle plants, the range is 11 - 22%, for pulverised coal plants 24 - 40%, and for integrated gasification combined cycle plants 14 - 25%.

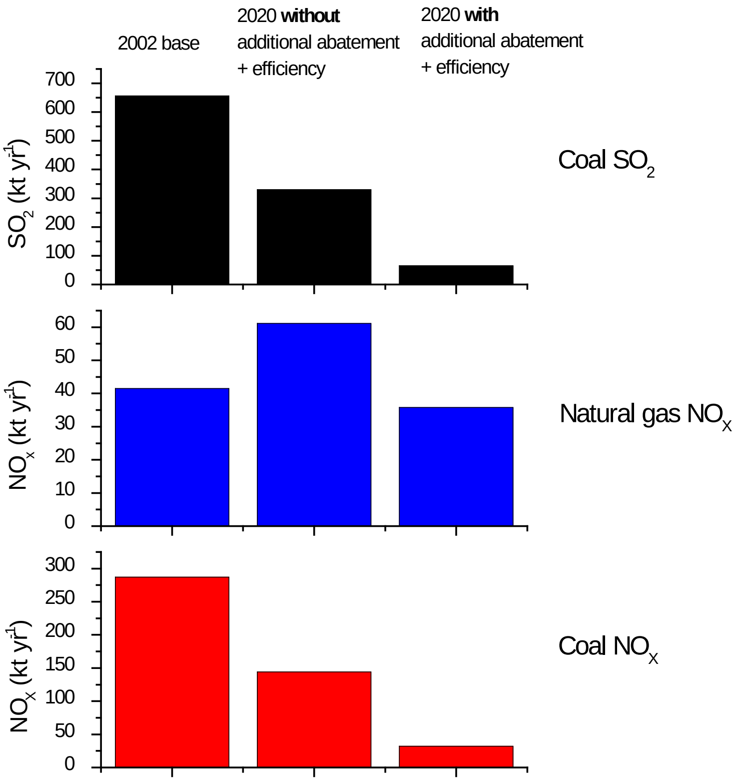
increase in electricity generation of 10% from 2000 – 20, C emissions from this sector are expected to decline by 23% from 2002 – 20, based on DTI figures (Table 5.10).

Table 5.14: Electricity generation in 2000 and projections for 2020 (DTI, 2004)

Fuel	2000 (TWh)	2000 (%)	2020 (TWh)	2020 (%)	% change, 2000 – 20
Coal	119.9	35	57	15	-52
Oil	2.1	1	2	1	-5
Gas	127.0	37	225	59	77
Nuclear	78.3	23	27	7	-66
Renewables	10.1	3	58	15	474
Imports	14.3	4	10	3	-30
Pumped supply	2.6	1	3	1	15
Total	346.3	100	382	100	10

415. The effect of fuel switching on AQ pollutants is complicated by the increased use of abatement measures (see Section 5.4.1.1). Figure 5.2 shows the effect that abatement measures have on electricity generation emissions in 2020, with base case emissions for 2002 also shown. Electricity generation emissions through coal combustion are expected to decline in 2020 through the switch to increased use of natural gas (shown by the middle bar in each plot). Consequently, without additional abatement, emissions of NO_X from natural gas combustion are shown to increase. However, for both fuels, additional abatement measures and efficiency improvements lead to reductions in both SO_2 and NO_X.

Figure 5.2 Effect of abatement and efficiency improvements on power generation emissions of sulphur dioxide and nitrogen oxides from coal and natural gas



416. The move from coal to natural gas use in power generation will also result in the decline of CH_4 from deep-mined coal. Although the natural gas fuel cycle is also an important source of CH_4 emissions in the UK (16% of UK emissions in 2002), it is unlikely that absolute CH_4 emissions would increase substantially because most of the CH_4 emissions from the natural gas fuel cycle are derived from the low-pressure distribution system and not the gas supply system to power stations. Emissions of CH_4 from the extraction of natural gas would probably increase however.

5.4.1.3 Combined Heat and Power

417. Combined Heat and Power (CHP) offers a high efficiency method of generating electricity and heat (co-generation) and has potential benefits for both AQ and CC. However CHP does require that there is a local demand for heat, which could be e.g. an industrial process or residential district heating. Combined heat and power can increase the overall efficiency of fuel use to more than 75%, compared with around 40-50% from conventional electricity generation (Defra, 2004). In addition, local electricity supply can also avoid transmission and distribution losses. Traditionally CHP has been used for large-scale applications (several hundred kW of electricity generated). However, there is also the potential for the development of micro-generation CHP units, which could replace domestic boilers. Combined heat and power is also a versatile technology that can use a variety of feedstocks, including conventional fuels such as natural gas, but also municipal waste and biomass (including biogas). The more efficient use of fuel results in reduced C and AQ emissions compared with conventional electricity generation. The impact on AQ pollutants will however depend on the feedstock. As outlined in Section 5.7.1, the incineration of municipal wastes can lead to trade-off because of increased emissions of AQ pollutants compared with a landfill option.

5.4.1.4 Integrated Gasification Combined Cycle

418. Integrated Gasification Combined Cycle (IGCC) plants offer the potential for the efficient combustion of coal, with efficiencies 37-43% (POST, 2005). In an IGCC plant, coal is fed into an enclosed pressurised reactor, which produces syngas (a mixture of CO, H_2, a small amount of CO_2) and pollutants such as sulphur compounds. This raw syngas is cooled and 'scrubbed' several times to remove pollutants such as sulphur, which are potentially corrosive. Integrated Gasification Combined Cycle plants can be fired with different coals or oil-derived feedstock such as heavy oil and tar, as well as with biomass and waste. In addition, SO_2 removal ranges from 90 to 99% and NO_X emissions are generally 70 to 80% lower than those from traditional coal-fired power plants. Particle emissions are usually below the relevant emission limits for large combustion plants. The IGCC technology is considered as a 'clean coal technology' and has advantages over existing coal techniques used in the UK. Worldwide, there are only four coal IGCC plant operating and none are in the UK (POST, 2005). The IGCC plants can also be designed to capture CO_2, where the CO_2 and H_2 can be separated using a solvent-based process.

5.4.1.5 Bio-energy

419. There are many potential biomass sources of fuel that can be used for the production of electricity and heat (RCEP, 2004). The principal interest in the use of biomass is the potential to reduce fossil fuel-derived CO_2 emissions, rather than the reduction of AQ pollutants. Fuel types include wood chip (e.g. from willow or poplar trees) and straw, which are sometimes referred to as energy crops. The combustion of these fuels would lead to a range of AQ pollutants and significant quantities of ash, which can also contain pollutants of concern (RCEP, 2004). The calorific value of most energy crops is lower than fossil fuels and so the combustion efficiency can be low. For this reason, there is interest in also using the heat generated by the combustion of these fuels in CHP (see Section 5.4.1.3). The use of CHP would require a local demand for heat and would therefore often require these plant to be sited close to areas of demand, such as residential housing. The release of AQ pollutants under these circumstances is more important because of the increased risk of exposure.

420. The growing of some bio-energy sources would result in the emission of other important species such as isoprene, as is the case for poplar and willow trees. Little attention has been given to the potential of different bio-energy sources and cropping systems to produce such emissions, but this is potentially an important trade-off that requires further study. The transport of energy crops to power plant would also represent a source of climate-active and AQ emissions. Further consideration of the forestry sector is given in Section 5.6.3.

421. In addition to solid feedstocks, bio-energy is also available via biogas sources. The term biogas is used to refer to gases created by the anaerobic fermentation of biological materials, whose main constituents are CH_4 and CO_2. Biogas is produced mainly by sludge digestion in the tanks of sewage treatment plants (sewage gas), and anaerobic fermentation of agricultural waste and organic residues, and in landfill gas. Biogas has many potential applications including its use in CHP and road transport. The use of biogas is closely related to some of the considerations in Section 5.7.1. In common with solid biomass feedstocks, the benefit of using biogas lies mostly with the reduction in fossil C emissions rather than reduction in AQ pollutants.

422. Overall, however, there is a lack of studies that report the combined effect of the use of bio-energy in reducing CO_2 emissions but potentially increasing other climate-active and of AQ emissions.

5.4.2 Domestic

423. The domestic sector represents an important direct source of CO_2 and NO_X. Historically, this sector has also been important for emissions of PM and SO_2 because of the wide-spread use of coal. However, coal use in this sector has declined dramatically in recent decades and will continue to decline from 2002 – 20 in favour of using natural gas. The fuel switching from coal to natural gas leads to a win-win for emissions of CO_2, SO_2, NO_X and PM. Measures that result in less energy use in this sector, such as improved thermal insulation, would also lead to a win-win.

424. The domestic sector also represents an important indirect source of emissions, through electricity use. In 2004, the domestic sector accounted for 34% of electricity consumption in the UK (DUKES, 2004). There has also been a move away from coal to natural gas use in this sector, thus leading to win-win. Reduced energy use, through improved efficiencies for domestic appliances, energy efficient lighting etc. would also represent a win-win.

425. It should be noted however, that efficiency improvements are not always necessarily associated with reductions in emissions. This is because a lower cost of carrying out a particular activity could encourage the increased use of it. Furthermore, effective increases in income can encourage the consumption of other goods and services. Indeed, Brännlund *et al*. (2006) shows that efficiency improvements can under some circumstances be associated with *increases* in emissions. A consideration of environmental economics is therefore likely to be important in assessing the efficacy of improved efficiency measures on all pollutant emissions.

5.5 Measures for the transport sector

5.5.1 Road transport

5.5.1.1 Abatement

426. There are many abatement measures for controlling emissions from road vehicles. Most of the focus is the control of emissions of NO_X and PM. Some of these measures require 'end-of-pipe' technologies e.g. catalysts and particle filters. However, an important and closely related issue is fuel quality, and in particular the sulphur content of fuels. Many abatement technologies fitted to vehicles require fuel with a very low sulphur content, to prevent poisoning of catalysts. New fuel formulations often lead to an increase in energy intensive operations at refineries, and consequently increased emissions. Hence, there are some potentially interesting trade-offs in this section.

Fuel sulphur content and refinery emissions

427. Although sulphur in fuel is a pollutant in its own right, in recent years it has become increasingly necessary to reduce fuel sulphur content to enable the use of pollution control equipment such as catalysts. Reducing petrol and diesel fuel sulphur content is, however, an energy intensive process. Producing sulphur-free fuels (assumed to be < 10 ppm sulphur), and meeting other fuel quality objectives is thought to lead to 5-10% additional refinery CO_2 emissions (Kavalov and Peteves, 2004). The reduction in fuel sulphur would therefore result in a trade-off between reducing AQ pollutants whilst increasing CO_2 emissions. These statements refer to off-road machinery emissions as well as road transport emissions.

428. It has already been necessary to reduce the sulphur content of road fuels to allow the advance of technologies like diesel particulate filters (DPF) for PM control. In the longer-term, further reducing sulphur in both diesel and petrol could provide an effective method for making further reductions in emissions of all major pollutants from the entire vehicle fleet. Sulphur-free petrol enables the uptake

of technologies being developed to cut emissions of CO_2 from new passenger cars. Lean-burn petrol engine designs can reduce fuel consumption by 15–20% (König *et al*., 2001). However, to avoid a trade-off between higher fuel efficiency and increased NO_x emissions, lean-burn engines will require new after-treatment technology. Nitrogen oxides storage traps, which appear to be the most efficient existing NO_x control technology for lean-burn engines, are much more affected by fuel sulphur than three-way catalysts (Blumberg *et al*., 2003). Sulphur-free fuels allow NO_x storage traps to be used, increasing NO_x control to over 90% in both diesel and petrol vehicles (Blumberg *et al*., 2003). This enables more fuel-efficient engine designs, thus leading to reduced vehicle CO_2 emissions. Despite likely increases in refinery CO_2 emissions through the increased energy used to make sulphur-free fuels, these emissions could be offset through the introduction of more efficient vehicles.

Control of petrol and diesel vehicle emissions

429. The introduction of three-way catalyst-equipped petrol cars in the early 1990s initially caused a slight penalty (1-2%) in CO_2 emissions. This would have been in part due to the requirement for engines to operate at stoichiometry, rather than slightly lean, in order for the three-way catalyst to be effective. This is borne out by the factors used in the NAEI, based on tests on in-service Euro I vehicles. However, this was only a temporary trend as further improvements in engine technology and vehicle design (e.g. improved body aerodynamics to reduce wind resistance) during the 1990s led to reductions in CO_2 emissions from cars of the same engine size. Test data suggest as much as a 5% reduction in CO_2 emissions from Euro I to Euro II cars, with further reductions indicated between Euro II and Euro III. Improvements in fuel economy and CO_2 emissions for heavy duty diesel vehicles have been restricted by the need to restrain NO_x emissions from the engines of these vehicles which have not been possible to control by tailpipe after-treatment technologies. Emerging NO_x control technologies for diesel exhausts such as SCR systems may remedy this.

430. Selective Catalytic Reduction uses aqueous urea as a means of producing NH_3, which can reduce (in both senses of the word) NO_x emissions. Selective Catalytic Reduction systems have been common in stationary combustion appliances for many years. Used in vehicles, SCR is effective in controlling emissions of NO_x, with suggested reductions of around 65% (Kollamthodi, 2005). Emission by-products can include NH_3 and N_2O. However, SCR allows engine manufacturers to optimise engines for performance and fuel efficiency, which leads to increased engine-out emissions of NO_x, but which can be effectively controlled by SCR. Fuel savings of around 3-5% have been reported (CONCAWE, 1999; Ricardo, 2005). In this respect, SCR use on vehicles could lead to a win-win. However, potentially important increases in the emissions of N_2O could more than offset this apparent advantage in terms of GHG emissions. Ammonia emissions from mobile SCR units is expected to be controlled by manufacturers and estimates by netcen suggested that, at worst, an additional 2 kt of NH_3 could be emitted by NH_3 slip from HGVs equipped with SCR compared with a total projected emission estimate from all sources of 270 kt in 2020.

431. An alternative method to SCR for controlling emissions of NO_X is to use exhaust gas recirculation (EGR) with a particle trap. Using EGR has a CO_2 penalty of about 2% but reduces NO_X emissions by around 45% (Kollamthodi, 2005). Particle filters are effective in controlling PM emissions and reduce particle mass emissions by > 95% (Richards *et al*., 2004). However, some types of filter (the catalytic DPF) can lead to increased emissions of NO_2 (AQEG, 2004).

432. Diesel particulate filters are being increasingly used as an end-of-pipe technology for reducing PM emissions from diesel vehicles. Some new vehicles are equipped with them by the manufacturers, while some existing vehicles in the fleet (especially captive fleets, such as buses) are being retrofitted with DPFs. Very stringent future emission regulations by the European Commission are likely to set such tight limits on PM emissions from diesel vehicles at the stage of type approval, that DPFs will effectively become mandatory for all new diesel vehicles within the next decade. The effect a DPF has on fuel consumption and CO_2 emissions is variable, and depends on the type of DPF fitted and the load conditions experienced by the engine. The main design feature that affects the response of CO_2 is the strategy used by the manufacturers to regenerate the filter. The most commonly used types with oxidation catalyst systems generally incur a small CO_2 penalty of a few percent. For a 2010 light duty diesel engine with an oxidation catalyst and particulate filter it has been estimated that there is a 7% fuel penalty over a baseline Euro IV vehicle (Ricardo, 2005). The Ricardo report also suggests that in 2010 – 15 the use of lean NO_X traps (LNT) on petrol vehicles would lead to a 7% improvement in fuel economy. Conversely for light duty diesel vehicles using four-way catalysts or LNT with a DPF, there will be an 8 – 9% fuel penalty over Euro IV vehicles. For heavy duty diesel vehicles (in 2013) the use of LNT with DPF is also thought to result in a fuel penalty of 7.5%. Without the introduction of limits on CO_2 emissions, it seems likely that future diesel engines will be associated with increased fuel and CO_2 penalties. Some methods using organometallic fuel additives to regenerate the filter via a fuel-borne catalytic process may have a small CO_2 benefit. There may also be differences between whether the system is a retrofit one or a dedicated system fitted to the vehicle when new.

433. Recent work by netcen (Defra, 2006) considered several scenarios for the abatement of vehicle emissions, both by introducing tighter European car and HGV emission standards (Euro V and VI) affecting new vehicles, and by implementing retrofit programmes to reduce emissions from existing vehicles in the fleet. The scenarios were defined by Defra in consultation with DfT and built upon evidence from recent research programmes (e.g. by Ricardo, 2005) on the effect different types of technology introduced to curb NO_X and PM emissions have on CO_2 emissions.

434. One of the scenarios considered the impact of retrofitting PM-controlling systems on HGVs and buses in a scheme that was rolled in gradually from 2006 to a specific target rate in 2010 at which point the scheme was terminated. The scheme was assumed to apply equally to all pre-Euro I to Euro IV vehicles. Three scenarios were modelled.

- 65% of pre-Euro I to Euro IV HGVs and buses retrofitted by 2010 with a DPF assisted with a Fuel Borne Catalyst. This was NO_X neutral, reduced PM by 95% and led to a fuel efficiency benefit of 1%.

- 20% of pre-Euro I to Euro IV HGVs and buses retrofitted by 2010 with a Pt-coated DPF. This was NO_X neutral, reduced PM by 95% and led to a fuel efficiency penalty of 1%.
- 35% of pre-Euro I to Euro IV HGVs and buses retrofitted by 2010 with a Pt-coated DPF. This was NO_X neutral, reduced PM by 95% and led to a fuel efficiency penalty of 1%.

435. Clearly this scheme is overall NO_X neutral, PM beneficial and either results in a win-win benefit with CO_2 (case 1) or results in a trade-off with CO_2 (cases 2 and 3).

Water-diesel emulsion

436. Water-diesel emulsion (WDE) is a water-emulsified diesel fuel that is designed to reduce emissions of NO_X and PM from diesel vehicles. On vehicles with no particle filters, reduction in NO_X and PM_{10} of 13% and 25% have been identified (Kollamthodi, 2005). There is some evidence to suggest that VOCs increase by using WDE. The California Environmental Protection Agency (CEPA) reports an increase of 87% in reactive organic gases (ROG) compared with conventional diesel, although these results are based on limited testing (CEPA, 2004). The CEPA also report that BC emissions could be considerably less compared with conventional diesel fuel, although this has not been quantified, and that there could be a slight increase in engine efficiency (CEPA, 2004). Overall, WDE is a measure which has most benefit for AQ issues, while more work is required to quantify the potential benefits to CC.

Hybrid vehicles

437. Hybrid vehicles that combine an internal combustion engine with an electric propulsion system offer significant benefits for the reduction of CO_2 emissions and AQ pollutants. There are many potential configurations of hybrid vehicle that could be adapted for a range of different driving conditions. However, hybrids have most benefit when a vehicle spends a large proportion of its time stationary or in congested stop-start conditions, such as in urban areas. This is because hybrids use electricity under these conditions and little or no power is required, unlike internal combustion engines that are at their most inefficient. These vehicles therefore offer the potential to reduce CO_2 and AQ pollutants substantially, particularly in urban areas, and as such represent a win-win.

438. Some indication of the potential benefits of hybrids on vehicle emissions can be gained from their performance over legislated emission test cycles. These test cycles offer a consistent way in which to compare vehicle CO_2 emissions. The Vehicle Certification Agency (VCA) lists the emissions performance of cars over legislated test cycles to inform potential buyers of their fuel economies. For CO_2, some indication of the benefit of hybrid vehicles over conventional petrol or diesel vehicles can be obtained. The VCA data were used to compare the CO_2 emissions from Euro IV vehicles of engines sizes from 1.4-1.6 litres. Over the combined cycle, the petrol hybrid emits 40% less CO_2 compared with comparable petrol cars and 17% less CO_2 compared with diesel cars (Table 5.15). The benefits of the hybrid are greater for urban-type driving conditions where it emits 48% and

17% less CO_2, respectively. The VCA data also give some indication of the effect on NO_X, CO and hydrocarbons, although these data will be less robust. Accepting this limitation, the hybrid vehicle over the combined test cycle emits 57% less CO and 66% less NO_X than comparable petrol vehicles. Compared with diesel vehicles, the hybrid emits similar quantities of CO and hydrocarbons and over 90% less NO_X.

