This is a summary of the third report produced by the Air Quality Expert Group

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


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Introduction

Our activities lead to the emission of a wide range of gases and small particles into the atmosphere. These emissions affect the quality of the air we breathe, and hence our health and that of ecosystems. Some emissions, carbon dioxide for example, are causing the climate to change. The Government develops policies to safeguard human health and protect sensitive ecosystems by improving air quality. The Government also develops policies to reduce emissions of pollutants in order to limit climate change. These policies currently operate independently. There are, however, many linkages between the two types of pollution. The pollutants may have common emission sources and some pollutants affect both climate change and human health. The aim of this report is to investigate these linkages and to see if there are advantages in bringing the two types of policy together.

This report summarises Air Quality and Climate Change: A UK Perspective, the third report of the Air Quality Expert Group. It provides a simplified overview of the full report. The details of the scientific methods used to study climate change and air quality are contained in the full report at www.defra.gov.uk/environment/airquality. The full report includes information on the results of scientific research that the Air Quality Expert Group has used to inform its analysis. It also includes an outline of those points which are uncertain and are the subject of debate in the international scientific community. These details are not included here, although areas where the science can support strong conclusions, and those where there is uncertainty are highlighted. The recommendations that are made in the full report are included at appropriate points in this summary.

We have also included a glossary at the back to explain certain terms (these are shown in bold the first time they appear in the document).

This report is in three main sections, which address the following questions:

1. Which air pollutants cause poor air quality and climate change?
2. What kinds of changes in climate and air quality will be caused by this mixture of pollutants?
3. Can we take action that will tackle climate change and air quality together?
1. **Which air pollutants cause poor air quality and climate change?**

Mixtures of pollutants are emitted from different sources and are further modified by chemical reactions in the atmosphere.

Table 1 lists the major atmospheric pollutants relevant to this report, together with examples of their emission sources. We are primarily concerned with pollutants because of their effects on human and ecosystem health, and climate change (also called global warming). The main effects of each pollutant are also shown in Table 1.

Primary pollutants are directly emitted to the atmosphere. Secondary pollutants, however, are not directly emitted, but are formed from chemical reactions in the atmosphere. Ozone is the best known secondary pollutant; it is a component of photochemical smog formed by reactions between nitrogen oxides (nitric oxide and nitrogen dioxide and volatile organic compounds) (e.g. benzene and butane). These reactions are promoted by sunlight and are termed photochemical reactions.

**Particulate matter** is also an important pollutant, affecting both the respiratory and cardiac systems. Primary particulate matter includes black carbon (soot) and other components from a range of sources (see Table 1). Secondary particulate matter is of three main types: sulphate formed from emissions of sulphur dioxide, nitrate from nitrogen oxides emissions, and organic from some volatile organic compounds. Ammonia also contributes to secondary particulate matter. Particulate matter affects climate and in this context, the term aerosols is used for particulate matter.

**Table 1: Primary air pollutants.**

<table>
<thead>
<tr>
<th>Pollutant (Chemical formula)</th>
<th>Main sources as a result of human activity</th>
<th>Major effects on air quality and climate change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerosol/Particulate matter [PM]$^a$</td>
<td>Burning fossil fuels, e.g., road transport, electricity generation. Brake dust and dust from road surfaces. Dusty processes such as quarrying.</td>
<td>1. Affects human health, particularly small particulate matter size fractions. 2. Reflects (causing cooling) or absorbs (causing warming) sunlight depending on the composition of the particulate matter. 3. Indirectly affects the radiation balance (see Box 1) by influencing cloud formation.</td>
</tr>
</tbody>
</table>

$^a$ PM$_{10}$ is the concentration of particulate matter with a diameter less than or equal to 10 µm.
<table>
<thead>
<tr>
<th>Pollutant (Chemical formula)</th>
<th>Main sources as a result of human activity</th>
<th>Major effects on air quality and climate change</th>
</tr>
</thead>
</table>
| Sulphur dioxide (SO$_2$)    | Burning fossil fuels, e.g., domestic, industrial combustion, shipping, electricity generation. | 1. Affects human health.  
2. Forms secondary aerosol (sulphate), which affects health and causes cooling of the atmosphere.  
3. Contributes to **acidification** of sensitive ecosystems. |
| Nitrogen oxides (NO$_x$) [nitric oxide, NO, and nitrogen dioxide, NO$_2$] | Burning fossil fuels, e.g., road transport, shipping, electricity generation. | 1. Nitrogen dioxide affects human health.  
2. Promotes formation of ozone, which affects human and ecosystem health and which is a **greenhouse gas**.  
3. Forms secondary particulate matter (nitrate), which affects health and causes cooling of the atmosphere.  
4. Contributes to acidification and **eutrophication** of sensitive ecosystems. |
| Ammonia (NH$_3$)            | Agriculture, mainly from the production and management of manure and slurry in livestock farming. | 1. Promotes the formation of secondary nitrate and sulphate aerosol, which affects human health and causes cooling of the atmosphere.  
2. Contributes to acidification and eutrophication of sensitive ecosystems. |
<p>| Nitrous oxide (N$_2$O)      | Biomass burning, nitrogen fertilisers, sewage. | <strong>Greenhouse gas.</strong> |</p>
<table>
<thead>
<tr>
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<th>Major effects on air quality and climate change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>Burning fossil fuel, e.g., road and air transport, shipping, electricity generation.</td>
<td>1. Greenhouse gas. 2. Increases plant growth when other factors are not limiting.</td>
</tr>
<tr>
<td>Methane (CH₄)</td>
<td>Natural gas leakage, agriculture, landfill.</td>
<td>1. Greenhouse gas. 2. Promotes formation of ozone, which affects human and ecosystem health, and which is a greenhouse gas.</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>Burning fossil fuels, e.g., road transport, electricity generation.</td>
<td>1. Affects human health. 2. Promotes formation of ozone, which affects human and ecosystem health and is a greenhouse gas.</td>
</tr>
<tr>
<td>Volatile organic compounds e.g. benzene, butane, isoprene</td>
<td>Incomplete combustion, evaporation from solvent use, use and distribution of petrol, chemical processes in industry.</td>
<td>1. Some volatile organic compounds are carcinogenic. 2. Promotes formation of ozone, which affects human and ecosystem health, and which is a greenhouse gas. 3. Some volatile organic compounds promote the formation of secondary organic aerosol, which affects health and causes cooling of the atmosphere.</td>
</tr>
</tbody>
</table>
Some pollutants contribute to poor air quality, others influence climate change, and some do both.

