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Ground-level ozone in the 21st century: future trends, impacts and policy implications

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SUMMARY FOR POLICY MAKERS

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Key messages

Tropospheric ozone (O_3) is a global air pollution problem and an important greenhouse gas. In large areas of the industrialised and developing world, ground-level O_3 is one of the most pervasive of the global air pollutants, with impacts on human health, food production, and the environment even at current ambient concentrations of 35-40 parts per billion (ppb).

Existing emission controls are insufficient to reduce current background O_3 concentrations to levels acceptable for human health and environmental protection. A new framework for action is needed to avoid a high O_3 future. This framework must:

- reduce both background and peak O_3, at global, regional, and national scales;
- control emissions from poorly regulated sources including international shipping, aviation, and biomass burning;
- improve integration between climate change and O_3 policies at the international, regional, and national scale;
- facilitate concerted global action to implement current emission controls, particularly of the oxides of nitrogen.

Key messages *(continued)*

Since the industrial revolution background O_3 has doubled in many parts of the Northern Hemisphere. High O_3 episodes exceeding the World Health Organisation guideline of 50 ppb, and peaks of 200 ppb or more continue to occur.

The full implementation of current legislation worldwide will be required to keep global O_3 concentrations in 2050 close to 2000 levels. In developing regions over the next few decades, O_3 pollution will increase and stronger controls will be needed to avoid further impacts on human health and the environment. Urban O_3 concentrations are expected to increase leading to greater human health impacts.

Ozone production, destruction and transport are closely coupled to climate processes which strongly influence O_3 concentrations at the regional and local scale. Climate change will make it harder to deliver O_3 policy targets even in countries where precursor emissions are projected to decrease.

Ozone will affect future climate due to its direct radiative forcing effect and as a result of the indirect effects of O_3 on the terrestrial carbon sink.

Global staple crop yield losses due to O_3 are likely to increase over the next two to three decades. In some rapidly developing regions, particularly Southern and Eastern Asia, O_3 pollution could pose as great a threat to food security as climate change. Emission controls and capacity building activities within these regions are required to avoid these impacts.

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1 Introduction

The 20th century was a period of unprecedented change: global population increased from 1.7 billion to 6.1 billion, global GDP increased nineteen-fold, and the use of fossil fuels grew fifteen fold. The enormous expansion in the global production of goods and services has allowed the world to sustain much larger populations and higher standards of living than at any time in human history. However, to support this growth, natural resources have been consumed at increasingly unsustainable rates and environmental degradation has accelerated.

Air pollution is one of the consequences of this unprecedented change. The World Health Organisation (WHO) estimates that 2 million people worldwide now die prematurely each year as a result of poor air quality; by comparison in 2005 an estimated 2.9 million people died from AIDS and in 2006 1.7 million died from tuberculosis. Air pollution is clearly a significant global problem.

The main air pollutants are particulate matter (PM), sulphur dioxide (SO_2), nitrogen dioxide (NO_2) and nitric oxide (NO) known together as nitrogen oxides (NO_X), carbon monoxide (CO), lead (Pb), and ground-level ozone (O_3). The Royal Society chose to undertake a detailed study on O_3[1] because it remains one of the most important of the global air pollutants in terms of impacts on human health, crops and forest yields, and natural plant communities, and may become more important in the future. It is also an important greenhouse gas and may have implications for future climate change. Despite efforts to control O_3 over recent decades, background mean concentrations in the Northern Hemisphere have more than doubled to 35-40 ppb since the industrial revolution, and daily peak concentrations continue to exceed the WHO guideline values of 50 ppb in many regions including Latin America, North America, Europe and Africa. Climate change over the next century also has the potential to influence future O_3 concentrations by modifying the rates of O_3 production and destruction in the atmosphere and at the Earth's surface, and the processes by which O_3 and its precursors are transported.

Global and regional O_3 concentrations over the coming century will be influenced by human activities, and particularly by emissions associated with population growth, industrialisation and economic growth. In addition to climate change, land use change and the effects of other local air pollution controls will also influence future O_3. This Royal Society study assesses possible future changes in global and regional O_3 concentrations to 2050 and 2100 given changes in socioeconomic factors, trends in emissions of precursor gases, emission control scenarios and climate change projections[2]. The report evaluates the potential effects of O_3 on human health, the natural environment, agriculture, and the climate system, and considers the policy implications of these impacts.