Table 5.15: Carbon dioxide emissions from petrol, diesel and petrol-hybrid vehicles based on Vehicle Certification Agency data

Fuel	Mean engine size (litres)*	CO_2 (g km^{-1}) Combined cycle (urban + extra-urban)
Petrol	1.58	173
Diesel	1.52	125
Hybrid (Toyota Prius)	1.50	104

*Note, that there is a preference for larger engined diesel cars to be purchased than petrol cars. Data from the SMMT for 2004 suggest that diesel cars emit only 6.2% less CO_2 than petrol cars across the UK fleet (SMMT, 2005).

5.5.1.2 Fuel switching

Petrol vs. diesel

439. There are a large number of potential fuels for use in road transport (e.g. liquified petroleum gas (LPG), natural gas, H_2) and a similarly large number of fuel switching options. However, conventional fuels (petrol and diesel) are likely to remain the dominant fuels for use in road vehicles for the foreseeable future. Some of the issues that are important when comparing petrol with diesel would also apply to comparisons made with other road transport fuels e.g. LPG and natural gas. The relative merits of petrol and diesel are constantly changing over time, driven by changes to technology and vehicle emissions legislation. Comparisons tend therefore to reflect a snapshot in time. There are, however, some general themes that can be identified. In the UK and Europe diesel fuel use is increasing, whereas petrol use is declining. The increased use of diesel as a fuel has several implications. There are benefits in terms of reduced emissions of CO_2, but disbenefits for particle emissions (PM_{10}, $PM_{2.5}$ and BC). The overall impact does depend on the time frame considered. Also, particulate emissions from diesel vehicles tend to be blacker than petrol vehicles.

440. Diesel cars are more fuel efficient than petrol, although this difference is likely to decrease in the future because of improvements in petrol car technology (WBCSD, 2004). Diesel is also about 10-15% more energy dense than petrol, so comparisons of fuel economy on a per litre basis favour diesel (derived from DUKES (2004)). Comparisons based on energy content are better and narrow the gap between petrol and diesel in terms of CO_2 emissions. Furthermore, for the UK vehicle fleet in 2004, diesel vehicles only emitted 6.2% less CO_2 per km than petrol cars because diesel cars tend to have larger engines (SMMT, 2005).

441. Based on 2005 EU emissions standards for light-duty vehicles, Jacobson (2002) calculates that emission of BC and OC from diesel vehicles would warm the climate more than petrol vehicles, despite diesel vehicles emitting less CO_2. However, there is a high level of uncertainty in the overall balance in terms

of climate sensitivity between the benefits in reducing CO_2 emissions and the disbenefits in increasing BC emissions that would occur by switching to diesel (see Section 3.2.2.5 for a more detailed treatment of this issue). In the next 10 years, particle traps will effectively become mandatory for all new diesel vehicles, thus leading to considerable further reduction in BC. This issue has wider importance for other fuel cycles that release BC e.g. for some of the biofuels.

442. Consideration also needs to be given to fuel production, energy use and emissions at refineries. Traditionally it has been more energy intensive to produce petrol at refineries compared to diesel (Gover *et al*., 1994). However, a recent EC report (Kavalov and Peteves, 2004) suggests that they are now comparable on refinery energy use. This is complicated by the fact that increasing diesel consumption in the EU will require refineries to change, leading to further increased energy consumption. Refinery emissions are also important with respect to sulphur removal, as discussed previously.

443. Data from the NAEI have been used to illustrate the implications of the increased use of diesel as a road transport fuel. From 2002 – 20 the share of emissions between petrol and diesel changes significantly. Overall, there is a growth in road traffic of 29% over this period. Table 5.16 shows emission projections for road transport from the NAEI. It is important to note the table footnote concerning the figures for CO_2 shown in this table. The CO_2 road transport figures are not the official UK CO_2 emission estimates as these are based on fuel consumption statistics and projections from the DTI (as required by international emission reporting agreements), but instead the values shown in Table 5.16 are modelled values produced by methods (based on traffic levels and projections) used for estimating and forecasting emissions of the other pollutants. This is to ensure emission trends for CO_2 can be compared on a consistent basis with those for the AQ pollutants. The DTI fuel consumption based CO_2 estimates for road transport exclude the contribution of vehicles travelling on UK roads using fuel purchased overseas.

Table 5.16: Change in emissions from road transport petrol and diesel fuel from 2002 – 20 (kt yr^{-1}) based on the NAEI

Pollutant	Fuel	2002	2020	% change
CO_2 (as carbon)[1]	petrol	19278	14223	-26%
	diesel	16343	24499	50%
	total	35621	38722	9%
NO_X	petrol	285	44	-85
	diesel	426	224	-47
	total	711	268	-62
VOC	petrol	172	28	-84
	diesel	39	26	-33
	total	211	54	-74
PM_{10}	petrol	2.6	1.4	-45
	diesel	27	13	-54
	total	30	14	-53

[1] Note: The figures for CO_2 are from the NAEI emissions model and are based on the same method as used for other pollutants in estimating and forecasting emissions based on traffic levels. The figures differ from the official UK CO_2 figures reported by the NAEI for 2002 and by the DTI for 2020, these being based on national fuel consumption figures. The purpose of showing the 'NAEI-modelled' values of CO_2 emissions in this table is for examining trends that are formed on a consistent basis used for all the other pollutants.

444. Table 5.16 shows that CO_2 emissions from petrol use is expected to decline by 26% from 2002 – 20. Over the same period, CO_2 emissions from diesel fuel use increase by 50%. Overall there is an increase in road transport CO_2 emissions of 9%. By contrast, the emissions of pollutants of direct concern to AQ all show significant decreases over this period. Table 5.16 highlights that decreases in emissions from petrol vehicles are most significant for NO_X and VOCs (around 85%), while decreases in emissions from diesel vehicles are most significant for PM_{10}.

445. Even though there is likely to be a large increase in the use of diesel fuel (shown by the 50% increase in diesel CO_2 emissions), reductions in the emissions of NO_X, VOC and PM_{10} are projected. These results do, however, disguise potentially important effects. The increase in C emissions is driven by an increase in road vehicle km rather than a switch to diesel. If the additional transport demand had been met by petrol, emissions of CO_2 would be higher than is indicated in Table 5.16. On this basis, the increased use of diesel fuel at the expense of petrol could be seen as a benefit overall. (Although this calculation ignores the potentially important climate effects of diesel emissions of BC/OC). By contrast, the overall reduction in PM_{10} of 53% (and similar reductions expected in $PM_{2.5}$ and BC) would be greater if there had not been a switch to the increased use of diesel. On this basis it could be argued that a switch to diesel is a disbenefit for particle emissions, even though emissions in 2020 are substantially less than in 2002. Similar arguments would also apply to emissions of NO_X.

446. These issues highlight that it is important to consider emissions and impacts that are not associated with point of use emissions and to consider how vehicle technologies are likely to change in the future. Further work is therefore required to determine the actual current or potential future advantages of diesel over petrol for the UK/European context. This work also needs to consider fuels other than petrol and diesel.

Biofuels

447. Biofuels cover a wide range of fuel types derived from biomass. Biofuels also offer a potential route for the production of H_2 (see below). In May 2003 the EU Biofuels Directive came into force, which requires Member States to set indicative targets for the use of biofuels in the transport sector by 2005 and 2010. The Directive includes ‘reference’ targets of 2% biofuel use by 2005 and 5.75% of energy content by 2010. Biofuels are likely to have an important role in the UK and Europe meeting its commitments for CO_2 emission reduction. In the transport sector, biofuels can be used in their pure form or, more commonly as a blend with petrol and diesel (typically less than 5%). The principal fuel types are biodiesel, bioethanol and biogas.

448. Several studies have considered the environmental performance of biofuels, focusing mostly on the GHG benefits (EUWTW, 2004; DfT, 2004). There is a wide range of emissions performance data for biofuels making it difficult to summarise the typical emissions of these fuels compared with petrol or diesel (e.g. Graboski and McCormick, 1998; Lance and Andersson, 2003). The emissions from biofuels depend on whether neat or blended fuels are used, the vehicle tested and the degree to which the vehicle has been optimised for the use of these fuels. At typical blends of 5%, it appears that biofuels have a similar emissions performance to a base vehicle using petrol or diesel (DfT, 2004). However, as the proportion of biofuel is increased in petrol or diesel, there is some evidence to suggest that biofuels could have difficulty meeting EU vehicle emissions standards (DfT, 2004). Another factor related to the use of bio-fuels for road transport is the amount of energy required to produce them, which results in emissions of AQ and potentially fossil CO_2 emissions. From an energy perspective it is much better to use biofuels directly in stationary combustion (EUWTW, 2004; CONCAWE 2002).

449. The production of biofuels leads to a variety of environmental impacts (IEE, 2004), many of which are related to land-use issues. For some biofuels that use nitrogen fertilisers, the formation of N_2O could be important (EUWTW, 2004; CONCAWE, 2002). Other impacts can be expected from fuel use to farm, process and distribute these fuels. Many studies that consider biofuels often consider the use of biofuels throughout the fuel chain. There is significant uncertainty and methodological issues involved in undertaking lifecycle assessments of biofuel emissions, which can have a substantial bearing on their environmental benefits in different circumstances (DfT, 2004).

450. A recent study for the London Borough of Camden considered both the climate and AQ impacts of transport fuels used in cars and vans (mainly complying with Euro IV emissions legislation), including biofuels, over their life cycle (Lane, 2006). The report relied on other studies for input information such as the EU 'well to wheels' report, (EUWTW, 2004). Some general observations can be made from this study. First, for CO_2, the emissions related to vehicle manufacture and fuel production account for around 20% of total Life Cycle Analysis (LCA) emissions for all vehicles. Second, biodiesel and bioethanol, which are both assumed to be used neat in cars, have higher LCA emissions of NO_X and PM_{10} over their life cycle compared with baseline petrol and diesel vehicles. The higher emissions for these fuels are the result of emissions generated during fuel production. The report also found that vehicle size was an important determinant of overall emissions, which is an issue that is also considered in Section 5.5.1.4.

Table 5.17: Life cycle emissions of different fuel types used in passenger cars (data from Lane, 2006)

Fuel Type	CO_2 (g km^{-1})	NO_x (g km^{-1})	PM_{10} (g km^{-1})
Petrol	240	0.20	0.018
Diesel	200	0.33	0.030
Bioethanol	150	0.63	0.052
Biodiesel	60	0.64	0.033

Hydrogen

451. Hydrogen as a road fuel can either be used directly in an internal combustion engine or in a fuel cell. When combusted directly, it results in zero emissions of CO_2 and very low emissions of other AQ pollutants. When used in a fuel cell, the only emission is water vapour. At the point of use, H_2 thus offers significant advantages over conventional and alternative road fuels. As such, the use of H_2 would bring large benefits to urban AQ. The key issue associated with H_2 is not the emissions at the point of use, but how it is produced, stored and distributed. For this reason it is important to consider total fuel cycle emissions.

452. There are several principal routes to the production of H_2: fossil fuels, biofuels, nuclear and renewable energy resources. There are numerous ways in which H_2 can be produced and consequently a very large range of impacts, both in terms of AQ and climate-active emissions. Most studies that consider H_2 as a vehicle fuel focus on its potential to reduce GHG emissions rather than the emissions of AQ pollutants. For GHG emissions the following can be noted in the European context (EUWTW, 2004).

- If H_2 is produced from natural gas, it only has a benefit if used in a fuel cell vehicle. In the short-term, natural gas is the only viable route to large-scale H_2 production. Electrolysis from the existing EU electricity mix would result in higher GHG emissions compared with production from natural gas.

- Hydrogen from renewable resources (biomass, wind, nuclear) offers very low emissions of GHGs, but is currently expensive. It is more efficient to use renewables to produce electricity rather than produce road fuels (EUWTW, 2004; DfT, 2004).

- Large-scale central H_2 production from coal or natural gas, with C sequestration is a possibility that merits further investigation. Carbon sequestration is considered in Section 5.4.1.1.

453. Because there are numerous ways of producing H_2 and a wide range of GHG impacts, it is also likely to be the case for emissions of local AQ pollutants. The greatest benefit for climate and local emissions is likely to result in the production of H_2 from renewable sources such as wind power or from nuclear power. Production from biomass would result in emissions of local AQ pollutants, as would the production of H_2 centrally from coal or natural gas with C sequestration. The precise impacts of these processes are difficult to judge, but it is reasonable to assume that the emission of most AQ pollutants would be greater than H_2 derived from wind or nuclear power. The benefit to urban AQ in particular could be one of the more significant attractions of using H_2.

454. Recent work by Jacobson *et al*. (2005), which considered the AQ and climate impacts of H_2 fuel cells in the USA, concluded that there could be considerable benefits for both issues. Jacobson *et al*. (2005) found that benefits would arise if H_2 was produced by steam reforming of natural gas, wind electrolysis or coal gasification. Use was made of nested models accounting for urban to global-scale-processes as well as accounting for life cycle emissions. Furthermore, most benefits were brought about by reducing exhaust emissions. These results (for USA conditions at least) suggest that the use of H_2 in fuel cells would result in a win-win for CC and AQ. Much more work is required to assess these effects under European conditions.

455. Because H_2 reacts with tropospheric hydroxyl radicals, emissions of H_2 to the atmosphere perturb the distributions of CH_4 and O_3, the second and third most important GHGs after CO_2. Hydrogen is therefore an indirect GHG with a GWP of 5.8 over a 100-year time horizon. A future H_2 economy would therefore have greenhouse consequences and would not be free from climate perturbations (Derwent, 2004). If a global H_2 economy replaced the current fossil fuel-based energy system and exhibited a leakage rate of 1% then it would produce a climate impact of 0.6% of the current fossil fuel based system. If the leakage rate were 10%, then the climate impact would be 6% of the current system. Careful attention must be given to reduce to a minimum the leakage of H_2 from the synthesis, storage and utilisation of H_2 in a future global H_2 economy if the full climate benefits are to be realised in comparison to fossil fuel-based energy systems.

5.5.1.3 Demand management

Congestion charging

456. Congestion charging (or road user charging) aims to reduce road traffic congestion by reducing demand through charging vehicles to travel. The impact that congestion charging has on the emissions of different pollutants varies depending on how specific schemes are implemented. Currently in the UK, London is the only urban area to implement such a scheme and thus provides a good example of the likely impact on emissions. The London scheme was implemented in February 2003 and covers a small area of central London (< 2% of the area of Greater London). Analysis of the impact on emissions of the London scheme has been carried out by Beevers and Carslaw (2005) for NO_X, PM_{10} and CO_2. The analysis showed that reductions in NO_X, PM_{10} and CO_2 were predicted both from an overall reduction in traffic activity, but also importantly through a change in the operating conditions of vehicles i.e. through the reduction in congestion and increased vehicle speed. Reductions in NO_X and PM_{10} were calculated to be about 12%, whereas CO_2 reductions of about 20% were predicted based on 2002 data. A possible trade-off of the scheme, which has resulted in the increased use of buses and in particular buses fitted with particle traps, is increasing primary NO_2 emissions because of the type of re-generating trap fitted to buses (Carslaw, 2005). Overall, however, congestion charging can be expected to reduce both AQ and climate-active emissions and is an example of a win-win measure.

457. In the future, a scheme such as the one in London could have a very different impact. This is because emissions of NO_X, PM_{10} (and other AQ pollutants) are declining through the increased penetration of new vehicle technologies over time. Carbon dioxide emissions from individual vehicles are declining also, but much less significantly. Furthermore, in future congestion charging is likely to be of more benefit to CO_2 emissions reduction than the reduction of AQ pollutant emissions in terms of absolute emissions change. Begg and Gray (2004) highlight that emissions of NO_X and PM_{10} will fall regardless of any demand management initiatives such as congestion charging. Begg and Gray (2004) also highlight that the Commission for Integrated Transport estimate that national charging would reduce overall traffic levels by 5%, with an associated reduction in CO_2. Furthermore, national congestion charging could also help reduce the emissions of AQ pollutants through higher charges at congestion black spots.

458. A recent assessment has been made of an all user road charging scheme in the UK (Defra, 2006). This measure was initially modelled by DfT using their National Transport Model that took account of the effect of an all user road charging scheme introduced in 2010 on traffic, congestion and emissions from different vehicle types in different areas of Great Britain. It covered ten different area types and used emission factors for NO_X, PM_{10} and CO_2 provided by the NAEI. These results suggested reductions of CO_2 3-4%; PM_{10} 2%, NO_X 2% relative to a case where no charging is assumed. Although these reductions are not as large as the London case, this measure does still represent an important win-win.

Low Emission Zones

459. A LEZ aims to reduce road transport emissions over a defined geographic area, usually by restricting certain vehicle types, ages or technologies from entering the zone. The focus of LEZs tends to be on the reduction of emissions that are of concern to local urban AQ issues and not the reduction in climate-active emissions. However, by aiming to reduce local AQ pollutant emissions there would also likely be impacts to the emissions of pollutants that are of concern for CC impacts. The impacts of a LEZ are dependent on several factors e.g. when and where a scheme is implemented and the vehicles affected. Work has been undertaken into the feasibility of a LEZ for London (Watkiss *et al*., 2003) and in other UK urban areas. In London three preferred schemes were identified (one in 2007 and two in 2010), which focussed on HGVs only or HGVs and Light Good Vehicles (LGVs). The study also focussed more on the reduction of particle emissions rather than other pollutants. Reductions in emissions were brought about either by restricting the age of vehicles or requiring that older vehicles be retrofitted with particle filters. The reduction in NO_X in 2007 was predicted to be 1.5%, up to 3.8% in 2010 depending on scheme. The PM_{10} reduction in 2007 was 9% and 19-23% in 2010. As highlighted in Section 5.5.1.1 the retrofitting of particle filters to HGVs could have a small CO_2 penalty. Likewise, some NO_X abatement techniques have a CO_2 penalty or result in the increased emission of other trace GHGs such as N_2O.

460. The impact on GHG emissions was not carried out as part of the London study although it was noted that bringing forward the introduction of new vehicle technologies (e.g. Euro IV) should bring benefits to CO_2. It would appear LEZs that result in the accelerated introduction of newer vehicle technologies that emit less AQ and GHG emissions rather than retrofitting older vehicles with emissions reduction technologies would bring about the greatest overall benefit. As with many measures, the impact of a LEZ would be transitory unless increasingly stringent schemes were introduced over time i.e. there would be benefits over a few years until the turn-over in vehicle technologies superseded an existing scheme. In principle, there is no reason why such schemes could not focus on GHG emissions as well as local AQ pollutants.

461. The emissions impact of LEZs has also been considered for seven UK urban areas from 2010, except in London where the scheme was assumed to start in 2007 (Defra, 2006). For these cities all pre-Euro I and Euro I HGVs and buses and coaches were assumed to be replaced by a fleet mix of Euro II/III/IV/V vehicles and all Euro II Heavy Duty Vehicles (HDVs) were fitted with a PM trap. The scheme leads to short-term benefits to NO_X, PM and very little impact on CO_2.

Urban planning

462. Higher density urban development is currently favoured for its potential to decrease transport sector energy consumption by reducing trip lengths. There is a small literature base discussing possible side-effects of this in terms of air pollution concentrations (e.g. Marshall *et al*. (2005) and references therein). Reducing trip length initially appears to be a win-win option as it reduces all transport emissions of GHGs and AQ pollutants. However, a higher density urban development causes the emissions of the city to be distributed over a smaller area. The pollutant concentration can therefore rise if the relative reduction in area is greater than the relative reduction in emissions. A trade-off arises because of the sensitivity of AQ pollutants to the location of emission relative to the location of receptors, which is irrelevant for GHGs. Non-transport emissions, if they are the same per capita in a dense city as in a sprawling city, enhance this effect further, although a greater proportion of terraced or tenement block housing in higher density developments may counteract this through improved insulation and efficiency.