Air quality pollutants generally stay in the atmosphere for a short period of time, that is days or weeks. Therefore their effects are mainly felt locally, for example within a city, or regionally, for example in the UK or in Europe. So policies for air quality are based on local and regional measures. By contrast, carbon dioxide has a lifetime of about 150 years and methane about 12 years. As a result, these pollutants travel large distances from where they are emitted. Our emissions affect the climate of other countries around the world and their emissions affect ours. International agreements are much more important for greenhouse gas emissions, although these must be implemented through actions at national level and through voluntary local action.

The Government’s Air Quality Strategy provides details of the air pollutants that it controls to protect our health and ecosystems. These are related to European legislation, to which we are subject. The Government’s air quality targets are listed as standards. These are concentrations of pollutants that should not be exceeded or should only be exceeded on a stated number of occasions. A mixture of local, national and European policies is used to ensure air quality standards are met. Where standards are not met, improvement measures are developed.

Greenhouse gases contribute to climate change because of their capacity to absorb infra red radiation, which can lead to warming of the atmosphere. Box 1 gives a brief summary of the way in which this process works. Some local authorities voluntarily set themselves targets to reduce local emissions of greenhouse gases.
gases, but, because the effects are felt globally, reductions are mostly tackled by national policies with initiatives taken by some industries. The Kyoto Protocol is an international agreement between the majority of the world’s countries to reduce emissions of greenhouse gases.

Carbon dioxide is the most important greenhouse gas and methane is the second most important. Both are present in the atmosphere quite naturally and the greenhouse effect is important in maintaining the surface of the Earth at a temperature that is suitable for life. Were carbon dioxide not present, the surface temperature would average less than -15°C, and would be too cold for most life as we know it. The problem is that concentrations of greenhouse gases have increased rapidly since the industrial revolution. Figure 1 shows the increases in the atmospheric concentrations of carbon dioxide and methane over the past few decades. Water is also a greenhouse gas, but it does not contribute directly to climate change (see discussion below).

**Figure 1:** Concentrations of carbon dioxide and methane measured at several observatories worldwide, Barrow in Alaska, Mauna Loa in Hawaii, Samoa, and the South Pole. The concentration of carbon dioxide is given in parts per million (ppm) (left hand axis) and that of methane in parts per billion (ppb) (right hand axis). Box 2 gives a brief explanation of these units. (Source: NOAA Climate Monitoring and Diagnostics Laboratory).
Box 1: Processes affecting the balance of radiation in the atmosphere

The Earth is warmed by absorbing radiation from the Sun. It is cooled by the emission of infra red radiation from its surface and the balance between this absorption–emission process serves to keep the Earth’s temperature steady. Any changes in the balance can lead to changes in temperature. Greenhouse gases, such as carbon dioxide, absorb some of the infra red radiation emitted by the Earth and then re-emit it in all directions, so that some is transmitted back towards the Earth’s surface and causes warming; this is the greenhouse effect (See Figure 2).

Not all of the radiation that strikes the surface of the Earth from the Sun is absorbed; some is scattered back. The reflectivity of the Earth’s surface is called its albedo. Snow has a high albedo and the oceans a relatively low albedo. The albedo can be changed, for example by agriculture, biomass burning, deposition of soot on snow and retreating ice sheets and glaciers.

Figure 2: Radiative processes in the Earth’s atmosphere and at its surface. (Source: Met Office).
Concentrations of trace gases in the atmosphere are usually expressed in units of parts per billion (1,000,000,000), ppb, or parts per million, ppm. These give the ratio of the number of molecules of the trace gas, carbon dioxide for example, to the total number of molecules in the volume of air of interest. European legislation requires that concentrations of air quality pollutants are given in units of micrograms of pollutant per cubic metre of air (μg m\(^{-3}\)). The conversion from ppb units to μg m\(^{-3}\) units depends on the pollutant and on the temperature and pressure. For ozone, at 20°C and a pressure of 1 atmosphere, 1 ppb is equal to 2 μg m\(^{-3}\).

Pollutants that affect the Earth’s radiation balance are called climate active pollutants. One way of describing their impact is through the idea of radiative forcing. Radiative forcing can be thought of as the change in this radiation balance since 1750, i.e. before the industrial revolution, which led to a continuing increase in emissions of pollutants from human activity. Radiative forcing is a measure of the change caused by man-made emissions of a particular primary pollutant, or of man-made emissions leading to formation of a particular secondary pollutant. Figure 3 shows a bar graph of the radiative forcing for both gases and for aerosols (particulate matter). Some radiative forcings are positive, for example, carbon dioxide, which means they lead to warming of the atmosphere; others are negative, such as the total effects of aerosols, which means they lead to cooling of the atmosphere. The graph shows uncertainties which are discussed in more detail in the following section.

The other main greenhouse gases in addition to carbon dioxide and methane, are nitrous oxide and halocarbons. Halocarbons are very long-lived gases which were used for a wide range of purposes, for example as refrigerants. Their impact on stratospheric ozone (ozone in the upper atmosphere) was recognised in the Montreal Protocol and their use was banned. Halocarbon concentrations in the atmosphere are slowly decreasing and so they are not included in Table 1.

Water vapour is present naturally in large quantities and contributes to the greenhouse effect. It is not included in Figure 3, however, because the amount of water vapour present in the atmosphere is controlled by evaporation and so by the temperature of the oceans and the air and by the amount of moisture in the soil (except in the very dry upper atmosphere where water...
vapour emitted directly from aircraft can be important). As the temperature of the atmosphere increases, the amount of water vapour will increase, leading to a further increase in the temperature – an example of positive feedback.