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[1] The Royal Society study can be downloaded from royalsociety.org

[2] Details of the new modelling work are provided in the full Royal Society report.

2 What is ground-level ozone?

Ozone is a natural constituent of the atmosphere and is present in the stratosphere (at abundances of a few ppm[3]) and throughout the troposphere down to the earth's surface (at much lower abundances of a few tens of ppb[4]). In the stratosphere, O_3 provides protection from potentially harmful UV radiation. In the troposphere, O_3 is a greenhouse gas, and especially at ground level, is a harmful pollutant; it is generated by sunlight driven chemical reactions between NO_X and volatile organic compounds (VOC) including methane (CH_4), CO and other more complex organic compounds. These O_3 precursors may be of natural origin (eg may be produced naturally by vegetation, soil, forest fires or lightning), or may be emitted as a consequence of human activities, especially those that involve combustion of fossil fuels (power plants or internal combustion engines) and biomass.

The average lifetime of O_3 in the troposphere is approximately three weeks but varies with altitude, and is determined by the processes which remove O_3 from the atmosphere. This relatively long tropospheric life-time means that O_3 can be transported large distances. This, in combination with the potential for O_3 to be produced from precursors long after they have been emitted, makes O_3 a global pollutant. A considerable fraction of the background O_3 over a region may originate from emissions in other continents. For example, over Europe, O_3 concentrations entering from the west range from 20-35 ppb, and in North Africa, emissions from Europe may increase O_3 concentrations by as much as 20 ppb.

The amount of O_3 in the atmosphere depends on meteorological conditions such as solar intensity and temperature, water vapour in the atmosphere, the flux of O_3 into the troposphere from the stratosphere, and the concentrations of O_3 precursors present. The main determinant of whether O_3 is produced or removed is the concentration of NO_X in the atmosphere.

At very low NO_X concentrations (<20 ppt[5]) O_3 is destroyed and this is the main cause of the very low O_3 concentrations over the remote oceans. In contrast, over the polluted continents, there is sufficient NO_X to produce O_3. However in the urban environment O_3 concentrations are generally lower than in surrounding areas. This is because at higher NO_X concentrations, which typically occur in urban areas due to emissions from vehicles and other sources, NO reacts with O_3 leading to the local depletion of O_3 concentrations (known as the NO_X titration effect). Regional air pollution policies aimed at reducing NO_X emissions have reduced the NO_X titration effect leading to increasing urban O_3 concentrations approaching those in rural areas.

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[3] Parts per million by volume air concentration.

[4] Parts per billion by volume.

[5] Parts per trillion (parts in 10^{12} by volume).

The atmospheric chemistry of tropospheric O_3 therefore shows great variability between the polluted urban areas and the remote, relatively clean air regions of the planet. This variability is an important consideration for the design of pollution abatement strategies for O_3 and can be summarised as follows:

- In remote areas, background O_3 is the primary contributor to surface concentrations;
- At the regional scale, the hemispheric background[6] and regional sources of O_3 precursors are the main contributors;
- At the local scale, O_3 concentrations are regulated by the hemispheric background, regional production, and the effects of local sources and sinks acting collectively.

3 Why is ground-level ozone a cause for concern?

Ground level O_3 is not a new problem. It has been recognised as a significant local and regional air quality issue for many decades. In the EU for example, 21,400 premature deaths each year are associated with O_3. Policies have been in place to reduce O_3 pollution for decades in North America, Japan and Europe. These have been national or regional in scope and targeted at reducing the very high concentrations that may occur in polluted regions under hot and sunny conditions. During these episodes, O_3 concentrations may peak at 200 ppb or more, with significant impacts on human health, crops and other vegetation. The WHO recommends that O_3 concentrations do not exceed 50 ppb (8 hour mean)[7] but health impacts have also been observed at current ambient concentrations (around 35 ppb), and total health impact is now understood to be driven more by the days at which O_3 is above baseline[8] concentrations, than by the occasional days during which episodes occur. Under the United Nations Economic Commission for Europe (UNECE) and EU environmental risk assessments, cumulative seasonal exposures in excess of 40 ppb are considered a threat to sensitive vegetation.