463. Urban planning has also been used, e.g. in the cities of Barcelona (Catalunia, Spain) and Curitiba (Brazil) to promote walking and public transport as zero emissions and lower emissions modes of transport, especially where rapid population growth or regeneration are occurring. Similar thinking is being incorporated into plans for several UK cities, not least the Thames Gateway development and the regeneration associated with the London 2012 Olympics.

464. The physical separation of walkers and motorised modes of transport by road space reallocation and pedestrianisation can deliver AQ improvements and exposure reduction for pedestrians even in the absence of any emissions reductions (Kaur *et al*., 2005). If the associated improvement in conditions for users of non-polluting modes of transport promotes modal change and resulting reduction in transport energy use and GHG emissions, then these measures can be considered win-win for AQ and CC.

5.5.1.4 Other measures

Mode switching

465. Switching from one transport mode to another offers a range of possibilities that could result in win-win, win-lose and even lose-lose. The usual method of comparison is to compare the vehicle km impacts of different modes. Studies that compare different transport modes also depend on several important assumptions e.g. the route, technologies used and occupancy rates. Such modal comparisons apply to the transport of goods and people.

466. Recently, there has been a large growth in short-haul flights in the UK, and it is useful to consider how these trips compare with high-speed rail. A study by Watkiss *et al*. (2001) compared the emissions impacts of rail and short-haul flights. This study compared the emissions per passenger km for trips between major UK cities such as between London and Leeds. It was found that short-haul flights result in considerably higher emissions (200-300 g passenger-km^{-1}) of CO_2 compared with high-speed rail (40 g passenger-km^{-1}). These per passenger CO_2 emission factors can usefully be compared with the voluntary agreement on CO_2 emissions for passenger cars, i.e. a target of 140 g vehicle km^{-1} by 2008.

467. Domestic aircraft also have disbenefits in terms of ground-level emissions of CO, NO_X and VOCs per passenger-km. It should be noted that the Watkiss *et al*. (2001) study did not account for non-CO_2 emissions at altitude, which would make rail even more advantageous. Furthermore, because most long-distance rail routes are electrified, future emissions (beyond 2006) of CO, NO_X and VOCs are likely to decline still further compared with aircraft. It was found that emissions of SO_2 were higher for rail; in part because of the use of coal in power stations but also because of the use of diesel trains on some rail routes. However, SO_2 emissions from high speed trains are expected to fall significantly in the medium-term (to 2020), because of changes to the generation of electricity – see Section 5.4.1.2. The Watkiss *et al*. (2001) study also suggested that emissions of PM_{10} were similar between the modes, but would decline more rapidly for rail for the same reasons as SO_2. The study indicated that surface access emissions are likely to be important. It can be concluded that mode switching from rail to air represents a lose-lose, whereas a switch from air to rail represents a win-win.

468. Emissions for different transport modes are often expressed in terms of g passenger-km^{-1} and used to compare the benefits of one transport mode against another. However, caution needs to be taken and the factors have sometimes been misinterpreted. This is because the factors have been assumed to be ‘fixed’ and passengers can be swayed by the transport mode having the lowest g passenger-km^{-1} emission factor without appreciating that their choice of transport mode will in itself affect the g passenger-km^{-1} factor of the mode the passenger chooses. This is through affecting the occupancy rate. For example, the g passenger-km^{-1} rating of a bus may not look attractive compared with a car, but would be made more attractive if a greater proportion of the seats in the bus were filled.

469. For the transport of goods, a recent report has highlighted the impact of transporting food into and around the UK (Smith *et al*., 2005). That report highlighted the growing importance of the distance food is transported and the difference in CO_2 and AQ pollutant emissions by mode.

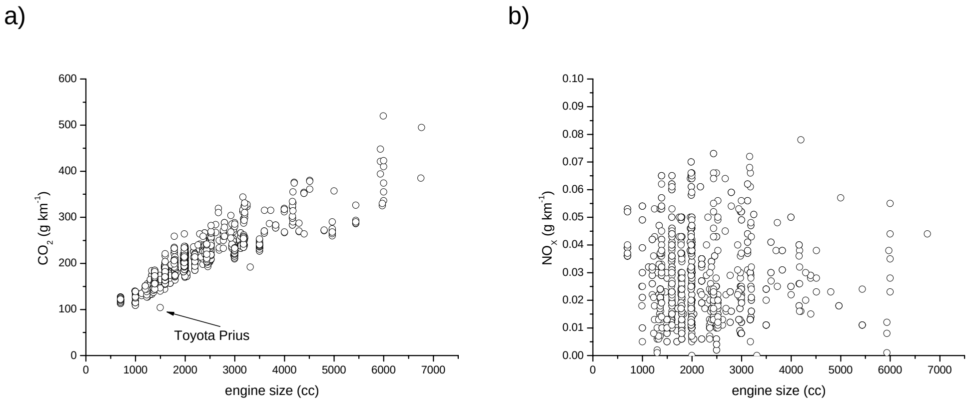
Changes in vehicle weight

470. Over the past 30 years, light duty vehicle (LDV) weight in Europe has increased by about 30% (WBCSD, 2004), and from 1995 – 2003 data from ACEA suggest that weight has increased by 12.2% (SMMT, 2005). This increase in weight has been caused by several factors including: increased safety, reduced noise and emissions requirements, and added components such as air conditioning. For example, there was a 25% increase in weight when Ford moved from the Sierra to the Mondeo; the latter with catalyst, airbags etc. (SMMT, 2005).

471. Generally, a decrease in vehicle weight by 10% could save around 5-7% on fuel and hence CO_2 (WBCSD, 2004). There is, however, significant potential to reduce vehicle weight through the use of lighter materials. The use of lighter materials such as aluminum or composites could reduce current vehicle weights by 28-36% without compromising vehicle performance etc. (WBCSD, 2004). Fuel cycle emissions are again important, because aluminum manufacture is an energy-intensive process. A reduced vehicle weight would also allow a smaller engine to be used. A consequence could be the reduction in CO_2 and AQ emissions. A life cycle approach would show that reductions in AQ pollutants would occur at other points in the fuel chain e.g. refining. The reduction in vehicle weight represents a win-win measure, which would be most beneficial for climate rather than AQ.

472. Because AQ emissions are controlled in modern vehicles through the use of catalysts and traps and because the legislative limit values of the AQ pollutant emissions are set the same for all car sizes, changes in vehicle weight do not necessarily affect the emissions of AQ pollutants. Figure 5.3 highlights the importance of vehicle size and CO_2 emissions, where larger-engined (heavier) vehicles result in higher CO_2 emissions. The relationship between engine size and NO_X is however less apparent and highlights that the link between CO_2 and AQ pollutants has to a large extent been broken.

Figure 5.3: a) Relationship between passenger car vehicle engine size and carbon dioxide emissions from petrol cars, and **b)** relationship between engine size and emissions of nitrogen oxides, based on Vehicle Certification Agency data



473. Decisions made by individuals in purchasing cars could have large benefits on the emissions from vehicles. Analysis conducted by the SMMT (SMMT, 2005) showed for example, that emissions of CO_2 could be reduced by around 30% if the lowest emitting cars were bought from each class of vehicle e.g. mini, executive, sports utility. The greatest benefits were for hybrids in the sports and larger car sectors. Also, it would be expected that there would be greater benefits for emissions of GHGs than AQ pollutants.

474. The EU voluntary agreement on CO_2 (1999/125/EC) has a target of 140 g km^{-1} CO_2 for the fleet average of newly registered passenger cars by 2008. Manufactures could meet this aim through a variety of approaches e.g. increased sale of smaller-engined vehicles, new engine technologies and reduced vehicle weight. Evidence suggests that while vehicles have increased in weight in recent years, vehicle manufacturers have been able to reduce the CO_2 emissions across the vehicle fleet. This agreement is also influenced by fuel switching from petrol to diesel. Recent data from the SMMT suggests that the 0.4 improvement in CO_2 from cars from 2003 to 2004 (171.4 g km^{-1}) was largely due to the increasing sales of diesel cars at the expense of petrol. Note, that the average new car in the UK emits 9.7% less CO_2 in 2004 than the average new car did in 1997 (SMMT, 2005).

475. From July 2005, all new cars sold in the UK contain a colour-coded rating for their CO_2 emissions, in a similar way to domestic appliances. There will be six bands with associated variations in Vehicle Excise Duty (VED). Typically, petrol vehicles will cost approximately 10% less to register than diesel vehicles for the same level of CO_2 emission due to the AQ benefits of petrol over diesel. Unlike domestic appliances however, that consume electricity resulting in emissions associated with both AQ and CC, the reduction in CO_2 is less likely to be associated with reduction in AQ emissions at the point of use. Nevertheless, as indicated previously, reduction in AQ emissions elsewhere in the fuel chain are likely.

476. Technical and non-technical measures for the reduction of AQ pollutants have recently been considered by netcen (Stedman *et al*., 2006). For some measures, the emission projections were used in AQ models to predict the impact on ambient concentrations in the UK and exceedances of AQ strategy objectives and EU limit values. Where possible, the impact of the measure on CO_2 emissions was calculated to identify and quantify the extent of any win-win benefits of the measure with respect to AQ and CC or the extent of any emission trade-offs with CO_2 that the measure could pose. Nine main measures (and some variants) were modelled that addressed emissions from road transport. Some of the measures were technology-based measures relying on tighter emission standards on vehicles and retrofitting of exhaust after-treatment systems, while others were non-technical measures relying on traffic demand management schemes. Further details of the assumptions used are given in Stedman *et al*. (2006).

Tighter vehicle emission standards

477. Recent analysis by netcen has considered the effect of implementing tighter vehicle emission standards (Defra, 2006). This measure considered the impact of tighter Euro V standards for diesel LDVs introduced from 2010 and Euro VI standards for HDVs introduced from 2013. It assumed a 20% reduction in NO_X

emissions from all diesel LDVs, a 50% reduction in NO_X emissions from diesel HDVs, but no change in NO_X emissions from petrol LDVs, relative to Euro IV/V levels. It assumed that DPFs were fitted on all diesel LDVs. There was no change in fuel efficiency of petrol vehicles, but a 3.5% fuel penalty on diesel LDVs relative to the base case 2010 levels and a penalty on diesel HDVs that increased fuel consumption to Euro III levels (an increase of about 6%).

478. This leads to an overall trade-off between NO_X, PM emission reductions and increases in CO_2 emissions for road transport. A more ambitious 'high' scenario was also considered that also resulted in similar trade-offs.

Car scrappage incentive scheme

479. This measure considered two different car scrappage schemes. First, a scenario that included the scrappage of pre-Euro I cars: 25% by 2007, 50% by 2008, 100% by 2009, each replaced by cars meeting Euro IV standards. Second, a scenario that included the scrappage of pre-Euro I and Euro I cars: 25% by 2007, 50% by 2008, 100% by 2009, each replaced by cars meeting Euro IV standards. This scheme leads to short-term benefits to NO_X, PM and CO_2 emissions. This scheme did not account for the emissions resulting from vehicle manufacture, which could be significant and might even cancel out the estimated benefits. One study by Maclean and Lave (1988) suggests that for cars manufactured in the USA, the total energy requirements of car manufacture over the life cycle of a typical car were about 10%. More recent work considering the life cycle emissions for a VW Golf suggests that car and materials production accounts for 17% of total life cycle CO_2 emissions based on a vehicle lifetime of 10 years and 150,000 km (Schweimer and Levin, 2000). This would suggest that taking account of vehicle manufacture is likely to be an important consideration for car scrappage schemes, particularly for GHG emissions.

Low Emission Vehicle incentive scheme

480. This measure considered the increased penetration of Low Emission Vehicles (LEVs, e.g. hybrids) into the UK fleet (Defra, 2006). It considered petrol and diesel LEVs. Petrol LEVs were assumed to lead to a 68% reduction in NO_X emissions, a 34% benefit in fuel efficiency and no change in PM emissions, relative to a Euro IV vehicle, but only in urban areas. There were no changes at all on motorways and half of these improvements on rural roads. Diesel LEVs were assumed to lead to a 65% reduction in NO_X emissions, a 90% reduction in PM emissions, and a 26% benefit in fuel efficiency relative to a Euro IV vehicle in all areas and road types. The benefit of this measure depends directly on the penetration of LEV vehicles into the UK fleet. For a 10% penetration (replacing equal numbers of petrol and diesel cars) of LEVs achieved by 2010, it was estimated that CO_2 from road transport would be reduced by 0.5%, whereas NO_X and PM_{10} would be reduced by 1%. It should be noted that the benefits increase towards 2020. This scheme leads to win-win benefits to NO_X, PM and CO_2 emissions.

5.5.2 Aviation

481. The aviation sector represents a growing source of both AQ and GHG emissions in the UK and Europe. Aircraft have improved in efficiency in recent years due to ongoing improvements in engine and airframe design to reduce drag, which has resulted in the reduction of GHG and AQ pollutants. For aircraft emissions there is, however, a trade-off between improving fuel efficiency and reducing emissions of NO_X. Improved engine fuel efficiency leads to higher combustion temperatures and thus higher emissions of NO_X.

482. Emissions from the aviation sector are accounted for in a different way compared with other source sectors because they cross national boundaries. National inventories such as the UK's Greenhouse Gas Inventory are reported to various international bodies like the UN Framework Convention on Climate Change following strict reporting guidelines and definitions of sectors that are generally guided by the principle of national responsibility. The problem with aviation and shipping emissions becomes one of national allocation. National emission inventories only include emissions from domestic flights. Emissions for international aviation are reported for information purposes only but do not contribute to the national totals for the country where they arrive at or depart. The estimates for 'international aviation' are based simply on the amount of aviation bunker fuels supplied, using data from national energy statistics, after subtracting the amount calculated to have been used for domestic flights and military purposes. The complexities involved in accounting for aircraft emissions in inventories can make it difficult to assess the overall importance of this sector to emissions of all pollutants. For example, the international aviation emission estimates reported by the UK do not make it easy to ascertain where the emissions of different pollutants occur in relation to the UK, although separate figures are given for emissions over the take-off and landing cycle (up to 1,000m altitude) and cruise cycle.

483. International inventories on specific sectors like aviation that fall outside the scope of national inventories have been produced for bodies like the EU and IPCC. Projected estimates of CO_2 emissions from UK and EU aviation have been produced by the Tyndall Centre and have illustrated the importance of aviation as a major source of CO_2 with the growth in aviation expected over the next 50 years. Such studies have highlighted how growth in CO_2 emissions from aviation will compromise the ambitions intended by setting national CO_2 reduction targets that do not include international aviation in the target plan. Although there is considerable interest in aviation emissions worldwide, there is presently no international agreement on how to apportion emissions between nations. There are discussions continuing on the possibility of including intra-EU aviation emissions in the second phase of the EU Emission Trading Scheme for GHGs allowing the industry to buy emission permits from other sectors or airlines (see Section 5.8). Compared with other forms of transport, there is less scope for the control of aircraft emissions. The use of control technologies that are important in other sectors such as SCR and particle filters, are not appropriate for aircraft. Most effort has been directed towards improved engine performance and refinements to the airframe, which can also improve efficiency. The relative importance of this sector to UK emissions will therefore increase over the coming decades.

484. Like other forms of transport there is the potential to use H_2 as a fuel in the longer-term. However, the attractiveness of H_2 as a fuel for aircraft is less appealing than for other forms of transport because of issues relating to weight and safety. Another important aspect of using H_2 in aircraft is the increased release of water vapour in the upper troposphere/lower stratosphere. At that altitude water vapour is an important GHG and some studies have suggested that its impact could be more important than CO_2 from kerosene.

485. The impact that airports have on local AQ is also an important aspect, particularly because of the growth in aviation and the lack of emissions control technology that can be used on aircraft. Nevertheless, there are several aspects relating to airport operation that could result in reduced AQ impacts. In common with other sectors there is the potential for fuel switching. Examples include the increased use of electricity for different operations, e.g. in ground control equipment and auxiliary power units on aircraft. In the aviation sector, there are other trade-offs that are important, such as the desire to reduce noise levels. Even with improvements in aircraft emissions and operations inside of airports, there can still be adverse effects on local AQ with growth in aviation due to increased traffic emissions in areas around airports.

5.5.3 Shipping

486. The shipping sector is recognised as an increasingly important sector, both for the emission of AQ and GHGs. AQEG (2005) highlighted the importance of ship SO_2 and NO_X emissions to the formation of secondary aerosol, while recent studies highlight their importance for CC effects through the formation of O_3 (Derwent *et al*., 2005a; Endresen, 2003).

487. From an emissions inventory point of view, many of the issues relevant to aviation also apply to shipping due to the fact that emissions cross national boundaries or occur in areas that do not fall within any national boundary so the problem of national allocation again becomes apparent. Like aviation, national inventories cover only coastal shipping and fishing vessels in national territorial waters. Emissions from international shipping are reported for information purposes but do not contribute to the national totals. Emission estimates for international shipping are based on sales of international marine bunker fuels available in national statistics, but these inventories in themselves do not indicate where the emissions occur. This means that foreign vessels passing through UK waters using fuel purchased outside the UK are not included in the UK's inventory, though these could be contributing to regional air pollution problems in the UK. There are specific shipping inventories produced, e.g. for the European Monitoring and Evaluation Programme (EMEP), covering shipping that falls outside the scope of the national inventories.

488. Unlike the aviation sector, there are a large number of abatement measures that could usefully be applied to shipping. Some of these share benefits or disbenefits that are similar to other sectors. The reduction in fuel sulphur, while leading to increased emissions of AQ and GHG emissions at refineries, would result in major benefits for the reduction of sulphur emissions and hence secondary aerosol formation.

489. For large ships, there is the potential to use SCR. In fact, SCR is already used by some ships (Cooper, 2001). Like the power generation and transport sector, the use of SCR could lead to increased emissions of NH_3 and possibly N_2O (although increased N_2O emissions were not found by Cooper (2001)).

490. While at port, there is the potential to use grid electricity for auxiliary power needs on board ships, which, depending on the fuel mix could offer benefits to AQ and CC.

5.6 Measures related to agriculture and land use

491. The measures considered in this section include those related to agricultural activities, but also other activities that would be better described as land-use. Some of the measures in this section are closely related to bio-energy and biofuels. As can be seen from the Tables earlier in this chapter, the agricultural sector in the UK is a very minor contributor to the total emissions of the standard AQ pollutants NO_X (~1%), SO_2 (<1%), VOCs (~1%), but a more significant contribution to the total primary PM_{10}, of around 9%, made up mainly from broilers (housed livestock, 4%) and arable farming (2%). Furthermore, emissions of CO_2 from the agricultural sector are also minor (<2%). However, the agriculture sector is a much more significant source for NH_3 (80%) and trace GHGs (N_2O and CH_4). Emissions of CH_4 and N_2O, and the proportion of the CH_4 contribution from agriculture are expected to increase by 2020.

492. The contribution made by sources in this sector are, however, likely to become more important in the future. The attractiveness of using non-fossil C fuel from bio-sources would mean that the emission of AQ pollutants over different fuel supply chains could become more important (see Section 5.4.1.5 and 5.5.1.2 for a more detailed discussion). Furthermore, measures in this sector, while offering low fossil C emissions, in many cases could result in increases in other trace GHGs and in particular N_2O. Emissions such as NH_3 and N_2O are much more difficult to control than other pollutants such as the products of combustion.

493. Mitigation measures are therefore of a rather different nature to those for the energy and transport sectors, as the important potential trade-offs are between CH_4, N_2O and NH_3, with any effects on other pollutants, with the possible exception of PM, being negligible overall.

494. There are three important processes related to agricultural emissions. Enteric fermentation contributes about 90% of the agricultural CH_4 emissions, virtually all through cattle and sheep (6% and 20% respectively, pigs 1%). Decomposition of manure and waste contributes the other 10% of CH_4 (cattle 7%, pigs 2%, poultry 1%), about 5% of agricultural N_2O emissions, and the large majority of NH_3 emissions (Entec, 2004). Agricultural soil and crop emissions (including fertiliser effects) contribute about 95% of N_2O emissions (Entec, 2004).