Ozone is found in the stratosphere and the troposphere, the upper and lower atmosphere. In the stratosphere, the ozone layer plays an important role in filtering out harmful ultra violet rays from the sun. In the troposphere, ozone is a greenhouse gas and has a warming effect on the climate.

At the Earth’s surface, ozone is an air pollutant and can be harmful to people’s health and ecosystems. Ozone is formed by chemical reactions in sunlight from precursor gases such as nitrous oxide and volatile organic compounds. A reduction in the emissions of precursors would lead to a reduction in ozone in the troposphere. Figure 3 shows that increases in tropospheric ozone have had a positive radiative forcing or a warming effect on climate, whilst stratospheric ozone depletion has led to a small, negative forcing or cooling effect.

**Figure 3:** Radiative forcing (in watts per m²) of the climate, due to human activity (anthropogenic), for the year 2005, relative to 1750. Where CO₂ is carbon dioxide, CH₄ is methane, and N₂O is nitrous oxide. The figure also shows the natural changes that have occurred from changes in solar radiation. The coloured bars given the radiative forcing, the black lines give the uncertainty range. (Source: IPCC Fourth Assessment Report, 2007; see bibliography).
Aerosols (particulate matter) have a complex effect on climate.

- Black carbon (soot) absorbs radiation from the Sun; this energy is then lost to the surrounding atmosphere leading to warming and a positive radiative forcing. It can also decrease the albedo of snow.

- Some other aerosols (e.g. sulphate) reflect radiation from the Sun back out to space and so can lead to cooling.

- Aerosols also act indirectly because they are involved in the formation of clouds, which have a large effect on the balance of radiation in the atmosphere.

Climate change is a long-term process and many of the predictions of temperature increase are made on a century timescale. The lifetime of an atmospheric pollutant – the time it is likely to remain in the atmosphere once emitted – is important in working out its impact on climate. Aerosols have a lifetime of about a week, in contrast to carbon dioxide's lifetime of about 150 years. If we stopped emitting aerosols, or the precursors of secondary aerosols, there would be no aerosols from human activity in the atmosphere after a matter of only a few weeks, whereas the carbon dioxide we emit remains in the atmosphere, and affects the radiation balance, for over a century.

The radiative forcings shown in Figure 3 do not reflect the differences in lifetime of different climate active pollutants and do not provide a fair reflection of the impact of current emissions on, say, a century timescale. Such a measure is provided by the global warming potential. The global warming potential is the ratio of the radiative forcing from the instantaneous release of 1 kg of a substance, relative to that of carbon dioxide, integrated over a period of time, usually 100
years. The global warming potential is 1 for carbon dioxide and 23 for methane, showing that emissions of methane are 23 times more effective than emission of the same mass of carbon dioxide in changing the radiation balance over the next century. Short-lived species, such as aerosols have small global warming potentials, even if they have large radiative forcings, because their effects rapidly disappear as they are removed from the atmosphere.

The distribution of pollutants throughout the atmosphere depends on their lifetimes. Carbon dioxide has a long lifetime, and can be carried large distances from its original source. As a result its concentration varies very little throughout the atmosphere (Figure 1). Methane is also well-mixed in the atmosphere, although its lifetime is about ten times less than that of carbon dioxide and its concentration shows some variation from place to place (Figure 1). Aerosols, though, are carried much shorter distances before they are lost from the atmosphere and stay within the region close to their source. This can lead to a local (or regional) effect on radiative forcing and hence on temperature, which is not well understood.

**Recommendation:**

The relationship between local radiative forcing and local temperature response has not been sufficiently investigated. This may be particularly important for short-lived climate active pollutants such as aerosol and tropospheric ozone and needs further research.

2. **What kinds of changes in climate and air quality will be caused by this mixture of pollutants?**

Models of the atmosphere and of the coupled processes affecting climate change and air quality

Predictions of the future climate, and of the effects of climate on air quality, are made using computer models. The most advanced are called Global Circulation Models. They divide the atmosphere into thousands of boxes and calculate the movement of the air between these boxes and the changes of the climate. The sides of the boxes are typically 100 km in length – to work with a larger number of smaller boxes would require far too much computer power. This means that important features, such as clouds, can not be treated directly and have to be included through their average effects, which are represented approximately, through what are termed parameterisations. This adds significantly to the uncertainties in the model predictions (see below). Interactions between the atmosphere, the oceans, the land surface and ice are included in climate models, as are natural variations in the radiation from the Sun. The components of the climate system are shown in Figure 4.

Radiation is a central element of the models. The models must be able to describe the ways in which the concentrations of greenhouse gases will change in the future. One element of such calculations is the use of emissions scenarios, models of the way in which emissions of, say, carbon dioxide
and methane will change in the future. It is difficult to predict exactly how emissions will change, because this depends on population growth, human behaviour, economic and technical developments and the effectiveness of international, national and local initiatives to reduce emissions, not only of carbon dioxide but also of other greenhouse gases.

Models must also calculate the concentrations of aerosols and of the greenhouse gases, such as ozone, that are affected by atmospheric chemistry. Figure 4 shows the types of processes that are included. The chemistry is complicated as are the processes affecting the interaction between aerosols and radiation. Simplifications are necessary to carry out the calculations with available computer power, adding to the uncertainties in the calculations.

One of the key issues is that of feedbacks between the changing climate and physical, chemical and biological processes. Higher temperatures generally lead to an increase in natural emissions of pollutants. These include methane from wetlands and tundra, carbon dioxide from soil and plant respiration, and volatile organic compounds from vegetation. These emissions are part of the overall carbon cycle, which is a key component in climate change and includes the exchange of carbon dioxide with the oceans, soils and vegetation, in addition to our emissions from burning fossil fuels. The response of the carbon cycle to changing temperature is a central element in climate models. Large amounts of carbon are released from land and ocean surfaces, for example from plant respiration and decaying plant matter. At the same time similar amounts of carbon are absorbed, for example by the oceans and plants. The rates of these processes will alter in a changing climate. The size and direction (overall emission or overall uptake) of the effects will depend on whether ecosystems are limited by temperature or moisture.