Ozone reduction strategies have led to significant decreases in NO_X and non-methane volatile organic compound (nmVOC) emissions, and in short term peak O_3 concentrations. Daily peak concentrations in Europe have declined by about 30 ppb and average hourly peak values in the US by 20%. However, in the northern mid-latitudes measurements have shown that the hemispheric background mean O_3 concentration doubled between1900 and1980, and in Europe, has since risen by a further 5 ppb to 35-40 ppb. The reasons for this increase are not fully understood, but are thought to be mainly due to increases in emissions from Northern Hemisphere countries, poorly regulated sectors such as international shipping and aviation, and possibly also due to an increase in O_3 influx from the stratosphere. This long-term increase in hemispheric background has eroded the benefits of emission reductions as average O_3 concentrations have increased to values that threaten human health and the environment.

The climate changes projected for the next century are expected to have an impact on O_3 as temperature, atmospheric humidity and sunshine levels influence background-levels through the controls they exert on O_3 photochemistry. Higher temperatures accelerate O_3 production (depending on the NO_X regime), and, especially in summer, are likely to increase biogenic VOC emissions leading to higher surface O_3 concentrations in high NO_X regions. Climate change will also have an impact on O_3 destruction as temperature and soil moisture strongly affects the rate of dry deposition which is the main removal process for O_3 at the surface.

Ozone, in turn, may contribute to increased rates of climate change, indirectly; due to its effect on rates of CO_2 uptake by terrestrial ecosystems; and directly due to its status as an important greenhouse gas. The magnitude and full extent of the potential interactions between climate change and O_3 are, however, poorly understood.

4 What is likely to happen to ground-level ozone in the future?

4.1 Impact of emission control legislation

Over this century, economic growth and an increasing global population will drive the processes that lead to emissions of O_3 precursors. Changes in climate and land use will influence emissions from natural sources. Increased demand for energy, transport, food and non-food crops and other resources will influence emissions from human activity, and changes in patterns of consumption and production will affect the distribution of O_3. Although the activities that lead to emissions will increase, the implementation of legislation and new emission reduction technologies will help to decouple O_3 pollution from economic growth.

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[6] Hemispheric background O_3 is the remaining concentration once the emissions of anthropogenic O_3 precursors from within a region are switched off. It comprises O_3 produced from natural sources of O_3 precursors within a region, together with O_3 imported into the region derived from all sources (anthropogenic and natural, including the stratosphere). The value varies seasonally and with latitude.

[7] Annual average of the daily maximum of the running 8-hour mean.

[8] Baseline O_3 is the average measured concentration of O_3 within a region and is made up of both the anthropogenic emissions produced within a region and the background concentration of O_3.

There are few studies that explore the global development of air pollutant emissions for the coming decades, and even fewer that consider the long term. In the Royal Society study, three emission scenarios were developed to give insight into the possible changes in O_3 precursor emissions to 2100[9]. These were based on the B1, B2 and A2 socioeconomic pathways used in the updated Intergovernmental Panel on Climate Change (IPCC) scenarios and the International Institute for Applied Systems Analysis (IIASA) Air Pollution Current Legislation (CLE) scenario. For the purposes of this study, the IIASA CLE scenario was updated to include legislation adopted globally between 2002 and late 2006, and extended from 2030 to 2100.

Previous analysis, based on a 'high (A2) emission' scenario in which emission control legislation was not included, projected an increase in Northern Hemisphere mean surface O_3 concentrations of between 10 to 30 ppb by 2100. As average ambient concentrations in the Northern Hemisphere are now around 35-40 ppb this would have major human health and environmental impacts. By comparing this result with the CLE scenario the Royal Society analysis demonstrates the importance of emission abatement, and shows that the extent to which current legislation is successfully implemented will largely determine future emissions and therefore O_3 concentrations.

The new scenario projections show that it is the changes in NO_X, but also CH_4, CO, and nmVOC emissions that will be the primary driver of O_3 concentrations globally in 2050. The analysis projects an increase in global CH_4 emissions, but a decline in anthropogenic NO_X and CO emissions globally to 2050, with the overall effect that global seasonal mean O_3 concentrations will have slightly declined, or remained constant by 2050 compared to 2000. While the CH_4 projections are uncertain, emissions are expected to increase as controls are not yet in place in many developing countries, emissions from agriculture, particularly in Asia, Latin America, and Africa, are expected to rise, and emissions from fossil fuels are expected to increase with demand. A release of CH_4 from melting permafrost areas in the Arctic regions may further increase emissions.