5.6.1 Mitigation measures and other factors affecting future emissions

495. A summary of mitigation measures for the agricultural sector is given below.

5.6.1.1 Reduction in numbers of cattle and sheep

496. Numbers of non-dairy cattle and sheep are expected to fall by 15-20% between 2001 and 2020 (Entec, 2004), with consequent reductions in CH_4 both from enteric fermentation and waste. Further reductions could be seen as a mitigation measure, though the knock-on effects such as alternative food sources are hard to gauge.

5.6.1.2 Reduction in the quantity of nitrogen-based inorganic fertilisers used

497. Inorganic fertiliser use is expected to decline by 5-10% between 2003 and 2020 (Entec, 2004), with consequent reductions in N_2O emissions. However, the impact of CAP reform is predicted to lead to a small (approximately 5%) increase in fertiliser-N use as set-aside become less attractive and the land reverts to cropping. This, and any further reduction as a mitigation measure, would not in itself be expected to increase CH_4 or NH_3, while reduced production of the fertiliser should lower rather than raise CO_2 because fertiliser manufacture is energy intensive.

498. Other possible measures include switching to urea fertiliser, which could reduce N_2O emissions by 21%, while chemical inhibitors could be used to reduce the rate of nitrification in the soil, reducing N_2O emissions by a further 12% (Entec, 2004). Switching to urea would, however, lead to substantial increases in NH_3 emissions. Even the use of urea inhibitors with urea (to reduce emissions) would lead to substantial increases in NH_3 emissions.

499. Increased use of slurry could, however, decrease N_2O emissions at the expense of increased NH_3 emissions. Slurry management measures to decrease NH_3 emissions by land-spreading, increasing the amounts of nitrogen entering the soil, have the potential to increase N_2O emissions. Whether there is an increase or decrease in N_2O emission following slurry injection or manure incorporation depends on many factors, mainly soil conditions at the time of application and subsequent weather conditions. Also, N_2O is emitted following deposition of NH_3 to land. Clearly, reducing NH_3 emissions will reduce the subsequent 'indirect' emissions of N_2O from NH_3 deposition. Hence, any switch to urea fertiliser would, by increasing NH_3 emission, lead to increased indirect emissions of N_2O.

500. While not related to AQ, measures taken as a result of the Nitrates Directive should help reduce emissions of N_2O. Once again, the issue of 'indirect' emissions is important here. Around 30% of N_2O emissions from agriculture are from denitrification of leached nitrate in estuaries and other slow-moving waters. Hence a reduction in nitrate leaching should reduce those indirect N_2O emissions.

5.6.1.3 Modification of enteric fermentation

501. There are several methods for reducing the CH_4 emissions per head of livestock, e.g. using ionophores such as monensin, salinomycin and narosin to inhibit CH_4 production, and encouraging propionate rather than CH_4 production, either by introducing propionate precursors or by increasing the amount of concentrate in the diet. These methods would not be expected to affect other emissions by significant amounts.

5.6.2 Land use as a carbon sink

5.6.2.1 Agricultural soils as a carbon sink

502. There are a number of agricultural land-management changes that could be used to enhance potential to increase the C sink in agricultural soils (Smith *et al*., 2000a, b). These include: switching all animal manure use to arable land, applying all sewage sludge to arable land and the use of surplus arable land for bio-energy crop production. Some work has been carried out to quantify how important the emission of non-CO_2 GHGs could be for these measures (Smith *et al*., 2001a).

5.6.3 Forestry

503. There has been extensive discussion of the role of forests in mitigating CC through increasing the sequestration of the large pool of C contained primarily in woody biomass and soils. At a global-scale, current concern is focused on the impact of deforestation, particular in the tropics, but since deforestation of the UK occurred several centuries ago, the interest is the extent to which increased tree planting might offset C emissions. For example, many companies offer the potential to purchase trees to offset personal or company C emissions.

504. For the UK to become C-neutral (in terms of CO_2 emissions at current rates) through tree planting alone, Broadmeadow & Matthews (2003) estimated that 50 million hectares of forest (twice the land surface of the UK) would need to be planted, while to offset the effect of car-use an estimated area of 75% of the UK would need to be planted.

505. At a smaller-scale, Griffiths *et al*. (2005) estimated that an area 1.4 times that of Glasgow would need to be planted to offset the annual CO_2 emissions from Scottish trunk roads. To place this potential in context, the net uptake of C in UK woodland as a whole is currently estimated to be 4.4 MtC yr^{-1} (Milne and Mobbs, 2006), while national emissions reductions commitments made under the Kyoto Protocol are 20 MtC yr^{-1}. Hence, woodland planting could play some role in reducing net emissions of CO_2 in the short-term. It is important to distinguish the annual uptake of C (which may be relatively large in the active growth stage of the forest), which relates to the rate at which the trees grow and incorporate C, from the total C storage once the forest reaches maturity, and net C uptake is zero. It is important to note that (a) the management of a forest can significantly influence both of these terms and (b) that forest damage, e.g. through storms, droughts or insect attack, all of which are predicted to increase in frequency in the future, may result in rapid release of the stored C. It is also important to note that forest planting can reduce surface albedo, thus producing a positive radiative forcing. However, Betts (2000) estimated that this effect was relatively small in western Europe, offsetting the C sequestration by only 10-20%.

506. Although there are many assumptions and difficulties in quantifying the precise amount of C that is sequestered by tree planting, in general terms, there are three ways in which forestry could be used to reduce net CO_2 emissions. Each of these have different implications for AQ: They are:

- Increasing the area of the UK used for commercial forestry, without changing management significantly.
- Managing forests to maximise C stocks, which would require a significant change from the economic social and environmental criteria used for current forest management in the UK.
- Using harvested wood, typically grown on short-term rotations, to substitute for fossil fuels either through use in power and heat generation (bioenergy) or through wood products which might substitute for materials such as concrete and steel which have high fossil fuel use in their production. Use of wood, or other biomass sources, for energy production is not entirely C-neutral, because of the energy associated with harvesting, transport and energy production, but has clear advantages over using fossil fuels. The policy and technical issues associated with using all forms of biomass (including agricultural) for energy production were reviewed by the Royal Commission on Environmental Pollution (RCEP, 2004). They concluded that energy from biomass was an important component of all scenarios leading to achieving its recommended national target of a 60% reduction in UK CO_2 emissions, and suggested a target of 12% UK energy production from biomass by 2050.

507. There are several implications of use of forest planting to improve the national C budget, using these approaches, which need to be considered. Increasing use of fast-growing species such as willow and poplar for energy production could affect biogenic VOC emissions, and hence production of O_3, as these are often high isoprene emitters. Stewart *et al*. (2003) estimate that if existing willow biomass in Great Britain were doubled for use as an energy crop emissions of isoprene could increase by 10%. While there is evidence from Scandinavia, where NO_X levels are relatively low, that individual plantations do not significantly affect local AQ (Olofsson *et al*., 2005), this may not be the case in regions of the UK with higher NO_X concentrations. Local-, national- or European-scale policies to increase the use of such species for energy production could therefore have significant effects on O_3 concentrations. For example, the ambitious target set by RCEP (2004) of 16 GW by 2050 would require an estimated land area of 5 million hectares (of a current 17 million hectares of agricultural land), although this would depend on the mix of biomass used. Currently land under willow is estimated to be 1500 hectares only. Forests are the main source of biogenic VOCs in the UK. Forests are the main source of biogenic VOCs in the UK. Since emissions vary between tree species, tree planting schemes aimed at energy production or carbon sequestration should take account of the potential for increased emission of VOCs and their impact on the formation of ozone and of secondary organic aerosol.

508. Emissions to the atmosphere from biomass combustion would need to be carefully assessed and controlled. RCEP (2004) provide data showing that emissions from biomass fuelled CHP plants in Sweden compare favourably with those from similar coal-fuelled CHP plants, although no comparisons are provided from gas. Emissions of dioxins and volatile metals may be of greater concern. In terms of the impacts of increased domestic use of wood, Mcdonald *et al*. (2000) showed that in some residential areas of the USA where wood was the dominant fuel for domestic heating, wood burning contributed the majority of winter $PM_{2.5}$, while Johnson (2006) reported that outdoor wood fired boilers were a significant source of $PM_{2.5}$. However, a recent study in Sweden (Molnar *et al*., 2005) reported no significant effects of domestic use of wood for space heating on personal exposure to $PM_{2.5}$, although exposure to some heavy metals was higher in the wood burning group.

509. Increased forest cover would increase deposition rates of a range of pollutants, leading to reduced transport distances, but also locally enhanced impacts on soils, vegetation and drainage waters.

510. The recent report of the Biomass Task Force (2005) strongly emphasises the potential to use biomass to reduce net UK CO_2 emissions, contribute to security of energy supply, and to meet rural development objectives. However, although the need for LCA of different biomass schemes is recognised by the report, the AQ implications of increased use of biomass are not considered specifically. It is the view of AQEG that these urgently need further assessment. In some cases, e.g. better use of waste wood, the implications for AQ are likely to be small, but in the case of conversion of land to energy forestry, these implications may be more significant.

5.7 Measures for other sectors

5.7.1 Waste incineration and energy from waste

511. Section 5.2.1 highlighted that waste disposal in landfill sites is an important source of CH_4 in the UK, accounting for 20% of total emissions. In addition, other wastes such as tyres, waste oil and sewage sludge are also incinerated in the UK. There are several alternatives to landfill for the disposal of wastes, which potentially lead to several tradeoffs.

512. Smith *et al*. (2001b) considered several different waste management options on GHG emissions. No consideration was given to emissions of AQ pollutants. It was concluded that most benefit (from a CC perspective) would be derived by source-segregation of various waste components from municipal solid waste (MSW), followed by recycling or composting or anaerobic digestion. Improved gas management at landfills was also found to do much to reduce the GHG flux from the landfilling of bulk MSW. Incineration with energy recovery (especially CHP) was found to provide a net saving in GHG emissions from bulk MSW incineration, but the efficacy of this option depended crucially on the energy source replaced. Mechanical biological treatment (MBT) was found to offer significant advantages over landfilling of bulk MSW or contaminated putrescible wastes in terms of net GHG flux.

513. In 2001/2, about 8% of municipal solid waste was incinerated with energy recovery in England and Wales. The UK incinerates a smaller proportion of its municipal waste than a number of other European countries, including Denmark (52%) and France (24%) (EA, 2005). As outlined above, this option reduces GHG emissions compared with landfilling. However, waste incineration leads to the emissions of several important AQ pollutants such as NO_X, PM, CO, polycyclic aromatic hydrocarbons (PAHs) and dioxins as well as creating toxic solid waste. Nevertheless, these emissions are controlled through EU emissions legislation. Energy from waste therefore, represents an example where there is likely to be a trade-off between AQ and CC.

514. Organic solid waste also offers the possibility of gasification for electricity generation or for direct use as a vehicle fuel. In the longer-term, the gasification process could be used together with a Fischer-Tropsch process known as biomass to liquid (BTL) to produce fuels for diesel vehicles (WBCSD, 2004). Such processes would tend to be of most benefit for CC, while their impact on AQ pollutants remains uncertain.

5.7.2 Hydroflurocarbon and perflurocarbon replacements

515. Actions taken under the Montreal Protocol and its Adjustments and Amendments have led to the replacement of chloroflurocarbons (CFCs) with hydrochloroflurocarbons (HCFCs), hydroflurocarbons (HFCs) and perfluorocarbons (PFCs). In turn actions under the Kyoto Protocol may well see actions taken to replace HFCs and PFCs with air-conditioning, refrigeration and foam-blowing applications based on hydrocarbons and NH_3. The local impacts of hydrocarbon and NH_3 substitutes has been estimated by comparing their anticipated emissions with those from local pollutant emissions from all sources. Small but not negligible impacts could occur near highly localised emission sources. However, even such small impacts may be of some concern in urban areas that currently fail to meet AQ standards (Metz *et al*., 2005b).

5.8 Emissions trading schemes

516. Emissions trading is emerging as a key instrument in the drive to reduce GHG emissions from businesses. The rationale behind emission trading is to ensure that the emission reductions take place where the cost of the reduction is lowest thus lowering the overall costs of combating CC. Emissions trading is particularly suited to the emissions of GHGs because they have the same effect wherever they are emitted. This allows the total amount of emissions to be regulated in the area where the scheme operates by setting the overall cap for the scheme but gives companies the flexibility of determining how and where the emissions reductions will be achieved. By allowing participants the flexibility to trade allowances the overall emissions reductions are achieved in the most cost-effective way possible.

517. Participating companies are allocated allowances, each allowance representing a tonne of the CO_2 equivalent emissions. Emissions trading allows companies to emit in excess of their allocation of allowances by purchasing allowances from the market. Similarly, a company that emits less than its allocation of allowances can sell its surplus allowances.

518. The UK emission trading scheme began in 2002. Thirty one organisations have so far voluntarily taken on emission reduction targets to reduce their emissions against 1998 –2000 levels, delivering 11.88 million tonnes of additional CO_2 equivalent emission reductions over the life of the scheme (2002 – 06). In 2003, participants achieved emission reductions of nearly 5.2 million tonnes CO_2-equivalent against their baselines.

519. The EU Emissions Trading Scheme (EU ETS) is one of the policies being introduced across Europe to reduce emissions of CO_2. Phase I of the Scheme began on 1 January 2005 and will run until 31 December 2007. Phase II will run from 2008 – 12 to coincide with the first Kyoto Protocol commitment period. Further details of the UK and EU Emissions Trading Schemes can be found at:

http://www.defra.gov.uk/environment/climatechange/trading/index.htm

520. An emission trading scheme of this sort is well suited to reducing emissions of GHGs and allows the overall outcome to be assured. However, the impacts of such a scheme on AQ pollutant emissions are not so clear. For AQ pollutants, where emissions occur does matter and so trading in this way does not necessarily guarantee any benefits to AQ. Furthermore, it is possible that a reduction in CO_2 emissions could be associated with an increase or a decrease in absolute emissions of AQ pollutants. In principle, an emission trading scheme for AQ pollutants may be possible to set up, but because of the importance of atmospheric transport, pollutant interactions and quantifying the effects, it would need to be a far more complex scheme to ensure it was both fair, practical and beneficial.

5.9 Development of combined mitigation strategies

5.9.1 Cost curves and the RAINS/GAINS projects

521. Much research has been conducted on strategies for reducing GHGs and combating CC, or on reduction of AQ pollutants and transboundary pollution. However, here we are concerned with combined strategies that address all simultaneously and explore the synergies between different groupings of pollutants, as in the GAINS (Greenhouse gas Air pollution INteractions and Synergies) project of IIASA. A key tool in such analysis is the ‘cost-curve’.

522. A cost curve provides a summary of the estimated cumulative cost of making successively larger reductions in emissions of a pollutant. Such cost curves, constructed for national emissions of selected pollutants for each country in Europe, have proved extremely useful tools in developing international protocols such as the Gothenburg protocol under the Convention on Long-Range Transport of Air Pollution (CLRTAP), and the EC’s National Emissions Ceilings Directive. In this context they have been used in integrated assessment modelling with the RAINS model (Alcamo *et al*., 1990, Amann *et al*., 1999) and complementary work with other similar models - ASAM (ApSimon *et al*., 1994), and MERLIN. In these models cost-curves coupled to predicted emissions are combined with source-receptor relationships derived from atmospheric modelling, and criteria for environmental protection, to investigate cost-effective strategies for environmental improvement with corresponding ceilings for emissions of each pollutant from each country. Having derived a cost-optimised strategy for

attaining environmental targets, independent assessment of the environmental benefits has been used to justify the costs of implementation. At a national level similar integrated assessment modelling is being undertaken with the UKIAM model (Oxley *et al*., 2003) to investigate compliance with UK emission ceilings and environmental benefits for the UK. This mostly covers the same pollutants, but includes urban AQ as well as transboundary issues, and uses much more detailed UK information and spatial resolution.

523. Although such an approach involves many approximations and assumptions, if well documented and transparent, cost curves provide a good way of summarising the potential for mitigation in different countries on a common basis, and which the individual countries can scrutinise and comment on. They also help to focus on those options which are likely to yield significant improvements and be cost-effective, as compared with options that achieve little in emission reduction, or imply very high costs per ton of emissions saved.

524. In work under CLRTAP and the subsequent Clean Air for Europe (CAFE) programme of the EC the development of cost curves for SO_2, NO_X, NH_3, VOCs and PM, have largely concentrated on add-on technologies superimposed on projected sources of emissions in accordance with official energy and agricultural projections from each country. Such official projections were taken as fixed, although it was recognised that steps such as fuel switching from coal to gas could be very effective in reducing SO_2 emissions for example - as in fact many countries have done, thus helping them to reduce their emissions in compliance with ceilings set for the year 2010 with less investment in installing abatement technology.

525. More recently the GAINS project has extended their work on cost-curves to cover GHG emissions as well. This work has been used to demonstrate the savings that can be made if GHGs and other atmospheric pollutants are considered in combination. This is illustrated by three case studies from the work by IIASA (Amann *et al*., 2004).

526. In the first case study the objective was to achieve a 15% GHG reduction in the EU25 countries addressing CO_2 alone. The starting point is based on national activity projections for 2020. The measures adopted to achieve this reduction based on the cost curves for CO_2 are accompanied by an estimated 10% reduction in SO_2 emissions and approximately 6% reduction in both NO_X and primary $PM_{2.5}$ with corresponding health benefits. Of the total estimated costs of 23.6 billion Euros per year for the EU25 for this scenario, about one quarter or 6 billion Euros per year is equivalent to the cost of achieving similar reductions of SO_2, NO_X and $PM_{2.5}$ according to the RAINS cost-curves based on add-on/end-of-pipe technologies for control of these pollutants. If such costs are avoided then this is a substantial offset against the costs ascribed to CO_2 reduction. There is also substantial value attached to the health benefits of cutting the atmospheric pollution as well (approximately 3 billion Euros per year).

527. In a second case study a reduction in GHGs in the EU 25 countries equivalent to the first one above was addressed by combined reduction of CO_2, CH_4 and N_2O based on use of GWPs for each gas over a period of 100 years. This case reduced the cost of GHG mitigation very substantially (approximately 6.8 billion Euros per year); and implied smaller but still very important co-benefits (approximately 3.7

billion Euros per year) in 'costs avoided' for simultaneous reductions of the other pollutants. Coupled with the health benefits this scenario gave a much lower net cost than the CO_2 only scenario. The smaller associated reduction in SO_2, NO_X and $PM_{2.5}$ is explained by less coupling between the sources involved, with more emphasis on the agricultural sector for CH_4 and N_2O.

528. However, not all such scenarios involving measures to reduce GHG emissions yield co-benefits by reducing air pollutants. A third case study by IIASA illustrated this, with 10% of light fuel oil for household heating replaced by biomass/wood-burning in modern stoves. The resulting reductions in CO_2 and SO_2 were accompanied by increases in primary $PM_{2.5}$ emissions - with a consequent increase in estimated premature deaths.

529. Table 5.18 outlines some of the measures that aim to reduce GHGs and summarises some of the benefits or disbenefits for other pollutants.