**Figure 4:** A simplified view of the climate system. The numerous components that comprise the system introduce a large degree of complexity into models.
Global models cannot provide sufficiently detailed information to allow us to predict the future climate in a given region, where the climate is influenced by features such as hills that are not included in the global models due to the size of the boxes used. Regional models can be run with such features included. They cover a smaller region of the Earth’s surface and so have smaller boxes. The climate at the edges of the region covered by the regional model is provided by the global model. These regional models are used to predict, for example, changes in rainfall in the UK. They could be used to predict regional air quality in a changed climate, but this has not yet been done.

**Uncertainty in model predictions**

There are a number of different models used by climate research groups across the world. These models all use the same basic science but differ in the ways the component processes are treated. For example the way clouds are represented and their effects on radiation differ in detail in the different models. In addition, we have an incomplete understanding of some of the important processes occurring in the atmosphere, for example, the complex feedback mechanisms discussed above. These introduce further uncertainty into the models. There is, however, a complete consensus between the models that the climate is changing and that the global average temperature is rising. The IPCC Fourth Assessment Report (see Bibliography) analyses the results of a number of climate models and states that the global average surface warming following a doubling of carbon dioxide concentrations is likely to be in the range 2°C to 4.5°C with a best estimate of about 3°C, and is very unlikely to be less than 1.5°C.

**Climate change and chemistry in the atmosphere**

The following sections examine the likely effects of climate change on the chemistry occurring in the atmosphere.

*Tropospheric ozone*

The formation of ozone in the troposphere depends on chemical reactions involving nitrogen oxides and volatile organic compounds in the presence of sunlight.
Ozone (O\textsubscript{3}) absorbs the radiation from the Sun and breaks apart, in a process called photolysis, to form an oxygen atom (O*) and an oxygen molecule (O\textsubscript{2}). The star signifies that O has retained enough energy from the reaction to allow it to react with water (H\textsubscript{2}O) to form two hydroxyl radicals (OH). The hydroxyl radical is highly reactive and starts a series of reactions involving nitrogen oxides and volatile organic compounds, carbon monoxide and hydrogen. Provided nitrogen oxides are present in a high enough concentration, the reaction sequence leads to formation of additional ozone. If the concentrations of nitrogen oxides are high then ozone is produced and its concentration rises. If the concentrations of nitrogen oxides are low then the concentration of ozone can be reduced.

Nitrogen oxides are emitted from soils and are also produced by lightning, but they are mainly emitted from burning of fossil fuels, for example, in power stations and vehicle engines. Their distribution throughout the atmosphere reflects their source regions, with the industrialised northern hemisphere providing most of the emissions. There are ways, though, in which nitrogen oxides can be transported from polluted to less polluted regions.

The effects of increased temperatures, resulting from climate change, on ozone formation are complicated. One consequence derives from the increased concentration of water vapour, which will result in an increase in the rates of loss of ozone by photolysis and of production of hydroxyl radicals.

In regions where the concentrations of nitrogen oxides are low, such as above the oceans, this will lead to a reduction in the concentration of ozone. In the more polluted regions, though, where the concentrations of nitrogen oxides are higher, there is predicted to be an increased rate of ozone formation.

**Methane**

Methane is removed from the atmosphere by reaction with hydroxyl radicals and any change in the concentration of hydroxyl radicals will affect the global concentration of methane and its contribution to global warming. The hydroxyl radical concentration depends on the chemistry described above for ozone, and so is affected by emissions of nitrogen oxides and of volatile organic compounds, from both man-made and natural sources. The effect of climate change on hydroxyl radicals is complex, but models predict that it will lead to increases in the hydroxyl radical concentration in the more polluted northern hemisphere and decreased concentrations in the southern hemisphere. Overall, the rate of removal of methane is likely to increase, thus reducing its concentration, but the uncertainty is large. The effects of emissions of volatile organic compounds and of nitrogen oxides on ozone and on methane provide an important link between air quality and climate change.

**Nitrogen oxides and volatile organic compounds**

Nitrogen oxides, volatile organic compounds, carbon monoxide and hydrogen have an indirect effect on radiative forcing through
their influence on the concentrations of the greenhouse gases methane and ozone, described above. The Kyoto protocol only covers the long-lived greenhouse gases carbon dioxide, methane, nitrous oxide and certain halocarbons. There are no controls on ozone, which is a secondary pollutant. Future policies and agreements could provide indirect control on ozone by including measures to limit emissions of the ozone precursors listed above. Such measures would provide a direct link between air quality and climate change policies on a global scale. Ozone precursor emissions are controlled for air quality purposes in Europe.

Recommendation:
Future climate change policy should consider extending the number of climate active pollutants that are included in the development of climate change policies.

Aerosols and climate change
Secondary aerosols (particulate matter) can be formed from emissions of sulphur dioxide, nitrogen oxides and volatile organic compounds. Emissions of ammonia also play an important role because sulphate and nitrate aerosols are often found in compounds with ammonia (ammonium salts). The chemistry involved in the formation and evolution of aerosols is related to that described above for ozone formation. The aerosols are changed by chemical and physical processes in the atmosphere, and these processes affect their contribution to the absorption or scattering of radiation and also to their role in the formation of clouds. The contributions of aerosols to climate change are, therefore, complex and change as the aerosols evolve in the atmosphere. Predicting how these processes will change as the climate changes is very difficult.

Aerosols are also directly emitted from the Earth’s surface. Emissions can result from human activity, for example soot from combustion, or from natural processes, such as sea salt and desert dust. These aerosols are also changed in the atmosphere and may become mixed with, for example, nitrate aerosol. Their contributions to climate change depend on their involvement in the formation of clouds and on whether they scatter or absorb radiation. Soot absorbs radiation whereas desert dust tends to scatter it. The effect of this scattering ability depends on the location of the aerosol and of the albedo (Box 1) of the Earth’s surface below the aerosol.
A moderately scattering aerosol, when located above the oceans, can lead to a cooling effect because it scatters more than the ocean surface below it would. The opposite applies if the aerosol is above snow or reflective cloud. These effects are illustrated in Figure 5.