At the regional level seasonal mean O_3 concentrations may increase or decrease by 2050 depending on the emissions profile of the region. During summer, typical reductions of 5 ppb are projected for the Northern Hemisphere mid-latitudes, with declines of up to 15 ppb (or 25% relative to present day levels) projected for parts of North America. During winter an increase in O_3 concentrations is projected due to lower NO_X emissions and reduced O_3 titration by NO. In developing regions, such as Asia and Africa, a modest increase in O_3 of up to 3 ppb (approximately 7%) during the maximum O_3 season[10] is projected.

In the rapidly developing regions O_3 concentrations are projected to increase over the next two to three decades before declining around 2050. This is largely due to increases in emissions from transport, energy production, land use change and biomass burning. In Asia, increases in power generation and traffic volumes are expected to lead to increases in NO_X emissions, although the implementation of current legislation should halt the increase in emissions from mobile sources by 2050. In Africa, NO_X emissions are also expected to increase as controls have not yet been adopted for mobile and stationary sources other than for new large combustion plants. In Latin America, Africa and Asia, emissions from deforestation, savannah burning, and agricultural waste are twice those from energy sources, and are significant contributors to CO and NO_X emissions. As few controls are in place for biomass burning in these regions emissions from these sources are projected to remain high or to decline only slightly by 2050.

At the urban scale the analysis suggests that by 2050 urban O_3 concentrations will rise towards regional background concentrations in many cities as NO_X emissions controls are progressively implemented and emissions decline (as recently seen in the UK for example). Future trends in background O_3 will be an important determinant of urban O_3 concentrations: an increase will further exacerbate O_3 increases at the local level whereas a decrease will have a counteracting effect.

4.2 The impacts of changes in climate and emissions on future ozone

The effects of climate change on future O_3 concentrations in 2050 will be regionally variable with impacts during the maximum O_3 season in the range of ±5 ppb depending on the underlying NO_X regime; O_3 will tend to increase in already polluted environments and decrease in clean environments.

When the combined effects of changes in climate and emissions on O_3 concentrations in 2050 are considered the global modelling analysis suggests that changes in emissions are generally more important than climate change in most locations. In locations where significant emission reductions are projected, for example the industrialised regions in the northern mid-latitudes, air quality will improve although the benefits achievable will be reduced by climate change. Where smaller emission reductions are projected, the impacts of climate change are proportionately larger, and tend to coincide with the tropical land regions. In many developing world regions especially large parts of Africa and Asia, air quality in 2050 will decline.

At the regional and local scale, climate change is expected to have significant impacts on O_3. An increase in the frequency of high pollution episodes globally is expected due to changes in weather and rainfall patterns even with the full implementation of emissions controls. Across Europe more frequent summer droughts, heatwave events and associated high O_3 episodes are expected. By 2100 it is projected that hot summers such as that experienced during 2003 will occur every year on average, and the incidence

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[9] The full Royal Society report gives details of the new scenarios.

[10] In the polluted northern mid-latitudes the maximum O_3 season is generally June, July August. In the northern extra tropics surface O_3 reaches a maximum in spring over remote regions, and in the tropics, during the dry season when biomass burning emissions of precursors peak.

of extreme heatwaves such as that experienced in August 2003 will increase and may occur across Europe one in every 10 summers. In other parts of the world weather patterns that limit the intensity of summertime or dry season peak pollution levels are expected to be less prevalent, leading to higher pollution levels.

4.3 Role of natural precursor emissions

It is not yet possible to accurately or fully quantify O_3 precursor emissions from natural sources such as lightning, soils, wetlands and vegetation. However these are important when evaluating potential changes in future O_3 concentrations. Isoprene is one of the most important biogenic VOC due to its very large global emission rates and reactivity in the atmosphere. The greatest changes, particularly of isoprene, will be due to changes in land use and climate. This study suggests that climate change may increase global isoprene emissions by 2050 although increasing atmospheric CO_2 will reduce the magnitude of this effect. Land use change, or the potential for replacement of high isoprene emitting species with low emitting species (and vice versa) will also be an important determinant. For example, if high emitting species (eg eucalyptus or oil palm) are planted in high NO_X areas regional O_3 production could increase, particularly during heatwave events. This is a concern when considering the replacement of natural tropical forests with plantation species.