Table 5.18: Potential abatement options for reducing greenhouse gases

CO_2	CH_4	N_2O
Power sector: Fuel switching e.g. coal to gas (less SO_2, NO_X), renewables, biofuels Fuel efficiency, Combined Heat and Power, Integrated Gasification Combined Cycle Carbon Capture (uses energy reducing efficiency) **Industry:** Fuel efficiency (all), electricity efficiency (all) Fuel switching Lime production/limestone use (SO_2 reduction) **Residential/domestic:** Electricity efficiency (all), Fuel switching, renewables (except biomass because of increased PM) **Transport:** Fuel efficiency, hybrid vehicles Fuel switching: to natural gas (increased CH_4) to diesel (increased PM) to bio-diesel/ethanol (increased N_2O) Fuel cell (depends on how H_2 is generated)	**Fossil fuels:** Fugitive emissions Gas production, processing and distribution (increased CO_2) Coal mining – gas recovery (increased CO_2) Oil production and refineries **Residential domestic:** Bio-fuel combustion (increased PM) **Waste management:** Biodegradable waste - paper recycling, incineration, land-fill options, composting Waste-water treatments (increased N_2O) **Agriculture:** Enteric fermentation (cattle etc.), agricultural productivity, dietary changes, proportionate precursors Manure management (NH_3, N_2O) Agricultural waste burning, forestry (increased PM, NO_X, VOCs) **Other (applies to all columns):** Demand management Efficiency improvements Behavioural change	**Fossil fuel:** Combustion processes may increase N_2O, e.g. SCR, NSCR Fluidised bed combustion (NO_X) **Industrial processes:** Acid production **Waste management:** Sewage treatment **Transport:** Catalytic converters **Agriculture:** Reduction of soil emissions (reduced NH_3, CH_4): N management reduced/optimised fertiliser application Nitrification inhibitors NB1) Measures to reduce NH_3 such as deep injection of slurries may increase N_2O emissions 2) increased energy crop plantation may increase N_2O through fertilisers used

5.10 Imports

530. The impact the UK has on emissions of all pollutant types extends beyond the UK due to imports of goods (i.e. the UK emission 'footprint'). Imports can be important for some sectors and in future could become more important depending on where fuels or goods are sourced and how they are transported. Currently, the emissions impacts of imported goods are only accounted for through their point of use emissions. However, this neglects the emissions of pollutants from the processing, manufacture or transport of goods from other countries. Furthermore, the country of origin is likely to have an important influence on the total emissions released (e.g. through affecting the distance travelled and transport mode used and by the level of environmental regulation and control relevant to a particular country). For transport fuels, Section 5.5.1.2 highlighted that to meet growing diesel fuel demand in Europe, it may be necessary to increasingly import diesel fuel from overseas. Similarly, it will be important to assess the country of origin for meeting increased demand for transport biofuels. Imports from South America for example, are likely to be associated with significant shipping emissions of SO_2, NO_X and CO_2, although no work to date has quantified the significance of these emissions. The UK currently imports of coal, electricity and natural gas for power generation and other purposes but the emission significance in other countries has not been considered. Finally, there are numerous manufactured goods that the UK imports and similar considerations apply to these.

5.11 Topics for further research

531. There is a need for more studies that consider the suite of pollutants that are important for both AQ issues and CC. Often, studies focus on a narrow range of pollutants and frequently consider either AQ impacts or CC impacts but not both. It can be difficult therefore to assess the overall impacts of different measures to AQ and CC issues.

532. There is an increased need for studies that consider life cycle emissions to allow for a more consistent comparison between measures.

533. Some consideration should be given to cumulative emissions over a specified time period when assessing different measures. Many of the measures identified in this section have transitory benefits (or disbenefits) making it difficult to assess their overall impact.

534. There is an increased need for a consistent set of emissions inventory projections for different pollutants of relevance to AQ and CC. These inventories also need to cover consistent time-scales. Currently, GHG inventories tend to cover longer time-scales than AQ inventories.

535. Further developments are required in the emissions inventories for shipping and aviation to assist in the analysis of links between AQ and CC emissions and assessments of policies and measures to reduce them.

536. The development of increasingly sophisticated modelling tools is required to assess the joint impact of CC and AQ impacts.

537. The impact that increased use of biomass energy has on emissions of NH_3, N_2O and isoprene is potentially important and requires further investigation for different species and cropping regimes.

538. There is a need to improve the quantification of some unregulated emissions species that can be emitted by different retrofit technologies. In particular, those which result in the emission of N_2O require particular attention.

539. In the case of bio-energy and biofuels, there is a need for more data on the AQ impacts of these fuel chains. In particular, an assessment of life cycle emissions and impacts of imported fuels is required.

540. The UK emissions 'footprint' is larger than emissions released in the UK because of imported fuels and goods. Further work is required to quantify these wider issues. In addition, there is also a need to develop methodologies to account for these emissions in emission inventories.

541. There is a need for a UK inventory that specifically considers BC emissions.

542. There are some examples of measures where the impact (emission) is shifted and it is important to consider these e.g. biofuel production. In some cases, this could result in similar emissions of AQ pollutants, but a different impact because of the shift in the location of the emissions.

Chapter 6

Conclusions

6.1 Integration of air quality and climate change

543. In recent years the UK has been at the vanguard of international efforts in the fields both of local air quality improvement and abatement of greenhouse gas emissions. The dramatic improvements in air quality taking place since the severe smogs of the 1950s are a great tribute to the effectiveness of air pollutant abatement policies. The massive growth in road traffic, which could so easily have led to very serious air quality problems, has to a large extent been accompanied in recent years by air quality improvements due to enhanced abatement technology. As well as achieving reductions in concentrations of the directly emitted primary pollutants, peak concentrations of secondary pollutants such as ozone, formed in the lower atmosphere through chemical reactions of pollutants, have also fallen dramatically. Such improvements in air quality have been a major policy success of the latter half of the 20th Century, and emissions reductions for most of the toxic air quality pollutants are predicted to continue well into the 21st Century. Nonetheless, our last two reports (AQEG, 2004; 2005) have emphasised the importance of further emissions reductions in maintaining the improving trends and in meeting the air quality objectives for nitrogen dioxide and particulate matter. We note, however, that there are serious upwards trends in emissions of air quality pollutants in some other parts of the world, which are having adverse local, regional and hemispheric consequences.

544. There are three major greenhouse gases emitted into the atmosphere: carbon dioxide, methane and nitrous oxide. Abatement measures have focussed largely upon carbon dioxide and there have been clear successes in the UK, such as emissions reductions from the electricity supply industry as a result of switching from coal to natural gas as a fuel in power stations. While UK emissions have been reducing over the last decade, global emissions of greenhouse gases continue to increase. There remain major challenges for the UK in meeting national targets for greenhouse gas reduction.

545. To date, policies for the improvement of local air quality have been driven largely by concerns for the protection of public health without taking direct account of the implications for emissions of greenhouse gases. For example, the abatement of sulphur dioxide emissions from power stations using flue gas desulphurisation typically consumes about 2% of the electricity generated by the power station, therefore leading to a commensurate increase in carbon dioxide emissions. Some of the measures for reduction of greenhouse gas emissions such as the switch from coal to natural gas as a fuel in power stations are beneficial to local air quality, although this is not always the case. The encouragement of the use of diesel fuel in road vehicles as a means of improving fuel efficiency and hence reducing carbon dioxide emissions has overall a detrimental effect upon local air quality because of the higher emissions of nitrogen oxides, and most notably particulate matter from diesel engines.

546. It also needs to be borne in mind that emissions of air quality pollutants can contribute in their own right to direct or indirect climate impacts. It does though need to be emphasised that the associated timescales of these impacts (days to months) are far less than those of the global pollutants (decades to centuries).

547. There are often important and sometimes complex interlinkages of pollutant emissions arising from interventions which are designed to improve local air quality or intended to reduce greenhouse gas emissions. Some are more complex than those outlined above. For example, emissions of sulphur dioxide lead to the formation of sulphate aerosol particles in the atmosphere, which reflect incoming solar radiation thereby reducing air temperatures. Aerosol particles also influence the reflectivity (albedo) of clouds so as to reduce temperatures at the earth's surface. The cooling effects of sulphate aerosol are believed to have masked some of the warming effects of increased greenhouse gas concentrations, and further abatement of sulphur dioxide emissions is likely to lead to an enhancement of global warming. Ozone plays an important role as a greenhouse gas and hence altering the emissions of ozone precursors such as nitrogen oxides and volatile organic compounds has implications for climate. In the case of aviation emissions, the climatic effects of ozone generated from precursor emissions are significant in magnitude, although different in timescale, to those associated with carbon dioxide emissions.

548. Such interlinkages between pollutants are now becoming increasingly well understood. However, some aspects, particularly those related to the influences of airborne particles on the global radiation balance, and hence upon global warming, currently require far more research before they can be incorporated in climate models in such a way as to make useful quantitative predictions. The consequence is that, in the past, policies for local air quality improvement have been developed largely without reference to effects on radiative forcing or greenhouse gas emissions. Similarly policies for reducing greenhouse gas emissions have taken little account of impacts on local air quality. The scientific understanding is now at a level where the full range of impacts of abatement measures can and should be considered.

RECOMMENDATION 1: Impact analysis of policies or specific developments, whether for industry, transport, housing etc., should take account of the interlinkages of emissions of air quality and climate change pollutants. In particular measures at the national level designed to improve local air quality or to abate greenhouse gases should not be implemented without prior consideration of all types of impact on the atmosphere and other environmental media.

6.2 Assessment of local developments

549. At the regional and local government level, there is currently a disparity between the regulatory regimes that are in place to control local air quality and emissions of greenhouse gases. Whilst there are legislative mechanisms and regulatory standards in place to improve local air quality, actions to regulate emissions of greenhouse gases within the public sector and planning regimes are based

predominantly on voluntary initiatives. It is recognised that regional and local governments have an important role to play in reducing emissions of carbon dioxide, through local transport planning, urban planning and design, and their own procurement and operations. However, in the absence of the appropriate legislation and accompanying technical guidance, climate change mitigation is rarely given the prominence that is needed, and in some cases is ignored. The 2006 Climate Change Programme commits Government to the provision of new funding for local authority best practice support, and to the preparation of a new Policy Planning Statement related to the reduction of carbon emissions which is to be welcomed. However, they may alone be insufficient to generate the substantial increase in the level of engagement by local and regional government that is required.

RECOMMENDATION 2: Detailed consideration should be given to appropriate policy drivers and legislation that could be introduced to ensure that the reduction of greenhouse gas emissions is properly incorporated into regional and local government planning decisions.

6.3 Influence of local air quality pollutants on climate change

550. Changes in the emissions of air quality pollutants such as sulphur dioxide, nitrogen oxides, particulate matter and ammonia have significant implications for global warming. Whilst these pollutants are not themselves important as greenhouse gases, they influence the formation of pollutants such as ozone which acts as a greenhouse gas. They are also associated with the formation of airborne particles whose effect is generally (although not exclusively) to reduce surface air temperatures thus lessening the effects of global warming. Broadly speaking, reductions in the emissions of gases such as sulphur dioxide, nitrogen oxides and ammonia which lead to the formation of airborne particles will result in increased global warming. This is not to say that these pollutants should not be reduced, as they have significant local and regional impacts, but there may need to be a balancing of priorities. One recent study suggests that the offsetting effects of aerosol in the atmosphere have been underestimated in the climate models, and that consequently the climate effects of greenhouse gases are greater than currently thought. The implication is that reductions in atmospheric concentrations of aerosol may cause considerably more warming than has been estimated to date. Set against these adverse effects of pollutant reductions, a reduction in the emissions of carbonaceous particles from combustion sources, and particularly those from diesel traffic, may lead to some reduction in surface temperatures since these particles tend to act in the same way as greenhouse gases.

551. Currently, it is very difficult to compare the relative significance of air quality improvements and greenhouse gas abatement as there is no common metric with which to express the benefits, and the timescales are entirely different. Additionally, the use of metrics such as Global Warming Potential and Radiative Forcing to describe the impacts of air quality pollutants upon climate is problematic.

RECOMMENDATION 3: Detailed consideration should be given to developing better means of expressing the influence of air quality pollutants on climate, and for inter-comparing the benefits of abatement strategies in respect of air quality and of climate change.

6.4 Interaction between local, regional and global scales

552. Understanding and quantifying the role of air quality pollutants in influencing climate change is a key issue. AQEG takes the view that when considering fossil fuel combustion, the dominant factor for climate change is the emission of carbon dioxide, with effects of air quality pollutants on climate change being both much shorter term and smaller in consequence. Aircraft have a greater potential for climate impacts from air quality pollutants than other combustion sources, due to the altitude at which emissions occur: carbon dioxide nonetheless dominates the global warming potential. However, when considering non-fossil fuel combustion (waste, biofuels, etc), the global warming consequences of the air quality pollutants should be carefully taken into account.

553. Whilst the location of emissions of greenhouse gases has little influence on their climate impact, this is not the case for air quality pollutants. The widely differing trends in emissions of air quality pollutants between, for example, Europe and Asia is leading to considerable inhomogeneities in atmospheric composition with respect to atmospheric aerosol. The implications for local and regional climate are not well understood.

RECOMMENDATION 4: The relationship between local radiative forcing and local temperature response has not been sufficiently investigated. This may be particularly important for spatially inhomogeneous radiative forcing agents such as aerosol (direct and indirect effects) and tropospheric ozone and needs further research.

6.5 Biosphere interactions

554. There are many complex feedbacks between the biosphere and the atmosphere which may have both beneficial and detrimental effects for air quality and the concentrations of atmospheric greenhouse gases and these need to be better understood. Additionally, improved seasonal resolution of temperature-dependent biogenic pollutant emissions is needed in the emissions inventories.

555. This report has considered, in depth, both the implications of climate change for local air quality and the impacts of abatement of locally acting air pollutants upon climate. In the former case it is concluded that the currently predicted future changes to the regional climate of the UK are likely in general to lead to modest improvements to air quality. This is due to increasing preponderance of a westerly type circulation resulting in lower background levels; however downwind of point sources this may lead to local increases in pollution concentrations. On the other hand, there are good reasons to believe that air quality during summer months could deteriorate significantly over coming decades as the climate warms. The combination of high temperatures and elevated ozone concentrations has already

been shown to be highly detrimental to human health. Climate-induced changes in temperature and humidity will also have significant effects on ozone chemistry in polluted areas, while reduced concentrations of nitrogen oxides should prove beneficial in limiting ozone formation at the regional level.

556. A significant factor in summer episodes could be increased emissions of biogenic hydrocarbons from trees which could lead to increased local and regional formation of ground-level ozone. Not all tree species are equally effective in producing biogenic hydrocarbons and some amelioration of this effect might be achieved through tree-planting policies. The effects of land use changes, such as possible increased methane emissions from upland soils also need to be considered. Currently, tree planting policies motivated by the objectives of increased carbon sequestration and increased use of biomass energy do not take full account of the possible implications for future local and regional air quality.

RECOMMENDATION 5: Research is needed on the extent to which policies for large-scale tree planting within the UK and elsewhere within Europe would influence air quality in high temperature summer pollution episodes. Wider impacts of land use change upon both air quality and global pollutants also need to be considered.

6.6 Strategies to minimise impacts

557. This report has also considered in some depth the short and medium term trade-offs inherent in various policy options linked to improving local air quality or abatement of greenhouse gases. Some of the more important sectors for pollutant emissions such as road traffic, aviation, generation of electric power and agriculture have been addressed explicitly. When possible abatement options such as fuel switching are examined, there are in many cases significant trade-offs between considerations of local air quality and impacts on the global atmosphere. There are very few technological measures that, in the short term, can benefit both local air quality and the global atmosphere. On the other hand, there are many potential non-technological approaches that have the potential to benefit air quality and climate change. In general, the beneficial options come under the following headings:

- **Conservation** – measures which reduce the use of resources through conservation are likely to reduce both local emissions and be beneficial for the global atmosphere. An example is the insulation of homes so as to use less energy for heating.
- **Efficiency improvements** – if it is possible to carry out the same activity but to do so more efficiently thus reducing resource use and pollutant emissions, this again is likely to benefit both local and global atmospheres.
- **Behavioural change** – there are many ways in which the behaviour of individuals influences the emissions of pollutants. Reversal of the growing trend for long-distance commuting and the massive growth in air travel would be highly beneficial for both local air quality and the global atmosphere as well as providing other benefits such as reduced traffic congestion.

RECOMMENDATION 6: Consideration should be given to promoting measures which result in benefits both for air quality and climate. These might include incentives for domestic energy conservation, improved industrial process efficiency and measures designed to modify the behaviour of individuals so as to reduce the impact of their activities on the atmosphere. Given the significant influence of transport emissions, measures which reduced the use of road vehicles, shipping and aircraft would be highly beneficial.

6.7 Life cycle analysis of new vehicles

558. The transport sector is a major source of emissions of both greenhouse gases and air quality pollutants. The increased use of electric and hybrid vehicles has the potential to yield substantial improvements in local air quality. However, the implications for the global atmosphere are largely unquantified. These need to take account not only of the emissions from generating electricity but also the different resource and energy costs of constructing this type of vehicle in comparison to conventionally-fuelled vehicles. The use of biofuels and other alternative fuels in transport (e.g. biodiesel, bioethanol) offer potentially significant net reductions in carbon emissions from transport, but the air quality implications and implications for other greenhouse gas emissions from the production, supply and use of biofuels need to be considered along the entire fuel cycle.

RECOMMENDATION 7: A comprehensive life cycle analysis should be conducted comparing the environmental implications of electric and hybrid vehicles with each other and with conventionally-fuelled vehicles, to inform policy on incentivising their use. A detailed fuel cycle analysis is required to consider the air quality and greenhouse gas emission implications for the production, supply and consumption of biofuels for transport.

6.8 Future power generation

559. When considering air quality and climate change impacts together, several options for power generation may look very attractive from the point of view of air quality or climate change when considered in isolation, for example switching to different fossil fuels or use of biofuels. However, these may in reality be less attractive because of trade-offs between air quality and climate impacts, especially where the whole fuel life cycle is considered. In contrast, more controversial changes including wind and tidal power and especially nuclear, suffer less from such trade-off difficulties, and so may appear comparatively more attractive with better integrated consideration of atmospheric impacts. It should however be noted that there are wider considerations, for example security of supply, and public safety aspects of generation infrastructure that are beyond the remit of AQEG, and are consequently not considered in this report.

RECOMMENDATION 8: The full fuel cycle environmental implications of non-fossil fuel means of electricity generation (i.e. wind, tidal, nuclear, etc.) should be evaluated, as part of the development of future energy supply policies. This should include the implications of large-scale biofuel and bioenergy production for land-surface exchange of both air pollutants and greenhouse gases.

6.9 Global perspective

560. The Clean Air for Europe (CAFE) process within Europe has been limited to considering the effect of European precursor emissions on ozone production within Europe. A much more international approach, taking account of the benefits of European abatement policies for the global hemisphere background of ozone, and the benefits for Europe of precursor abatement in other continents would be advantageous. This is especially important given the imbalances in emissions in different parts of the world and the widely differing trends.

RECOMMENDATION 9: The development of well informed European policy on ozone precursors would benefit greatly from a more global view of emissions, trends and abatement issues.

561. Because the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol do not include tropospheric ozone and aerosols in the basket of radiative forcing agents, there is no policy forum through which the local, regional and global scale impacts of tropospheric ozone and aerosol precursor emissions can be addressed. There is therefore no mechanism to ensure that the steps taken to reduce local and regional air pollution problems will not exacerbate global climate change by increasing tropospheric ozone formation and the rate of growth of methane emissions, and by reducing the radiative forcing by aerosols.

RECOMMENDATION 10: Future climate change policy should consider extending the basket of radiative forcing agents included in the development of climate change policies.