Aerosols have a short lifetime in the atmosphere, typically about a week near the Earth’s surface. This means that they have only a small global warming potential, because the effects of aerosol emitted now would be very small in 100 years. If we were to continue to emit aerosols at our present rate their effects on climate would continue. There is pressure to reduce emissions of aerosols (particulate matter) and their precursors because of their effects on air quality and human health. Future decreases in emissions of an absorbing aerosol such as soot would have a cooling effect, whereas reducing emissions of sulphur dioxide, thus reducing the concentrations of sulphate aerosol, would lead to warming. This is a very difficult issue that has led to extensive debate and to suggestions to add sea salt or sulphate aerosol to the atmosphere, which would increase the albedo and lead to a cooling effect. Our limited understanding of the processes involved has led to widespread concern over such proposals.

The importance of the impact of particulate matter on human health provides a key link between air quality and climate change that is discussed in greater detail below.

Figure 5: Satellite image of smoke from biomass burning in Portugal. The red dots are fires and the smoke plume is seen moving to the NE. The presence of the smoke enhances the Earth’s albedo over ocean and reduces the Earth’s albedo over cloud.
Ecosystems and climate change
Climate change can also influence air quality though its impacts on ecosystems. The deposition of air pollutants to the ground surface, mainly through uptake by vegetation, is reduced in summer droughts which are likely to become more frequent. This would lead to higher pollutant concentrations, but to a reduced impact of the air pollutants on ecosystems. However, if vegetation is active over a longer growing season and if forest cover is increased, this would lead to greater deposition of air pollutants to vegetation in non-drought periods, thereby lowering concentrations in the air. Emissions of methane from soils and volatile organic compounds from vegetation may be increased in a warmer climate, leading potentially to greater concentrations of ozone.

How is air quality likely to change in the future?
Increasing temperatures will cause changes in behaviour which in turn will lead to changes in emissions of air quality pollutants. Examples of such changes include greater use of air conditioning in summer, decreased use of heating in homes and offices in winter and increased evaporative emissions of petrol. In the UK, however, there is likely to be a decrease in emissions of most air quality pollutants and their precursors over the next 20 – 30 years, not because of a decrease in our use of fossil fuels, but because of improved technology, such as particle traps in vehicles and nitrogen oxide reduction techniques. These improvements are driven by legislation, for example EU legislation to reduce emissions from road transport. In addition, the UK Government has pledged to cut carbon dioxide emissions by 60%, relative to 1990 levels, by 2060. If appropriate decisions are made, this is also likely to reduce emissions of air quality pollutants, since many air quality and climate change pollutants have the same sources.

Emissions from rapidly developing countries such as China and India are unlikely to decrease, unless there are quite dramatic, and presently unanticipated, changes in technology. This will lead to significant local and regional problems in these countries, but also to effects that are felt globally. An important issue is an increase in background ozone concentration. Measurements at
the Mace Head observatory in Western Ireland show that the ozone concentration is slowly but steadily increasing when the air is coming from the west and so has not been exposed to significant emissions for several days. Current monthly mean concentrations are about 80 µg m\(^{-3}\) in the spring. The Government’s air quality objective for ozone is around 100 µg m\(^{-3}\) so that there is little room for manoeuvre in adding to this concentration from our own emissions of the ozone precursors, volatile organic compounds and nitrogen oxides. Increases in temperature could increase this background ozone concentration in the Northern Hemisphere, although the uncertainties are large. Increases in Asian emissions of ozone precursors will almost certainly lead to increased Northern Hemisphere background concentrations.

**Recommendation:**

The development of well informed European policy on ozone precursors would benefit greatly from a more global view of emissions, trends and abatement issues.

Predicted increases in temperature in the summer due to climate change are likely to lead to increased summer-time ozone concentrations in the UK and Europe. We saw an example of what may lie in store for us in the heatwave experienced especially in SE England in August 2003, when the temperature rose to the high 30s °C. High concentrations of ozone were experienced, with maximum values above 200 µg m\(^{-3}\). The air was very still and there was minimal cloud cover, so that the photochemical reactions leading to ozone formation were strongly promoted. Concentrations of secondary particulate matter also increased. Under these anticyclonic conditions, the slow air flow is frequently from the east or south east, and there was a substantial contribution from European emissions of ozone precursors. The drought conditions accompanying the episode decreased deposition of ozone to vegetation, while, the high temperatures led to increased emissions of isoprene, a highly reactive volatile organic compound that is emitted from vegetation, and is an ozone precursor. Both of these effects further contributed to the high ozone concentrations. The potential importance of future emissions from vegetation of isoprene and other volatile organic compounds for UK air quality is discussed further below.

The effects of the heatwave on air quality were even more extreme in Europe and Figure 6 shows the wide occurrence of high measured concentrations of ozone on several days during the episode.

Calculations performed at the UK Met Office have shown that summers like 2003 are likely to occur regularly by about 2040. It is difficult to be precise about the likelihood of
future ozone episodes because of the likely future reductions in emissions of nitrogen oxides, which are ozone precursors. It is also not yet clear whether or not the very still air conditions experienced in 2003 will prevail in these future heatwaves. Windier conditions would tend to reduce the ground-level concentrations of ozone.

Poor air quality in winter occurs in cold conditions with stagnant air. Under these conditions, called inversions, the air is colder near the ground than it is at a height of approximately 100 metres. This traps the air near the ground and emissions, especially from road vehicles, can build up leading to high concentrations of nitrogen dioxide and

Figure 6: Monitoring stations reporting an hourly ozone concentration in excess of 180 \( \mu g \) m\(^{-3} \) during the August 2003 heatwave. (Source: European Environment Agency).
particulate matter in cities. Such conditions led to very poor air quality in London in December 1991 and in several cities across the UK in December 2001. Climate change is likely to reduce the frequency of such episodes, because our winters are predicted to become windier. Climate change is already bringing an increase in winter rainfall. Since rainfall washes aerosols and soluble gases from the atmosphere, this change could also improve air quality.