Abbreviations and glossary

Abbreviations

A1 and A2	Different scenarios in SRES
ABCs	Atmospheric brown clouds
ACCENT	Atmospheric Composition Change: European Network of Excellence
AOGCM	Atmosphere-ocean general circulation model
AQ	Air quality
AQEG	Air Quality Expert Group
ATC	Annual tropospheric column
AURN	Automatic Urban and Rural Network (air quality monitoring)
AZM	Annual zonal mean
B1 and B2	Different scenarios in SRES
BAU	Business as usual
BC	Black carbon
BS	Black smoke
BTL	Biomass to liquid
°C	Degrees Celsius
C	Carbon
CAFE	Clean Air For Europe
CAP	Common Agricultural Policy
CC	Climate change
CCGT	Combined cycle gas turbines
CCN	Cloud condensation nuclei
CCM	Chemistry climate model
CCZ	Congestion charging zone
C/N	Ratio of carbon to nitrogen
CDNC	Cloud droplet number concentration
CEPA	California Environmental Protection Agency
CERC	Cambridge Environmental Research Consultants
CFC	Chlorofluorocarbon

CH_3SH	methanethiol
CH_3SCH_3	dimethyl sulphide (DMS)
CH_3SSCH_3	Dimethyldisulphide (DMDS)
CH_4	Methane
CHP	Combined heat and power
CLE	The current legislation scenario for emissions by IIASA
CLRTAP	Convention on Long-Range Transport of Air Pollution
CO	Carbon monoxide
CO_2	Carbon dioxide
COP	Conference of Parties
COS	Carbonyl sulphide
CS_2	Carbon disulphide
CSM	Climate systems model
CTM	Chemical transport model
Defra	Department for Environment, Food and Rural Affairs
DfT	Department for Transport
DMDS	Dimethyldisulphide (CH_3SSCH_3)
DMS	Dimethyl sulphide (CH_3SCH_3)
DPF	Diesel particulate filter
DTI	Department for Trade and Industry
DU	Dobson unit, 1DU= 2.68 x 10^{16}molecule per cm
EA	Environment Agency
ECCP	European Climate Change Programme
EEA	European Environmental Agency
EGR	Exhaust gas recirculation
EMEP	European Monitoring and Evaluation Programme - a Cooperative Programme under CLRTAP
EU	European Union
EU25	The 25 countries that were members of the European Union before Romania and Bulgaria joined on 1 January 2007
EU ETS	EU Emission Trading Scheme

FACE	Free air carbon dioxide enrichment
FGD	Flue gas desulphurisation
GAINS	Greenhouse gas air pollution interactions and synergies, an IIASA model
GCM	General circulation model
GHG	Greenhouse gas
GHGI	Greenhouse gas inventory
GISS	Goddard Institute for Space Studies (USA)
$g\ km^{-1}$	Grams per kilometre
GOME	Global Ozone Monitoring Experiment
$g\ passenger\text{-}km^{-1}$	Grams per passenger kilometre
GVW	Gross vehicle weight
GWP	Global warming potential
H_2	Hydrogen
HadAM3	Hadley Centre Global Atmosphere Climate Model
HadCM3	Hadley Centre Coupled Ocean Atmosphere Global Climate Model
HadRM3	Hadley Centre Regional Climate Model
HCFC	Hydrochloroflurocarbon
HCHO	Formaldehyde
HDV	Heavy duty vehicles – road vehicles greater than 3.5 tonnes weight (GVW)
HFC	Hydroflurocarbon
HGV	Heavy goods vehicles – road vehicle greater 7.5 tonnes (GVW), where GVW is the gross vehicle weight i.e. the combined weight of the vehicle and the goods
hr^{-1}	Per hour
HNO_3	Nitric acid
H_2S	Hydrogen sulphide
H_2SO_4	Sulphuric acid
H_2O_2	Hydrogen peroxide
HO_2	Hydroperoxy radical
IGCC	Integrated gasification combined cycle
IIASA	International Institute for Applied Systems Analysis

IPCC	Intergovernmental Panel on Climate Change
K	Kelvin (thermodynamic temperature)
KPa	Kilopascal (unit of pressure)
kt	Kilotonne
ktC	Kilotonne Carbon
LCA	Life Cycle Analysis
LDV	Light Duty Vehicles – road vehicles less than 3.5 tonnes weight
LEV	Low emission vehicles
LEZ	Low emission zone
LGV	Light goods vehicles – goods vehicles less than 3.5 tonnes in weight
LNT	Lean NO_X traps
LOSU	Level of scientific understanding
LPG	Liquefied petroleum gas
LRTAP	Long–Range Transboundary Air Pollution
LWC	Liquid water content (of cloud)
MATCH	Multiscale Atmospheric Transport and Chemistry Model
MBT	Mechanical biological treatment
MFR	The maximum feasible reduction scenario for emissions by IIASA
MODIS	Moderate resolution imaging spectroradiometer
MOZART	Model of ozone and related chemical tracers version 2
ms^{-1}	Metres per second
$\mu g\ m^{-3}$	Micrograms per cubic metre of air
MSW	Municipal solid waste
N	Nitrogen (element)
N_2	Nitrogen (gas)
NAEI	National Atmospheric Emissions Inventory
NASA	National Aeronautics and Space Administration (USA)
NCAR	National Centre for Atmospheric Research
NCEP	National Centres for Environmental Prediction
NECD	National Emissions Ceilings Directive

NEGTAP	The National Expert Group on Transboundary Air Pollution
NERC	Natural Environment Research Council
netcen	National environmental technology centre, part of AEA Technology plc – now AEA Energy & Environment
NH_3	Ammonia
NH_4	Ammonium
NMVOC	Non-methane volatile organic compound
NO	Nitrogen monoxide, also termed nitric oxide
NO_2	Nitrogen dioxide
NO_3	Nitrate
NO_X	Nitrogen oxides ($NO + NO_2$)
NO_y	Total reactive nitrogen oxides
N_2O	Nitrous oxide
N_2O_5	Nitrogen pentoxide
O_3	Ozone
OC	Organic carbon
OH	Hydroxyl radical
PAH	Polycyclic aromatic hydrocarbon
PAN	Peroxyacetyl nitrate
PCB	Polychlorinated biphenyl
PFC	Perfluorocarbons
Pg	Petagrams (10^{15}g)
POCP	Ozone forming potential
POP	Persistent organic pollutants
PORG	Photochemical Oxidant Review Group
PM	Particulate matter
PM_{10}	Airborne particulate matter passing a sampling inlet with a 50% efficiency cut-off at 10 μm aerodynamic diameter and which transmits particles of below this size
$PM_{2.5}$	Airborne particulate matter passing a sampling inlet with a 50% efficiency cut-off at 2.5 μm aerodynamic diameter and which transmits particles of below this size

PM_1	Airborne particulate matter passing a sampling inlet with a 50% efficiency cut-off at 1 µm aerodynamic diameter and which transmits particles of below this size
$PM_{0.1}$	Airborne particulate matter passing a sampling inlet with a 50% efficiency cut-off at 0.1 µm aerodynamic diameter and which transmits particles of below this size
PM_{coarse}	Fraction of the measured particle mass concentration determined from PM_{10} minus $PM_{2.5}$
ppb	Parts per billion (1,000,000,000)
ppm	Parts per million (1,000,000)
ppt	Parts per trillion (1,000,000,000,000)
PRUDENCE	Prediction of Regional scenarios and Uncertainties for defining European Climate Change Risks and Effects
PTM	Photochemical trajectory model
QBO	Quasi biennial oscillation
RAINS	Regional Air Pollution and Simulation, model used by IIASA
RFI	Radiative forcing index
RO_2	Organic peroxy radical
RCA	Rossby centre regional atmosphere climate model
RCEP	The Royal Commission on Environmental Pollution
RCM	Regional climate model
ROG	Reactive organic gases
RVP	Reid vapour pressure
S	Sulphur
SCR	Selective catalytic reduction
SDSM	Statistical downscaling model
SF_6	Sulphur hexafluoride
SH	Southern hemisphere
SIA	Secondary inorganic aerosol
SMMT	Society of Motor Manufacturers and Traders Limited
SO_2	Sulphur dioxide

SO_4	Sulphate
SO_x	Oxides of sulphur
SOA	Secondary organic aerosol
SRES	Special Report on Emissions Scenarios
SSF	Solid smokeless fuel
STE	Stratosphere-troposphere exchange
STOCHEM	Three dimensional Lagrangian model of tropospheric chemistry
Tg	Teragrams (10^{12} g)
TORCH	Tropospheric organic chemistry experiment
TWh	TeraWatt hours
UK	United Kingdom
UKCIP	UK Climate Impacts Programme
UKMO	United Kingdom Meteorological Office
UNFCCC	United Nations Framework Convention on Climate Change
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environment Programme
USA	United States of America
UTLS	Upper Troposphere Lower Stratosphere
VCA	The Vehicle Certification Agency
VED	Vehicle excise duty
VOC	Volatile organic compound
WBCSD	World Business Council for Sustainable Development
WDE	Water-diesel emulsion
WMO	World Meteorological Organisation
W	Watt (unit of power)
$W\ m^{-2}$	Watts per square metre
Yr	Year

Glossary

Acid deposition	The removal of acidic or acidifying compounds from the atmosphere by precipitation (rain, cloud droplets, fog, snow or hail), also known as acid rain or acid precipitation.
Acidification	The generation of more hydrogen ions (H^+) than hydroxyl -ions (OH^-) so that the pH becomes less than 7.
Aerosol	A collection of airborne solid or liquid particles, with a typical size between 0.01 and 10 µm and residing in the atmosphere for at least several hours. Aerosols may be of either natural or anthropogenic origin. Aerosols may influence climate in two ways: directly through scattering and absorbing radiation, and indirectly through acting as condensation nuclei for cloud formation or modifying the optical properties and lifetime of clouds.
Air quality objective	Policy targets generally expressed as a maximum ambient concentration to be achieved, either without exception or with a permitted number of exceedences within a specified timescale (see also air quality standard).
Air quality standard	The concentration of a pollutant, and associated averaging period, which is without significant effect on human health at a population level.
Albedo	The fraction of solar radiation reflected by a surface or object, often expressed as a percentage. Snow covered surfaces have a high albedo; the albedo of soils ranges from high to low; vegetation covered surfaces and oceans have a low albedo. The Earth's albedo varies mainly through varying cloudiness, snow, ice, leaf area and land cover changes.
Alternative energy	Energy derived from non-fossil fuel sources.
Ambient air	Outdoor air in the troposphere, excluding workplace air.
Anticyclone	High pressure system in which air descends to give calm conditions and clear skies. Associated with summer heatwaves and winter frosts and fogs.
Atmosphere	The gaseous envelope surrounding the Earth. The dry atmosphere consists almost entirely of nitrogen (78.1% volume mixing ratio) and oxygen (20.9% volume mixing ratio), together with a number of trace gases, such as argon (0.93% volume mixing ratio), helium, and radiatively active greenhouse gases such as carbon dioxide (0.035% volume mixing ratio), and ozone. In addition the atmosphere contains water vapour, whose amount is highly variable but typically 1% volume mixing ratio. The atmosphere also contains clouds and aerosols.

Atmospheric dispersion model	A mathematical, often computer-based method for calculating pollutant concentrations from emissions data and specified meteorological conditions. Models vary from screening models to detailed, 'new-generation' types.
Anthropogenic	Resulting from or produced by human beings.
AURN	Automatic Urban and Rural Network of air pollution measurement sites, managed by contractors on behalf of Defra and the devolved administrations.
Baseline	A non-intervention scenario used as a base in the analysis of intervention scenarios.
Biofuel	A fuel produced from dry organic matter or combustible oils produced by plants. Examples of biofuel include alcohol (from fermented sugar), wood and soybean oil.
Biogenic	Produced by the actions of living organisms.
Biomass	The total mass of living organisms in a given area or volume; recently dead plant material is often included as dead biomass.
Biosphere	The part of the Earth system comprising all ecosystems and living organisms, in the atmosphere, on land (terrestrial biosphere) or in the oceans (marine biosphere), including derived dead organic matter, such as litter, soil organic matter and oceanic detritus.
Black carbon	Operationally defined species based on measurement of light absorption and chemical reactivity and/or thermal stability; consists of soot, charcoal, and/or possible light-absorbing refractory organic matter.
Black Smoke	Non-reflective (dark) particulate matter, associated with the smoke stain measurement method (BS 1747 pt 2: BSI 1969).
Business as usual	One possible scenario often used to generate climate change and air quality predictions and evaluate potential impacts. The 'business as usual' scenario implies that no actions specifically directed at limiting emissions will be taken by governments, companies, or individuals.
CAFE	The Clean Air for Europe (CAFE) Programme was launched by the European Commission in March 2001. CAFE is a programme of technical analysis and policy development that underpinned the development of the Thematic Strategy on Air Pollution under the Sixth Environmental Action Programme which was published in September 2005. Following this, a new phase of CAFE – the implementation of the Thematic Strategy on Air Pollution was begun.

CarboEurope	An Integrated Project which aims to ‘understand and quantify the carbon balance of Europe’.
Carbon cycle	The term used to describe the flow of carbon (in various forms, e.g. as carbon dioxide) through the atmosphere, ocean, terrestrial biosphere and lithosphere.
Carbon dioxide	A naturally occurring gas, also a by-product of burning fossil fuels and biomass, as well as land-use changes and other industrial processes. It is the principal anthropogenic greenhouse gas that affects the earth’s radiative balance. It is the reference gas against which other greenhouse gases are measured and therefore has a Global Warming Potential of 1.
Climate	Climate in a narrow sense is usually defined as the ‘average weather’, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period is 30 years, as defined by the World Meteorological Organisation (WMO). These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.
Climate change	Climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines ‘climate change’ as: ‘a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods’. The UNFCCC thus makes a distinction between ‘climate change’ attributable to human activities altering the atmospheric composition, and “climate variability” attributable to natural causes.
Climate feedback	An interaction mechanism between processes in the climate system is called a climate feedback, when the result of an initial process triggers changes in a second process that in turn influences the initial one. A positive feedback intensifies the original process, and a negative feedback reduces it.

Climate model	A numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes, and accounting for all or some of its known properties. The climate system can be represented by models of varying complexity, i.e. for any one component or combination of components a hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parametrisations are involved. Coupled atmosphere/ocean/sea-ice General Circulation Models (AOGCMs) provide a comprehensive representation of the climate system. There is an evolution towards more complex models with active chemistry and biology.
Climate scenario	A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships, that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as about the observed current climate. A climate change scenario is the difference between the climate scenario and the current climate.
Cloud condensation nuclei	Airborne particles that serve as an initial site for the condensation of liquid water and which can lead to the formation of cloud droplets.
Concentration	The amount of a (polluting) substance in a volume (of air), typically expressed as a mass of pollutant per unit volume of air at standard conditions of temperature and pressure (e.g. micrograms per cubic metre, μg m^{-3}) or as the ratio of the number of molecules of the pollutant to the total number of molecules in the volume of air (e.g. parts per billion, ppb).
Critical level	The maximum pollutant concentration a part of the environment can be exposed to without significant harmful effects.
Critical load	The maximum amount of pollutant deposition a part of the environment can be exposed to without significant harmful effects.
Detection and attribution	Climate varies continually on all time scales. Detection of climate change is the process of demonstrating that climate has changed in some defined statistical sense, without providing a reason for that change. Attribution of causes of climate change is the process of establishing the most likely causes for the detected change with some defined level of confidence.

Devolved Administrations	The relevant administrations in Scotland, Wales and Northern Ireland.
Dobson Unit (DU)	A unit to measure the total amount of ozone in a vertical column above the Earth's surface. The number of Dobson Units is the thickness in units of 10–5 m, that the ozone column would occupy if compressed into a layer of uniform density at a pressure of 1013 hPa, and a temperature of 0°C. One DU corresponds to a column of ozone containing 2.69 × 1020 molecules per square metre. A typical value for the amount of ozone in a column of the Earth's atmosphere, although very variable, is 300 DU.
Ecosystem	A system of interacting living organisms together with their physical environment.
El Niño-Southern Oscillation (ENSO)	El Niño, in its original sense, is a warm water current which periodically flows along the coast of Ecuador and Peru, disrupting the local fishery. This oceanic event is associated with a fluctuation of the intertropical surface pressure pattern and circulation in the Indian and Pacific oceans, called the Southern Oscillation. This coupled atmosphere-ocean phenomenon is collectively known as El Niño-Southern Oscillation, or ENSO. During an El Niño event, the prevailing trade winds weaken and the equatorial countercurrent strengthens, causing warm surface waters in the Indonesian area to flow eastward to overlie the cold waters of the Peru current. This event has great impact on the wind, sea surface temperature and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific region and in many other parts of the world. The opposite of an El Niño event is called La Niña.
Emission	The amount of a (polluting) substance emitted in a certain amount of time, typically expressed as a mass of pollutant per unit time (e.g. grams per second, or tonnes per year for a single source). May also be expressed per unit length of a road (e.g. $g\ s^{-1}\ m^{-1}$), or per unit area of an urban area (e.g. $t\ a^{-1}\ km^{-2}$).
Emissions inventory	A quantification and compilation of emission sources by geography and time, usually including data covering one or several years.
Emission scenario	A plausible representation of the future development of emissions of substances, based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socio-economic development, technological change) and their key relationships.
Enteric fermentation	A digestive process by which carbohydrates are broken down by microorganisms into simple molecules for absorption into the bloodstream of an animal.

Euro I	Europe-wide vehicle standard that required vehicles manufactured after 1992 to achieve set emissions limits. For petrol cars this was achieved by the fitting of three way catalysts.
Euro II, III, IV & V	Europe-wide vehicle standards that are progressively stricter, for years 1996, 2000, 2006 and 2008 respectively.
Eutrophic	Abundant supply of nutrients and a high rate of formation of organic matter by photosynthesis.
Eutrophication	An increase in the amount of nutrients in waters or soils.
Feedback	See Climate feedback.
Flue gas desulphurisation	The process used to remove sulphur from industrial waste gases before they are emitted to the atmosphere. They are most commonly used on coal-fired power stations.
Fossil fuels	Carbon-based fuels from fossil carbon deposits, including oil, coal and natural gas.
General circulation model (GCM)	See Climate model.
Global warming potential (GWP)	An index, describing the radiative characteristics of well mixed greenhouse gases, that represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation. This index approximates the time-integrated warming effect of a unit mass of a given greenhouse gas in today's atmosphere, relative to that of carbon dioxide.
Greenhouse effect	Greenhouse gases effectively absorb infrared radiation, emitted by the Earth's surface, by the atmosphere itself due to the same gases, and by clouds. Atmospheric radiation is emitted to all sides, including downward to the Earth's surface. Thus greenhouse gases trap heat within the surface-troposphere system. This is called the natural greenhouse effect. Atmospheric radiation is strongly coupled to the temperature of the level at which it is emitted. In the troposphere the temperature generally decreases with height. Effectively, infrared radiation emitted to space originates from an altitude with a temperature of, on average, −19°C, in balance with the net incoming solar radiation, whereas the Earth's surface is kept at a much higher temperature of, on average, +14°C. An increase in the concentration of greenhouse gases leads to an increased infrared opacity of the atmosphere, and therefore to an effective radiation into space from a higher altitude at a lower temperature. This causes a radiative forcing, an imbalance that can only be compensated for by an increase of the temperature of the surface-troposphere system. This is the enhanced greenhouse effect.

Greenhouse gas (GHG)	Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere and clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine and bromine containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O and CH_4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).
Fuel cycle analysis	The assessment of a fuel's environmental costs, from the extraction of the primary fuel through its processing, transport and final use.
Headline air quality indicator	An Indicator that shows air pollution trends in UK urban and rural areas. The Indicator shows the average number of days in each year on which pollution levels for five pollutants (NO_2, CO, O_3, PM_{10} and SO_2) were above the National Standard.
Halocarbons	Compounds containing either chlorine, bromine or fluorine and carbon. Such compounds can act as powerful greenhouse gases in the atmosphere. The chlorine- and bromine-containing halocarbons are also involved in the depletion of the ozone layer.
Hygrophobic	Moisture repelling.
Hygroscopic	Tending to absorb moisture.
Kyoto Protocol	Agreement made under the United Nations Framework Convention on Climate Change (UNFCCC). Countries that ratify the protocol commit to reduce their emissions of carbon dioxide and five other greenhouse gases, or engage in emissions trading if they maintain or increase emissions of these gases. The Kyoto Protocol covers more than 160 countries globally and over 55% of global greenhouse gas (GHG) emissions.
La Niña	See El Niño-Southern Oscillation.
Life cycle analysis (LCA)	The assessment of a product's full environmental costs, from raw material to final disposal, in terms of consumption of resources, energy and waste.
Low Emissions Zone (LEZ)	A defined area from which polluting vehicles that do not comply with set emissions standards are barred from entering.
mesotrophic	Intermediate between eutrophic and oligotrophic in the amount of nutrients contained.

mg m^{-3}	Milligrams per cubic metre of air. A unit for describing the concentration of air pollutants in the atmosphere, as a mass of pollutant per unit volume of air. This unit is one thousand times larger than the µg m^{-3} unit listed below.
Microgram (µg)	One millionth of a gram.
µg m^{-3}	Micrograms per cubic metre of air. A unit for describing the concentration of air pollutants in the atmosphere, as a mass of pollutant per unit volume of air. A concentration of 1 µg m^{-3} means that one cubic metre of air contains one microgram of pollutant.
Micrometre (µm)	One millionth of a metre, also referred to as a micron.
Mitigation	A human intervention to reduce the sources or enhance the sinks of pollutants.
Nanometer (nm)	Nanometre 10^{-9} metres.
Nanoparticle	Particle smaller than 50 nm diameter.
Oligotropic	Poor supply of nutrients and a low rate of formation of organic matter by photosynthesis.
Organic carbon	Carbon in the form of organic compounds, either primary from automotive or industrial sources or secondary from the oxidation of VOCs.
Ozone	Ozone, the triatomic form of oxygen (O_3), is a gaseous atmospheric constituent. In the troposphere it is created both naturally and by photochemical reactions involving gases resulting from human activities (smog). Tropospheric ozone acts as a greenhouse gas. In the stratosphere it is created by the interaction between solar ultraviolet radiation and molecular oxygen (O_2). Stratospheric ozone plays a decisive role in the stratospheric radiative balance. Its concentration is highest in the ozone layer.
Particulate matter	Suspended particulate matter is any non-gaseous material (liquid or solid) which, owing to its small gravitational settling rate, remains suspended in the atmosphere for appreciable time periods.
Phenology	The study of the relationship between climate and the timing of periodic natural phenomena such as migration of birds, bud bursting, or flowering of plants.
Photochemical reaction	Chemical reactions which occur following the absorption of light by a molecule.
Photolysis	The decomposition of molecules following the absorption of light.

PM_{10}	Airborne particulate matter passing a sampling inlet with a 50% efficiency cut-off at 10 µm aerodynamic diameter and which transmits particles of below this size.
$PM_{2.5}$	Airborne particulate matter passing a sampling inlet with a 50% efficiency cut-off at 2.5 µm aerodynamic diameter and which transmits particles of below this size.
PM_{coarse}	Particles measured by mass, determined by the difference.
ppb	Parts per billion. The concentration of a pollutant in air in terms of molar ratio. A concentration of 1 ppb means that for every billion (10^9) molecules in a volume of air, there is one molecule of the specified pollutant present. For practical purposes in ambient air, the molar ratio and volume ratio (the volume occupied by the pollutant gas within a given volume of air) are identical.
ppm	Parts per million. The concentration of a pollutant in air in terms of molar ratio. A concentration of 1 ppm means that for every million (10^6) molecules in a volume of air, there is one molecule of the specified pollutant present. For practical purposes in ambient air, the molar ratio and volume ratio (the volume occupied by the pollutant gas within a given volume of air) are identical.
Primary particles	Particles emitted directly into the environment. This includes particles from both natural sources, such as the entrainment of soils by the wind, and anthropogenic sources, such as particles arising directly from processes such as combustion and quarrying.
Radiative forcing	Radiative forcing is the change in the net vertical irradiance (expressed in Watts per square metre: $W m^{-2}$) at the tropopause due to an internal change or a change in the external forcing of the climate system, such as, for example, a change in the concentration of carbon dioxide or the output of the Sun.
Renewables	Energy sources that are, within a short timeframe relative to the earth's natural cycles, sustainable and include non-carbon technologies such as solar energy, hydropower and wind as well as carbon neutral technologies such as biomass.
Scenario (generic)	A plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Scenarios may be derived from projections, but are often based on additional information from other sources.
Secondary particles	Particles formed in the atmosphere as a result of chemical reactions leading to the formation of substances of low volatility which consequently condense into the solid or liquid phase.

Sequestation	The process of increasing the carbon content of a carbon reservoir other than the atmosphere. Biological approaches to sequestration include direct removal of carbon dioxide from the atmosphere through land-use change, afforestation, reforestation, and practices that enhance soil carbon in agriculture. Physical approaches include separation and disposal of carbon dioxide from flue gases or from processing fossil fuels to produce hydrogen- (H_2) and carbon dioxide-rich fractions and long-term storage underground in depleted oil and gas reservoirs, coal seams, and saline aquifers.
Sink	Any process, activity or mechanism which removes a pollutant or precursor gas or from the atmosphere.
Source	Any process, activity or mechanism which releases a pollutant or precursor gas or to the atmosphere.
SRES scenarios	Special Report on Emissions Scenarios (SRES) are emission scenarios developed by the Intergovernmental Panel on Climate Change (IPPC).
Stagnation	Lack of motion in a mass of air.
Stomata	Tiny pores on the surface of plant leaves that can open and close to take in and give out water vapour and other gases such as CO_2 and O_2.
Stratosphere	The highly stratified region of the atmosphere above the troposphere extending from about 10 km (ranging from 9 km in high latitudes to 16 km in the tropics on average) to about 50 km.
Thermohaline circulation	Large-scale density-driven circulation in the ocean, caused by differences in temperature and salinity. In the North Atlantic the thermohaline circulation consists of warm surface water flowing northward and cold deep water flowing southward, resulting in a net poleward transport of heat. The surface water sinks in highly restricted sinking regions located in high latitudes.
Tropopause	The boundary between the troposphere and the stratosphere.
Troposphere	The lowest part of the atmosphere from the surface to about 10 km in altitude in mid-latitudes (ranging from 9 km in high latitudes to 16 km in the tropics on average) where clouds and 'weather' phenomena occur. In the troposphere temperatures generally decrease with height.
Ultrafine particle	Particles smaller than 100nm diameter.
UNFCCC	The United Nations Convention on Climate Change sets an overall framework for intergovernmental efforts to tackle the challenge posed by climate change.

Vapour pressure deficit	The difference between the actual water vapour pressure and the saturation of water vapour pressure at a particular temperature. Unlike relative humidity, vapour pressure deficit has a simple nearly straight-line relationship to the rate of evapotranspiration and other measures of evaporation.

Definitions come from a range of sources including AQEG (2005) and IPCC (2001c).

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Annex 1

Relevant policy introduction

A1.1 Introduction

1. This annex gives a brief overview of the main legislative drivers addressing the problems brought about by poor air quality (AQ) and global climate change (CC). Wherever appropriate, reference is made to relevant scientific bodies responsible for providing supporting evidence that shapes policy decisions. The overview is not designed to give a definitive guide to policy in both areas, rather to indicate the main relevant programmes and obligations at international, regional and domestic levels for both AQ and CC.

A1.2 International programmes

A1.2.1 United Nations policy agreements

A1.2.1.1 Air quality

2. After links between sulphur emissions in continental Europe and the acidification of Scandinavian lakes had been clearly established, concern regarding ecosystem damage led to the development of the Geneva Convention on Long-Range Transboundary Air Pollution (LRTAP) through the United Nations Economic Commission for Europe (UNECE). The Convention was adopted in Geneva in 1979 and came into force in 1983. Almost 50 countries in Eastern and Western Europe and the USA and Canada are Parties to the Convention. It is important to note that, at the time, there was some doubt as to whether long-range transport of pollutants could be responsible for harming Scandinavian lakes. It was only after some very careful scientific work was performed, that the evidence was considered irrefutable. This then set the role of scientific evidence as a support tool for policy development.

3. The Convention requested that countries should '*endeavour to limit and, as far as possible, gradually reduce and prevent air pollution, including long-range transboundary air pollution*'. It was agreed that this should be achieved through the '*use of best available technology that is economically feasible*'. The Convention has addressed the long-range transport of a variety of pollutants through a series of Protocols setting binding targets for Parties in the form of emission reductions. Amongst the pollutants covered by these Protocols are sulphur dioxide (SO_2), oxides of nitrogen (NO_x), ammonia (NH_3), volatile organic compounds (VOC), persistent organic pollutants (POP) and heavy metals.

4. After a report to the Executive Body of the Convention in the early 1990s it was agreed that the reductions in emissions of acidifying, eutrophying and ozone forming pollutants should be negotiated '*taking into account the best available scientific and technical developments……and internationally accepted critical loads*'. This meant that targets could be set in such a way as to account for the level of pollutant that any one receptor (i.e. ecosystem, humans, materials etc.)

could tolerate without suffering long-term detrimental effects. Emission targets for countries were accordingly set based on their contribution to environmental problems. More information on the Convention and the individual Protocols can be found at: http://www.unece.org/env/lrtap/.

A1.2.1.2 Climate change

United Nations Framework Convention on Climate Change

5. The United Nations Framework Convention on Climate Change (UNFCCC) was opened for signature at the 'Earth Summit' in Rio de Janeiro, Brazil in 1992. The Convention enjoys near universal membership, with 189 countries having ratified.

6. The ultimate objective of the UNFCCC is the '*stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*', and included commitments towards this end. The Convention enshrined the principle of '*common but differentiated responsibilities*', which is commonly interpreted as a commitment from the developed countries to act first, in recognition of their higher economic development. Annex I to the Convention listed the '*developed economies*'.

7. Amongst many others, the Convention also includes provisions on monitoring and reporting of greenhouse gas (GHG) emissions; the establishment of national and regional programmes to mitigate GHG emissions; research and systematic observation to further understand the science of CC; and education, training and public awareness.

8. The UNFCCC established an ongoing process to monitor progress towards the ultimate aim of the Convention – the Subsidiary Bodies for Implementation (SBI), and Scientific and Technical Advice (SBSTA). These bodies provide information to the Conference of Parties to the Convention at annual meetings.

9. Even as they adopted the Convention, Parties were aware that its provisions alone would not be sufficient to tackle CC effectively. At the first Conference of Parties (COP1), held in Berlin, Germany in early 1995, a new round of talks was launched to discuss firmer, more detailed commitments for the industrialised countries.

The Kyoto Protocol

10. In December 1997, after 2 years of extensive negotiations, a Protocol to the Convention was adopted at COP3 in Kyoto, Japan. The Kyoto Protocol assigned quantified emission reduction or limitation commitments for the Parties in Annex I to the UNFCCC. Annex I Parties committed to reducing their emissions over the period 2008 – 12 by 5.2% compared to the base-year emission levels (mainly 1990). The EU15 took on a combined commitment of an 8% reduction, after this was distributed between member states the UK's target was a 12.5% reduction. The basket of six GHGs covered by the Protocol includes carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFC), perfluorocarbons (PFC) and sulphur hexafluoride (SF_6).

11. The Kyoto Protocol included new mechanisms to help countries meet their commitments in the most economic way. It gave provisions for an international system of emissions trading, and established the flexible mechanisms under which countries could make progress towards their own commitments through projects undertaken in other countries. Joint Implementation provided for projects undertaken jointly by Annex I countries, while the Clean Development Mechanism opened up the possibility of reducing emissions in developing countries as a way of meeting commitments. However, the Kyoto Protocol did not establish specific rules for its implementation, and these were not agreed until COP7 in Marrakech, Morocco in 2001.

12. The Protocol could only enter into force after at least 55 Parties to the Convention had ratified it, including enough Annex I countries to encompass 55% of Annex I emissions. This threshold was only reached after Russia ratified the Protocol on 18 November 2004, triggering the 90-day countdown: the Kyoto Protocol entered into force on 16 February 2005.

13. For the UK, the Kyoto agreement requires an average reduction in emissions of 12.5% below base-year levels for the years 2008 – 12. In addition to this the UK has set itself a more ambitious commitment to reduce CO_2 emissions by 20% below 1990 levels by 2010. With publication of the draft UK Climate Change Bill in March 2007, the Government signalled its intention to introduce a legally binding target to reduce carbon dioxide emissions to between 26% and 32% below 1990 levels by 2020. The Bill will also introduce a legally binding target to reduce carbon dioxide by 60% by 2050.

Intergovernmental Panel on Climate Change

14. The Intergovernmental Panel on Climate Change (IPCC) was established by the World Meteorological Organisation (WMO) and the UN Environment Programme (UNEP) to assess scientific, technical and socio-economic information relevant for the understanding of CC, its potential impacts and options for adaptation and mitigation.

15. The IPCC is open to all member countries of the UNEP and the WMO. The Panel meets in plenary sessions about once a year. It decides on the IPCC's structure, principles, procedures, work programme and reports, and it elects the IPCC Chair and the Bureau.

16. The IPCC has three Working Groups and a Task Force:

    - Working Group I assesses the scientific aspects of the climate system and CC
    - Working Group II assesses the vulnerability of socio-economic and natural systems to CC, negative and positive consequences of CC, and options for adapting to it
    - Working Group III assesses options for limiting GHG emissions and otherwise mitigating CC
    - Task Force on National Greenhouse Gas Inventories is responsible for the IPCC National Greenhouse Gas Inventories Programme.

17. Since its establishment the IPCC has produced a series of publications, which have become standard works of reference. The main IPCC products are Assessment Reports, Special Reports, Methodology Reports and Technical Papers. Each IPCC report includes a Summary for Policymakers published in all official UN languages. These summaries reflect the state-of-the-art understanding of the subject matter.

18. The IPCC is currently working on completing the Forth Assessment Report (AR4), Climate Change 2007. In February 2007, Working Group I released the Summary for Policymakers of the first volume of AR4, *Climate Change 2007: The Physical Science Basis*. The report assesses the current scientific knowledge of the natural and human drivers of climate change, observed changes in climate, the ability of science to attribute changes to different causes, and projections for future climate change. The impacts of climate change and options for mitigation will be covered in subsequent reports by Working Group II (impacts, adaptation and vulnerability), and Working Group III (mitigation options) to be finalised respectively in April and May 2007. In addition a Synthesis Report covering key findings of all three Working Groups will be released in late 2007.

A1.3 Regional programmes

A1.3.1 European policy agreements

A1.3.1.1 Air quality

19. The development of policies such as the Convention on LRTAP was instrumental in opening up the free exchange of information on emissions and AQ in Europe. Over the years, the European Union has set a series of standards for emissions from petrol-engined vehicles and followed this with a series of Directives aimed at reducing emissions from diesel-engined vehicles and on the sulphur content of liquid fuels. One of the most effective Directives was the so-called 'Luxembourg Agreement' (88/76/EEC), which put limits on vehicle emissions. This agreement was formally adopted in 1987 and was followed by a series of Directives aimed at reducing emissions specifically from light and heavy-duty vehicles. Legislative control extended to the release of particulate as well as gaseous emissions. More recently in the 1990's the EU has developed a tripartite research programme with the European oil and motor industries. The Auto/Oil Programme was set up to investigate technical measures to help achieve health based AQ targets while minimising the overall costs to society. They also investigated the potential contributions that could be offered by traffic management schemes, public transport, new technologies and vehicle maintenance programmes.

20. Other important legislation affecting industrial emissions included the 1988 Large Combustion Plant Directive (88/609/EEC) which committed Member States to specified reductions in emissions from large fossil fuel burning plants[1] of SO_2 and NO_x.

21. In 2001 the National Emission Ceilings Directive (2001/81/EC) was agreed. This Directive set national emission limits for SO_2, NO_x, VOCs and NH_3 for each Member State and built on the work in the UNECE. The agreed limits were introduced to combat the problems in the EU associated with acidification, health related exposure to tropospheric ozone (O_3) and the impact of O_3 on vegetation.

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[1] Plants of 50 MW output or more.

22. Early attempts to reduce emissions were embodied in the 1980 ambient air quality Directive on SO_2 and suspended particulates ('smoke'; 80/779/EEC). This Directive introduced for the first time, health-based AQ standards as opposed to non-statutory emission standards. Subsequently, similar Directives controlling lead (82/884/EEC) and nitrogen dioxide (NO_2; 85/203/EEC) followed. Later, the need for a more strategic approach for managing AQ resulted in the Air Quality Framework Directive of 1996 (96/62/EC). This Directive aimed to protect both human health and that of the environment by avoiding, reducing or preventing harmful pollution concentrations. The Directive made provision for a more harmonised approach to the assessment of AQ in Europe, making information available to the public, defining and fixing AQ Limit or Target Values and maintaining or improving ambient AQ. The Framework Directive required a series of Daughter Directives to be proposed for a list of 13 pollutants. Four Daughter Directives were subsequently developed to set numerical limit values and thresholds for specific pollutants. The First Daughter Directive (1999/30/EC) addressed SO_2, NO_2, particulate matter (as PM_{10}), suspended PM and lead. Carbon monoxide (CO) and benzene in ambient air were tackled in the Second Daughter Directive (2000/69/EC) and the Third Daughter Directive (2002/3/EC) related to ambient levels of O_3 replacing the previous O_3 Directive (92/72/EEC). The Fourth Daughter Directive (2004/107/EC) addressed ambient levels of the heavy metals arsenic, cadmium, mercury, nickel, and polycyclic aromatic hydrocarbons.

23. In May 2001 the European Commission began the Clean Air For Europe programme (CAFE) – COM (2001) 245) which developed an integrated framework within which other strategic measures such as the Auto/Oil Programme, National Emissions Ceiling Directive and the Air Quality Daughter Directive can be co-ordinated. CAFE provides the overall strategic framework for improving European AQ. The Commission published its Thematic Strategy on Air Pollution together in September 2005 with a proposal for a Directive to update and replace the Air Quality Framework Directive and its first three Daughter Directives. These can be found on the DG Environment website at http://ec.europa.eu/environment/air/cafe/

A1.3.1.2 Climate change

European Climate Change Programme

24. The European Climate Change Programme (ECCP) is the Commission's main instrument to discuss and prepare the further development of the EU's climate policy.

25. A number of these are now in operation; Directives on the promotion of electricity from renewable energy sources and the energy performance of buildings, for the promotion of bio-fuels and of course the Directive on emissions trading.

26. Other key measures from the first phase of the ECCP that are in an advanced stage of preparation and which will have a significant impact on the EU's GHG emissions include legislative measures relating to energy services, Directives for the eco-design of energy using products and fluorinated gases and the public awareness campaign on energy efficiency.

European Climate Change Programme II

27. Whilst the original ECCP was about ensuring the EU met its Kyoto commitments, ECCPII is intended to signal to the world the EU's determination to take on deeper and longer term reductions in its GHG emissions in the context of an international agreement on a future strategy post-2012 which will deliver global reductions commensurate with a 2°C increase in temperature.

28. In putting together ECCPII, attention will be paid in particular to energy efficiency, renewable energy, the transport sector (including aviation and maritime transport), technology and carbon capture and storage. Additionally, there will be work looking at the role of the EU in reducing vulnerability and promoting adaptation which is a new area of interest for the EU in the context of the ECCP.

A1.4 Domestic programmes:

A1.4.1 National and local agreements

A1.4.1.1 Air quality

29. After the 1952 London Smog, which was responsible for between 3500 and 4000 deaths, work began that resulted in the Clean Air Act 1956. This Act introduced smoke controlled areas, controlled chimney heights and prohibited (with some exceptions) the release of dark smoke from chimneys. The provisions stated in this Act were subsequently extended in the Clean Air Act of 1968, which included additional prohibitions on dark smoke emissions. These were eventually consolidated in the Clean Air Act 1993 and the 1956 and 1968 Acts were repealed.

30. While the early Clean Air Acts in the UK concentrated on emission sources, the emphasis of the more recent Environment Act in 1995 focussed on setting standards and objectives for improving ambient AQ and reviewing and assessing local air quality against these a standards and objectives. Although the standards are based on health effects (i.e. hazard assessment), the targets incorporate other considerations such as technological, economic and social factors and have associated achievement dates specified (i.e. risk management). The Act itself required the formulation of a national air quality strategy. The resulting UK National Air Quality Strategy was first published in 1997. The Strategy has been kept under regular review to take account of the latest information on the health and other effects of air pollution and technological and policy developments. As a result the first review, the Air Quality Strategy for England, Scotland, Wales and Northern Ireland was published in 2000, with an Addendum issued in 2003. The current Strategy sets objectives for the protection of human health and the environment to be achieved for nine key air pollutants between 2003 and 2010. The pollutants currently covered are SO_2, NO_2, PM, CO, O_3, lead, benzene, 1, 3-butadiene and Polycyclic Aromatic Hydrocarbons. The Air Quality Strategy is currently being updated. A review was published for consultation in April 2006. Views were sought on the Strategy's current objectives for air pollutants and an option for a new policy framework and a new provisional objective for controlling ultrafine particulate matter. A final version of the Strategy is due to be published in Spring 2007.