It is likely that changes in rainfall patterns, increased frequencies of summer droughts, increased temperatures and extended growing seasons will modify the impacts of sulphur and nitrogen deposition, and of ozone, on UK ecosystems. These effects will be considered in a separate report which is due to be published next year.

3. **Can we take action that will tackle climate change and air quality together?**

There is clearly a close relationship between air quality and climate change pollutants. Table 1 shows that they have common sources and some air quality pollutants, such as ozone and particulate matter, have a direct effect on climate. Are there ways in which we can tackle climate change and air quality together? Are there measures that will reduce the impact of human activity on climate change and, at the same time, improve air quality (win-win measures)? What about measures which lead to reduction in emissions of a climate active pollutant but to an increase in emissions of air quality pollutants or vice versa (win-lose measures)?

The UK has an excellent record of reducing emissions of air quality pollutants. While there is a commitment to reducing carbon dioxide emissions over the next 50 years, our record in this regard is less good. Following a reduction of 7.5% from 1990 to 2002, the predicted reduction in carbon dioxide emissions between 2002 and 2020 is only 4%. This contrasts with the predicted reductions in emissions of air quality pollutants: nitrogen oxides, 45%, sulphur dioxide, 64%, volatile organic compounds, 26% and PM$_{10}$, 19% over the period 1990 to 2002. Less of a reduction is predicted for ammonia (10%). Improved technology driven by legislation and consequent pollution abatement, rather than reductions in use, has played a key role in reductions of emissions of air quality pollutants. Examples include reductions in emissions of nitrogen oxides since the 1990s, following the fitting of three way catalysts to petrol vehicles and low nitrogen oxide burners in power stations. There are a number of actions, in addition to abatement, that can be taken to reduce emissions of air quality and climate active pollutants.
They can be grouped under the following headings:

- **Conservation** – reducing the use of resources through energy conservation, for example by improving the insulation in our houses.

- **Efficiency** – carrying out the same activity, but doing so more efficiently, and so reducing the use of resources and emissions of air quality and climate active pollutants, for example by improving the efficiency of car engines.

- **Fuel switching** – substituting a higher emission fuel with a lower emission fuel; the switch from coal to natural gas in power stations led to significant reductions in carbon dioxide emissions.

- **Demand management** – implementation of policies or measures which serve to control or influence demand, for example the congestion charge in central London.

- **Behavioural change** – changes in the habits of individuals or organisations that result in reduced emissions, for example travelling by train instead of by air.

Recommendation:

Measures which result in benefits both for air quality and climate should be promoted. 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.

Table 2 gives some examples of win-win measures that are able to reduce emissions of both air quality and climate change pollutants. It is relatively easy to make decisions on the use of win-win measures, provided they are technically feasible and economically viable. It is more difficult to evaluate measures which lead to win-lose outcomes. A major difficulty lies in measuring the outcomes. Emissions of particulate matter directly affect human health and the effects can be quantified, for example through the number of deaths that are likely to result from the emissions or the increase in the number of hospital admissions. Emissions of greenhouse gases are assessed through global warming potentials, but how do you equate this measure with the health impact measures for air quality pollutants? In the end, more general estimates and comparisons have to be made in the development of policy by Government, but putting effort into
the provision of the measures themselves, even if they cannot be directly compared, is essential, as is continuing work to improve the basis of the comparison.

**Recommendation:**
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 strategies reducing emission of air quality and climate active pollutants.

An example of the difficulty in assessing carbon dioxide emissions vs emissions of air quality pollutants is provided by the increasing use of diesel cars in the UK. This is driven by the perception that diesel-engined cars are more fuel-efficient than petrol cars, leading to lower carbon dioxide emissions. The measure that is used to compare the two is grams of carbon dioxide emitted per kilometre travelled. Diesel vehicles are undoubtedly more efficient in this respect, although the difference in 2005 has been estimated, on average, as only 6.5%, partly because diesel cars tend to have larger engines than petrol cars. Other issues should also be included in the calculation, for example the emissions of carbon dioxide involved in producing the fuels at refineries. Emissions of particulate matter and nitrogen oxides are greater for diesel vehicles than for petrol vehicles, which means replacing petrol by diesel is a win–lose measure, reducing carbon dioxide emissions, but increasing emissions of air quality pollutants. Finally, diesel particle emissions are more sooty that those from petrol vehicles, which leads to a warming of the climate because soot absorbs radiation. But the soot lasts only a short time in the atmosphere and so its global warming potential is very small. So it is difficult to assess its climate change impact using the conventional measure. All of these considerations emphasise the difficulty of off-setting one effect against another. The important point is that all effects should be considered in making any decision. That decision is likely to change with time, for example as tighter limits are placed on emissions of particles and nitrogen oxides from vehicles; the methods adopted may well reduce fuel efficiency and so increase carbon dioxide emissions in order to achieve the required air quality benefits. As far as the effects of emissions from burning fossil fuels are concerned, the dominant effect for climate change is the emission of carbon dioxide. The effects of air quality pollutants on climate change are both much shorter term and of smaller consequence.

**Recommendation:**
Analysis of the impact 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 parts of the environment.
It is also important that, where possible, we include full life cycle or fuel cycle analyses in our considerations. The aim of such analyses is to assess emissions of both air quality and climate active pollutants at all stages of the production and use of a fuel, including extraction, transport of the crude and the refined fuel, refining, distribution and use. Life cycle analyses carry out similar assessments of emissions in the production and use of, say, a car. For example, hydrogen is much less polluting at the point of use than conventionally fuelled vehicles, but the emissions involved in producing the hydrogen must also be assessed. Renewable fuels, such as biofuels, must be subjected to similar assessments, which should also include the emissions of volatile organic compounds, such as isoprene, which are substantial for trees such as willow and poplar. Isoprene emissions increase as the temperature rises and act as ozone precursors. This analysis is not trivial when there is potentially more than one type of crop available to produce fuels like biodiesel or bioethanol (for example from grain or sugar beet), each source leading to potentially different emissions along the fuel chain. National policies to increase forest planting to increase the UK carbon sink may also lead to increases in emissions of volatile organic compounds, depending on the species selected, but would also 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.