31. The Environment Act 1995 also required Local Authorities to carry out a review and assessment of AQ against the standards and objectives in the National Air Quality Strategy in their areas. Their subsequent report includes an assessment of the current state of AQ and how this is likely to change in the following years. For areas thought not to meet these objectives, the Local Authority will declare them as an 'air quality management area' subject to improvement measures as outlined in a Local Air Quality Action Plan.

32. Part I of the Environmental Protection Act 1990 gave Local Authorities powers to control air pollution from a range of prescribed (Part B) processes. These processes had to apply for authorisation to emit from their local authorities. The Act also established a system of integrated pollution control for the most potentially polluting industrial processes which were regulated by the Environment Agency in England and Wales and the Scottish Environment Protection Agency in Scotland.

A1.4.1.2 Climate change

UK Climate Change Programme

33. The UK Climate Change Programme, published in 2000, set the Government's and devolved administrations' strategic approach to tackling CC, focusing on practical action to reduce our GHG emissions, in particular CO_2, and how the UK can reduce its dependence on fossil fuels and make a radical shift to more sustainable patterns of energy generation and consumption. The policies and measures featured in the programme set out to help the UK move towards its Kyoto target. In March 2006, the UK Governments published a new Climate Change Programme which sets out the Government's policies and priorities for action in the UK and internationally to meet the challenge of climate change. The programme contained new policy measures to help achieve two key targets:

    i. the challenging domestic target of reducing CO_2 by 20% below 1990 levels by 2010 and

    ii. the long-term goal, committed to in the 2003 Energy White Paper, to reducing CO_2 emissions by some 60% by about 2050, with real progress by 2020.

    With publication of the draft Climate Change Bill in March 2007, the UK Government has signalled its intention to make these long-term goals legally binding.

34. An updated UK Climate Change Programme[2], containing additional policies and measures, was published in 2006. This Programme will ensure that the UK achieves, and goes far beyond, its Kyoto target. The Energy Review 2006[3] announced additional measures that are being considered. These measures, if implemented, will put the UK on track to meet its long term goals in reducing carbon dioxide emissions.

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[2] http://www.defra.gov.uk/environment/climatechange/uk/ukccp/

[3] http://www.dti.gov.uk/energy/review/page31995.html

UK Climate Impacts Programme

35. The UK Government set up the UK Climate Impacts Programme (UKCIP) in 1997 to encourage private and public sector organisations to assess their vulnerability to CC so that they can plan their own adaptation strategies. UKCIP aims to co-ordinate and integrate an assessment of the impacts of CC at a regional and national level, led by stakeholders. Stakeholders or partners commission research and determine the research agenda so that it meets their needs. UKCIP gives support and guidance throughout the process, providing a bridge between researchers and the decision-makers in government organisations and business.

36. UKCIP has produced a wide range of research, guidance, and tools for different sectors. These include: scenarios of CC for the UK; scoping studies in all the English regions and the Devolved Administrations looking at impacts of CC; guidance for Local Authorities on how they might need to adapt; risk and uncertainty decision-making framework; and methods to cost the impacts of CC.

Draft Climate Change Bill

37. The draft Climate Change Bill, published on 13 March 2007 for pre-legislative scrutiny, sets out the policy measures necessary to provide a clear, credible and long-term domestic framework for tackling climate change in the UK.

38. The draft Bill comprises of four overarching 'pillars':

    i. a system to establish a credible emissions reduction pathway to 2050, with the UK's existing CO_2 reduction targets of 60% by 2050 and 26 - 32% by 2020 placed in statute;

    ii. a strong institutional framework within which to manage the transition to a lower carbon economy, through establishing a new independent body, the *Committee on Climate Change*, to work with the Government on how to reduce emissions over time and across the economy;

    iii. enabling powers to provide additional means with which to achieve emissions reductions; and

    iv. a clear accountability framework, in particular in relation to Government's reporting to Parliament on mitigation and adaptation.

39. A durable and long-term domestic framework will provide greater clarity for UK industry to effectively plan and invest in the technology needed in order to move towards a low carbon economy, while at the same time, allowing the UK to demonstrate strong international leadership, which is key to helping achieve multilateral agreements. It will enable the UK to meet its international obligations, while maximising the social and economic benefits and minimising costs at home.

Annex 2

Units and conversion methods

A2.1 Gaseous concentrations

There are two main systems of units for air pollutants in common use:

Mass per unit volume: usually µg m^{-3}. The mass of pollutant is expressed as a ratio to the volume of air. Since the volume of a given parcel of air is dependent upon the temperature and pressure at the time of sampling, the pollutant concentration expressed in these units should, strictly speaking, specify the conditions at the time of sampling.

Volume mixing ratio: usually ppm – parts per million (10^6); or ppb – parts per billion (10^9). This unit expresses the amount of pollutant as the ratio of its volume if segregated pure, to the volume of the air in which it is contained. Ideal gas behaviour is assumed and thus the volume mixing ratio is not dependent upon temperature and pressure as these affect both the pollutant and the air to the same extent. As a consequence of the gas laws, a gas present at a volume mixing ration of 1 ppm is not only 1 cm^3 per $10cm^3$ of polluted air, it is also 1 molecule per 10^6 molecules and has a partial pressure of one millionth of the atmospheric pressure.

Some pollutants (e.g. sulphate, nitrate) are present as particles in the air and the concept of a volume mixing ratio of gases is not obviously applicable. Their concentrations are normally expressed only in µg m^{-3} units.

A2.2 Conversion factors

Interconversion of the two sets of units can be achieved as follows:

$$\frac{\mu\text{g m}^{-3}}{1000} = \text{ppb x } \frac{\text{molecular weight (g mol}^{-1})}{\text{molecular volume (litres)}}$$

$$\text{Where, molecular volume} = 22.41 \text{ x } \frac{T}{273} \text{ x } \frac{101.3}{P} \text{ litres}$$

In which: T = absolute temperature (K)

P = atmopheric pressure (kPa)

$$\text{Similarly, ppb} = \frac{\mu\text{g m}^{-3}}{1000} \text{ x } \frac{\text{molecular volume (litres)}}{\text{molecular weight (g mol}^{-1})}$$

Volume mixing ratios are invariant with temperature and pressure, whilst µg m^{-3} concentrations change with temperature and pressure. Mass per unit volumes should therefore expressed at a standard temperature and pressure. European legislation specifies that air pollutant concentrations should be expressed as µg m^{-3}, corrected to a pressure of 101.3 kPa (about average atmospheric pressure at sea level) and 293 K (about 20°C).

Conversion factors for gaseous pollutants at 20°C and 101.3kPa

Pollutant	μg m^{-3} to ppb multiply by	ppb to μg m^{-3} multiply by
Ammonia (NH_3)	1.42	0.71
Carbon dioxide (CO_2)	0.55	1.83
Carbon monoxide (CO)	0.86	1.16
1, 3- Butadiene	0.44	2.25
Isoprene (C_5H_8)	0.35	2.83
Methane (CH_4)	1.5	0.67
Nitric oxide (NO)	0.80	1.25
Nitrogen Dioxide (NO_2)	0.52	1.91
Nitrogen Oxides (NO_x)	N/A	1.91[a]
Nitrous oxide (N_2O)	0.55	1.83
Ozone (O_3)	0.5	2.00

[a] This is calculated as if all NO has been oxidised to NO_2 and is written μg m^{-3}, as NO_2.

A2.3 Prefixes and multiplication factors

Multiplication factor	Abbreviation	Prefix	Symbol
1,000,000,000,000,000	10^{15}	peta	P
1,000,000,000,000	10^{12}	tera	T
1,000,000,000	10^{9}	giga	G
1,000,000	10^{6}	mega	M
1,000	10^{3}	kilo	k
100	10^{2}	hecto	h
10	10^{1}	deca	Da
0.1	10^{-1}	deci	d
0.01	10^{-2}	centi	c
0.001	10^{-3}	milli	m
0.000,001	10^{-6}	micro	μ

Annex 3

Emission inventories – how emissions are reported and what it means for modelling and assessments purposes

1. The UK has two emission inventories very closely related to one another and both compiled by netcen. Over many years, these inventories have served to provide the UK's official response to its international obligations to report emissions to bodies like the UN Framework Convention on Climate Change (UNFCCC), the EU European Monitoring and Evaluation Programme (EMEP) and the UN Economic Commission for Europe (UNECE).

2. The UK's Greenhouse Gas Inventory (GHGI) provides the inventories of emissions of greenhouse gases (GHGs) (carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and the so-called F-gases covering a range of fluorocarbons and sulphur hexafluoride (SF_6)) and gases that have an indirect effect on the climate (e.g. nitrogen oxides (NO_X), carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), sulphur dioxide (SO_2)). The GHGI is the inventory reported to the UNFCCC. The UK's National Atmospheric Emissions Inventory (NAEI) provides an inventory of emissions of these pollutants and many more including particulate matter (PM_{10} and finer particle sizes), ammonia (NH_3), benzene, 1,3-butadiene, metals, polyaromatic hydrocarbons (PAHs) and other persistent organic compounds that are toxic. This inventory is submitted to European bodies including the EU and UNECE. The inventories are also published for public interest in the UK in various environmental, energy and transport statistics bulletins.

3. The UK's two main inventories submitted to these international bodies have a common and consistent basis, but differ slightly in terms of what sources are included, the definition of sectors and the way emissions are allocated between sectors. These are strictly set out in inventory guidance documents produced by the Intergovernmental Panel on Climate Change (IPCC) (for the GHGI submitted to the UNFCCC) and the UNECE (e.g. CORINAIR). This is mainly to suit the particular purposes they serve, whether in terms of information on climate change (CC), regional air pollution and its effect on health and ecosystems or on more localised air quality (AQ) and health impacts. Each of these international bodies aims to have emissions data reported to it from different countries developed on a consistent basis so they can be compared with each other. It could be argued that the inventories are designed mainly to help answer the question of who, if anyone, is responsible for the emissions and by how much rather than what the total emissions are and where they actually occur.

4. However, over the years, more has been expected of the UK inventory, both by policy makers in Government and air quality modellers. In recognition of this and at the request of Defra, the NAEI includes emission estimates for sources that are not covered in the international submissions, e.g. PM emissions from road dust resuspension and volatile organic compound (VOC) emissions from natural sources. But even with these additions, UK policy makers and modellers still sometimes find the sector definitions and terms of allocations inconvenient in the national inventories.

5. Transport is a good example of this because it sometimes crosses national boundaries and inventories do not always help establish where emissions occur but rather who should take responsibility for them. Aviation can be taken as an example. Aviation emissions in both the GHGI and the NAEI are reported following strict rules and only explicitly cover emissions from domestic flights in the UK. Emissions from international flights are reported as a 'Memo Item' (meaning they are not included in the country totals) on the basis of total aviation fuel consumed in the UK after subtracting the amounts used for domestic flights and military aviation. It says nothing about where these international aviation emissions occur in relation to the UK and therefore makes it difficult for modellers, e.g., to assess the UK contribution to climate problems associated with aviation NO_X emissions at altitude across the Atlantic.

6. In the case of shipping, the inventories cover only emissions from UK coastal shipping and fishing in UK territorial waters. Emissions from international shipping using UK fuels are not included in the national totals, but are reported as emissions associated with 'International marine bunker fuels'. This means that foreign vessels passing through UK waters using fuel purchased outside the UK are not included in the inventory, though these could be contributing to regional air pollution problems in the UK. There are separate inventories, produced e.g. for EMEP, covering aviation and shipping that fall outside the remit of the national inventories for such assessments because they tackle the strong international, cross-boundary nature of emissions from these sources.

7. For rail, the GHGI and NAEI, again following reporting guidelines, include only emissions from diesel-engined locomotives. Emissions associated with generation of electricity to power electric trains are included in the power station sector. This makes sense if one is primarily concerned with emissions at the point of activity, e.g. the impact of rail emissions on AQ in cities where only exhaust emissions from the diesel trains are relevant, but it does not help to answer questions relating to the full CO_2 costs of rail transport.

8. Even for road transport there can be difficulties in interpreting CO_2 emissions that are reported in the inventory. The IPCC Guidance Notes require national CO_2 emissions from the road transport sector to be calculated on the basis of road fuel sales. The Guidelines state "*the IPCC is bound to the principle of political responsibility (allocation according to fuel sale)…National totals [of CO_2 from road transport] must be on the basis of fuel sales*" (IPCC, 1996). For the UK, this means that it excludes CO_2 emissions on UK roads from the increasing amount of traffic using fuels purchased outside the UK, e.g. by international road haulage. These emissions would be included if the estimates were based on traffic movements within the country, as they are for the other pollutant emissions in the inventory, e.g. NO_X and PM_{10}. Therefore, because the inventories for CO_2 and NO_X and PM_{10} (and other pollutant emissions from road transport) have a different basis, it is difficult to assess on a consistent basis from national figures what impact a measure brought in to tackle say NO_X and PM emissions would have on CO_2, i.e. whether a measure is win-win with respect to impacts on AQ and CC, or whether there is a trade-off. It is because of this that Defra recently asked the NAEI to provide a 'traffic based' inventory for CO_2 so that various potential scenarios could be modelled for 'Beyond Business As Usual' transport measures that can impact on NO_X, PM and CO_2 emissions.

9. When comparing the merits of different fuels or power systems in terms of CO_2 emissions, it is essential to do a full life or fuel cycle analysis from the fuel extraction and production stage, through to its transportation, supply and storage and its end use. Output from the national inventories do not lend themselves for doing this easily, although the NAEI does go some way by producing what it refers to as a 'Final Users' Inventory. This, for example, allocates some of the refinery emissions to the road transport sector.

10. Emission inventories are expected to project forward to the future. The NAEI provides the UK projections for all pollutants except the GHGs using a methodology consistent with the base inventory (reporting the historic time-series in emissions) and the most up-to-date information from Government sources on projections in economic growth, energy demand and fuel mix, transport growth and demographics. These take account of current Government policy in these areas. The projections also account for current and forthcoming regulations and legislation and improvements in technology and efficiency following a 'Business As Usual' scenario. The NAEI projections are used for forecasting the UK's air pollution climate and to assess progress in achieving future emissions ceilings and targets (e.g. the National Emissions Ceilings Directive).

11. Emission projections for CO_2 in the UK are provided by the DTI who produce the energy forecasts used by the NAEI. This has always been the case because of the very close way that CO_2 emissions are coupled with energy consumption, so it has made sense for the DTI to generate CO_2 forecasts compatible with its energy forecasts. However, as previously mentioned, the NAEI has recently produced its own CO_2 projections using methodologies consistent with the projections developed for other pollutants. The NAEI CO_2 projections were developed using a detailed 'bottom-up' approach specifically so that the figures could provide a benchmark against which projected CO_2 emissions could be compared for various 'Beyond Business As Usual' emission abatement measures, primarily aimed at reducing AQ pollutant emissions but which might also have a positive or negative effect on CO_2. Although the 'headline' DTI and NAEI CO_2 projections have a consistent basis at one level, there were found to be differences between them. This is believed to be due to some differences in the sectorial aggregations being used. In the case of road transport, the DTI and NAEI projections for CO_2 are based on different approaches. The NAEI's are based on data on traffic growth, average fuel efficiency of cars supplied by DfT and a fleet turnover model, whereas DTI's are based on a more top down approach looking at fuel demand and pricing. Another cause of the difference relates to a point mentioned earlier. The DTI figures, like the GHGI and NAEI figures submitted for international emissions reporting, are based on UK fuel demand and so exclude emissions from UK traffic using fuel purchased overseas. For comparability with the NAEI's projections for other pollutants, these are included in the NAEI CO_2 projections through use of 'all traffic' data.

12. UK emission projections for non-CO_2 GHGs are produced by Entec and use activity projections consistent with the NAEI.

13. There are other emission projection figures compiled for the UK that are not consistent with the NAEI or the DTI. International Institute for Applied Systems Analysis (IIASA) produce emission projections for all European countries for use in the Clean Air for Europe (CAFE) programme and integrated assessments. Their aim is to produce projections for all European countries on a consistent basis. This gives rise to differences with projections produced by individual countries like the UK. The UK updates its own projections regularly as Government policy changes or Government departments modify their opinions about how future demands will change. IIASA use projections in activity at a less detailed level than the UK's own projections and they cannot be expected to be updated as regularly or include all the levels of detail that make up the UK projections. This means that at any given time, the IIASA and UK's own projections could be different.

14. Apart from differences in activity data, there could even be differences in emission factors used in the UK's NAEI projections and projections produced by IIASA. IIASA would aim to use consistent 'default' emission factors from inventory sources like CORINAIR, IPCC, COPERT etc., some of which are quite old. The NAEI has always been driven by the demand of Government Departments (e.g. Defra, DfT) and industry to use factors that are as up-to-date and UK-specific as possible. This means that data from UK test programmes would take precedence over these default factors if they were felt to be a better reflection of emissions from industry sources in the UK. DfT carry out continuous and extensive emission factor test programmes on vehicles representative of the UK fleet. They too are keen to see their data used in the UK's national inventory which again can lead to divergence from inventories developed from European-wide default factors.

15. Individual countries are permitted to submit to IIASA their own national projections for use in the CAFE assessments.

Annex 4

Useful websites

ACCENT – Atmospheric Composition Change: The European Network of Excellence.	http://www.accent-network.org/
Air Quality Expert Group (AQEG)	http://www.defra.gov.uk/environment/airquality/panels/aqeg/
Clean Air for Europe (CAFE)	http://ec.europa.eu/environment/air/cafe/
CONservation of Clean Air and Water in Europe	www.concawe.org
Convention on Long Range Transboundary Air Pollution	http://www.unece.org/env/lrtap/
Department for Environment, Food and Rural Affairs (Defra)	http://www.defra.gov.uk/
Air Quality	http://www.defra.gov.uk/environment/airquality/
Climate Change	http://www.defra.gov.uk/environment/climatechange/
Department for Transport	http://www.dft.gov.uk/
Department of Trade and Industry	http://www.dti.gov.uk/
Environment Agency	www.environment-agency.gov.uk
European Environment Agency	http://www.eea.europa.eu/
Intergovernmental Panel on Climate Change	http://www.ipcc.ch/
National Expert Group on Transboundary Air Pollution	http://www.edinburgh.ceh.ac.uk/negtap/
Met Office Hadley Centre for Climate Change	http://www.metoffice.gov.uk/research/hadleycentre/
PRUDENCE - Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects	http://prudence.dmi.dk/
Regional Air Pollution and Information and Simulation (RAINS) model.	http://www.iiasa.ac.at/web-apps/tap/RainsWeb/
Royal Commission on Environmental Pollution	www.rcep.org.uk

UK Air Quality Archive	http://www.airquality.co.uk/archive/
UK Climate Impacts Programme	http://www.ukcip.org.uk/
UK National Atmospheric Emissions Inventory	http://www.naei.org.uk
United Nations Framework Convention on Climate Change	http://unfccc.int/

Annex 5

Respondents to the draft *Air Quality and Climate Change: A UK Perspective* report

Comments were gratefully received from the following organisations and/or individuals on the draft of this report, which was published in December 2005.

The Royal College of Physicians

UK Cleaning Products Industry Association

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British Aerosol Manufacturers' Association

Met Office

Hillingdon Borough Council

RWE npower

The Society of Motor Manufacturers and Traders Limited

Mr Simon Francis

The Scotch Whiskey Association

Haskoning UK Ltd.

Cyfellion y Ddaear (Welsh FoE)

London School of Hygiene & Tropical Medicine

University of British Columbia

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GLA

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