**Recommendations:**
A comprehensive life cycle analysis should be carried out comparing the environmental implications of electric and hybrid vehicles with each other and with conventionally-fuelled vehicles, to inform policy on encouraging their use. A detailed fuel cycle analysis is required to consider the air quality and climate change implications of the production, supply and consumption of biofuels for transport.
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 emissions of air quality pollutants and greenhouse gases.

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 air quality and global pollutants also need to be considered.

The substantial improvements in air quality in the UK over recent years are largely due to emissions abatement measures driven by legislation. Local authorities have also played a key role, through Local Air Quality Management, in which the Government has given responsibility for exceedences of air quality objectives to local authorities. Ozone is excluded from Local Air Quality Management, because it is a regional pollutant and cannot be controlled by local measures. If exceedences of the Government’s air quality objectives for other pollutants, such as nitrogen dioxide and PM$_{10}$, are observed, or predicted through models, then local authorities are required to set up Air Quality Management Areas, with plans to reduce concentrations in those areas, for example by control of traffic flows. This policy has led to considerable air quality expertise in local authorities and to innovative approaches to air quality management. No such statutory responsibility has yet been placed on local authorities for local controls on emissions of greenhouse gases. The Government encourages voluntary action and, for example, is consulting on how to tackle climate change through the planning system. Regional and local governments have an important role to play in reducing emissions of carbon dioxide, through community leadership, local transport planning, urban planning and design, and their own procurement and operations. They are also well placed to link air quality and climate change policies, but they need appropriate direction, support and guidance that recognises the synergies and conflicts that have been outlined in this report.

**Recommendation:**

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.
Table 2: Examples of measures to reduce emissions of air quality and climate active pollutants and their effects.

*Win-win measures that can lead to reductions in emissions of both air quality and climate active pollutants*

<table>
<thead>
<tr>
<th>Measure</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching from coal to natural gas for power generation.</td>
<td>Reduces carbon dioxide emissions for each kiloWatt generated. Emissions of sulphur dioxide and nitrogen oxides are also reduced.</td>
</tr>
<tr>
<td>Use of new technologies in road transport, e.g. (i) hybrid vehicles (ii)</td>
<td>Reduces carbon dioxide emissions for each kilometre travelled and also emissions of nitrogen oxides and particulate matter. Essential that the whole fuel/vehicle cycle is analysed (e.g. the emissions associated with hydrogen generation).</td>
</tr>
<tr>
<td>hydrogen from natural gas or from renewables (iii) lean burn petrol vehicles fitted with nitrogen oxide traps.</td>
<td></td>
</tr>
<tr>
<td>Efficiency improvements in domestic appliances and industrial processes,</td>
<td>Reduces emissions of both types of pollutant, but efficiency measures sometimes result in increased demand, which must be avoided.</td>
</tr>
<tr>
<td>e.g. through technical developments.</td>
<td></td>
</tr>
<tr>
<td>Energy conservation, e.g. through improved insulation of houses.</td>
<td>Reduces emissions of both types of pollutant.</td>
</tr>
<tr>
<td>Demand management/behavioural change: improved public transport coupled</td>
<td>Reduces emissions of both types of pollutant.</td>
</tr>
<tr>
<td>with disincentives for private car usage.</td>
<td></td>
</tr>
</tbody>
</table>

*Win-lose: measures that reduce emissions of climate active pollutants but could increase emissions of air quality pollutants*

<table>
<thead>
<tr>
<th>Measure</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased use of diesel in vehicles in place of petrol.</td>
<td>Reduces carbon dioxide emissions but increases emissions of particulate matter and nitrogen oxides. Diesel soot emissions lead to warming of the atmosphere, but soot has only a short atmospheric lifetime.</td>
</tr>
<tr>
<td>Use of biofuels for transport and domestic use.</td>
<td>Reduces carbon dioxide emissions but may lead to increased emissions of ammonia, nitrous oxide and volatile organic compounds, depending on species and management regime.</td>
</tr>
<tr>
<td>Waste incineration rather than landfill, especially if used for combined heat and power generation.</td>
<td>Reduces methane emissions, and emissions of carbon dioxide with combined heat and power generation, but increases emissions of some air quality pollutants.</td>
</tr>
</tbody>
</table>
**Lose-win: measures that reduce emissions of air quality pollutants but could increase emissions of climate active pollutants**

<table>
<thead>
<tr>
<th>Measure</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use of flue gas desulphurisation in power stations.</td>
<td>Reduces sulphur dioxide emissions, but reduces efficiency and therefore leads to increased carbon dioxide emissions per kiloWatt generated.</td>
</tr>
<tr>
<td>Fitting some nitrogen oxide reduction traps to diesel vehicles (e.g. through the use of selective catalytic reduction).</td>
<td>Reduces nitrogen oxides but may lead to increased emissions of nitrous oxide.</td>
</tr>
<tr>
<td>Fitting particulate traps on diesel vehicles.</td>
<td>Reduces particulate matter emissions, but may introduce a fuel penalty and an increase in carbon dioxide emissions.</td>
</tr>
<tr>
<td>Fitting three way catalysts to petrol cars.</td>
<td>Reduces the emissions of nitrogen oxides, carbon monoxide and volatile organic compounds but leads to small increases in fuel consumption and hence in emissions of carbon dioxide.</td>
</tr>
<tr>
<td>Reducing sulphur in fuel.</td>
<td>Increases refinery carbon dioxide emissions, but reduces sulphur dioxide emissions.</td>
</tr>
</tbody>
</table>

**Lose-lose: measures that could lead to increases in emissions of both air quality and climate active pollutants**

<table>
<thead>
<tr>
<th>Measure</th>
<th>Effect</th>
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</thead>
<tbody>
<tr>
<td>Shifts from train to short haul flights.</td>
<td>Increases emissions of carbon dioxide, nitrogen oxides and particulate matter.</td>
</tr>
<tr>
<td>Increased use of coal in power stations, rather than natural gas, renewables or nuclear.</td>
<td>Increases emissions of carbon dioxide, nitrogen oxides and particulate matter.</td>
</tr>
<tr>
<td>Increased demand for products and services.</td>
<td>Increased fuel efficiency in aircraft, for example, has been more than offset by increased demand.</td>
</tr>
</tbody>
</table>
Bibliography

A full set of references can be found in the main report at: www.defra.gov.uk/environment/airquality

The brief of the Intergovernmental Panel on Climate Change (IPCC) is to assess scientific, technical and socio-economic information relevant for the understanding of climate change, its potential impacts and options for adaptation and mitigation. Their website is: http://www.ipcc.ch/

The IPCC Third Assessment Report, published in 2001, that was extensively used by AQEG, can be found at http://www.grida.no/climate/ipcc_tar/

The summary for policy makers of Working Group I of the IPCC Fourth Assessment Report, Climate Change 2007, was released on February 2nd 2007 and can be found on the IPCC website. Working Group I reports on The Physical Science Basis. Their full report will be published shortly. Reports of Working Groups II (Impacts, Adaptation and Vulnerability) and III (Mitigation of Climate Change) and a Synthesis Report will be approved and released throughout 2007.


Information on the Government’s policies on climate change including the Climate Change Programme and the Climate Change Bill can be found at: http://www.defra.gov.uk/environment/climatechange/index.htm
Glossary

**Acidification**
Formation of acids, mainly sulphuric and nitric acids, in the atmosphere and their deposition at the Earth’s surface.

**Aerosol**
Solid or liquid particles, with typical sizes between a few thousand millionths of a metre (about the size of a virus) to 100 millionths of a metre (about the thickness of a human hair). Aerosols may be of either natural or man-made origin. Aerosols may be *primary* (directly emitted into the atmosphere such as dust and soot) or secondary (formed in the atmosphere by chemical reactions such as sulphate aerosols). Aerosols settle back to the Earth’s surface slowly because of their small mass, and may remain in the lower part of the atmosphere from a few hours to about a week. They influence climate in two ways: directly through scattering and absorbing radiation, and indirectly through their involvement in cloud formation.

Aerosols are a key air quality pollutant. In this context they are generally called particulate matter. Particulate matter can affect human health, with the smaller particles tending to be more damaging.

**Biofuel**
Plant material, animal waste and specifically grown crops which can be burnt to produce energy. Examples of biofuel include alcohol (ethanol) from fermented sugar, wood and soybean oil.

**Climate**
The weather averaged over a period of time, for example 30 years. Elements averaged include temperature, rainfall and wind.

**Climate change**
Climate change is a change in the average weather, including, for example, the temperature, that lasts for an extended period (say 10 years or longer).

**Ecosystem**
A system of interacting living organisms together with their physical environment.

**Eutrophication**
Eutrophication is the accumulation of excess nutrients (e.g. nitrogen) in an ecosystem. This can result in loss of sensitive species of plants and animals.
<table>
<thead>
<tr>
<th><strong>Global warming potential</strong></th>
<th>A measure of how much a given mass of greenhouse gas is estimated to contribute to global warming. It is a relative scale which compares the gas in question to that of the same mass of carbon dioxide over a given time period, usually 100 years. The global warming potential of carbon dioxide is by definition 1 for any time period.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Greenhouse effect</strong></td>
<td>Greenhouse gases absorb outgoing infrared radiation, emitted by the Earth’s surface. They then emit this infrared radiation in all directions, including downward, back to the Earth’s surface. This traps heat, causing warming within the surface-troposphere system and is called the greenhouse effect. Over the last 200 years, an increase in the concentration of greenhouse gases due to human activity, has led to more heat being trapped. This is called the enhanced greenhouse effect or global warming.</td>
</tr>
<tr>
<td><strong>Greenhouse gas</strong></td>
<td>Gases that cause the greenhouse effect (see above). Water vapour, carbon dioxide, nitrous oxide, methane and ozone are the primary greenhouse gases in the Earth’s atmosphere. There are a number of entirely man-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine and bromine containing substances.</td>
</tr>
<tr>
<td><strong>Particulate matter</strong></td>
<td>See aerosol.</td>
</tr>
<tr>
<td><strong>Photochemical reaction</strong></td>
<td>Chemical reactions which occur following the absorption of light by a molecule.</td>
</tr>
<tr>
<td><strong>Photochemical smog</strong></td>
<td>A mixture of pollutants, including ozone, in the surface layer of the atmosphere. Photochemical smog is caused by the action of sunlight on nitrogen oxides and volatile organic compounds (see below).</td>
</tr>
<tr>
<td><strong>Radiative forcing</strong></td>
<td>The change in the balance of incoming radiation from the Sun and of outgoing radiation from the Earth since 1750, i.e. since before the industrial revolution, which led to a continuing increase in emissions from human activity. Human-induced radiative forcing is the change caused by human emissions of a particular primary pollutant, or of human emissions leading to formation of a particular secondary pollutant.</td>
</tr>
<tr>
<td><strong>Stratosphere</strong></td>
<td>The region of the atmosphere above the troposphere (see below) that extends from an altitude of about 10 km to about 50 km. The bulk of the Earth’s ozone is in the stratosphere, where it acts to filter dangerous ultraviolet radiation.</td>
</tr>
<tr>
<td><strong>Troposphere</strong></td>
<td>The lowest part of the atmosphere from the surface to about 10 km in altitude where clouds and ‘weather’ phenomena occur. In the troposphere temperatures generally decrease with height and the air is generally very well mixed in this region.</td>
</tr>
</tbody>
</table>