5 Current and future impacts of ozone

5.1 Human health impacts

Traditionally the impacts of O_3 on human health have been associated with high O_3 episodes. However human health impacts also occur at background concentrations (35-40 ppb). In North America and Europe current O_3 exposure levels are associated with short term acute effects on the respiratory system resulting in increased mortality and morbidity in already vulnerable individuals. Long-term chronic exposure may cause permanent lung damage, although the significance of this for long-term health is unknown.

Estimation of future human health impacts is limited by the information currently available, including, a lack of accurate baseline health data in many countries, the use of mean annual O_3 exposure to estimate population exposure (which may obscure important individual exposure events), and poor understanding of the O_3 exposure-response relationship. Whether or not there is a threshold[11] for effects on humans remains unclear. If no threshold exists, the health impact attributable to O_3 in the future will depend largely on trends in hemispheric background concentrations. If a threshold exists, it is close to or below current annually averaged ambient concentrations (about 35 ppb) and the health impact will depend more on emissions of precursors together with meteorological conditions. This has important policy implications because if there is no threshold the health impacts attributable to O_3 will be much greater and therefore stronger O_3 control measures will be required. The increasing evidence for O_3 impacts at relatively low O_3 concentrations led the WHO to reduce the O_3 air quality guideline for daily 8h mean concentrations from 60 ppb to 50 ppb. Because of the uncertainty regarding thresholds for effects on human health, it is now common practice to estimate human health impact with and without a threshold assumption.

A recent UK Department of Health study estimated the number of deaths in the UK attributable to O_3 in 2003 and 2020 with or without climate change. With no threshold assumption the increase in estimated annual O_3 concentrations between 2003 and 2020 led to a 15% increase in deaths with climate change (from 11,272 to 12,930), or an 8% (12,140) increase under a 2003 climate. Under a threshold assumption of 35 ppb there was a 51% (1,582-2,391) increase with climate change, which was reduced to 14% (1,802) under a 2003 climate. In the no threshold model, about half of the increase in health impact is due to changes in UK and European emissions (particularly NO_X emissions) and the remainder to climate change. In the threshold model, most of the increase is attributable to climate change. The relative importance of trends in climate vs trends in precursor emissions on future O_3 health impacts is therefore critically dependent on the threshold assumption.

An assessment of the current and future health impacts of O_3 has been completed for the EU as part of the EU Clean Air for Europe Strategy (CAFE). This evaluated O_3 health effects in 2000 and 2020 and showed that under current EU legislation the number of premature deaths due to O_3 is estimated to decline slightly from 21,400 in 2000 to 20,800 in 2020. The relatively small change in mortality reflects the assumption that current EU legislation will be fully implemented and complied with, thereby keeping population exposure to O_3 close to 2000 levels. This estimate is likely to be conservative however as it does not include morbidity effects, and is based only on days at which O_3 concentrations are above 35 ppb.

Due to data limitations equivalent estimates are not available in regions such as Asia, Africa, and Latin America where emissions of O_3 precursors are projected to increase over the next two to three decades. In these regions higher O_3 concentrations are expected to lead to increased human exposure and therefore increased mortality and morbidity impact.

The analysis suggests that the human health impacts of O_3 in many regions could increase significantly over this century even with the implementation of current legislation due to the predicted increase in high O_3 episodes associated with hot weather events and increases in urban O_3 concentrations (due to reduced NO titration). At least 22, 000 people died

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[11] A threshold is the exposure level or dose of an agent above which toxicity or adverse health effects can occur, and below which toxicity or adverse health effects are unlikely.

during the 2003 European heatwave and in nine cities across Europe, the excess deaths attributable to O_3 ranged from 2.5 % (in Bordeaux) to 83.5% in Toulouse. With an increase in the frequency and magnitude of such events, mortality and morbidity are also expected to increase. Like many urban areas, O_3 concentrations in London are expected to increase as NO_x emission controls take effect (although by how much will depend on the trend in background O_3) leading to increased human exposure to O_3 and increases in daily mortality and respiratory hospital admissions. The health benefits of NO_x emissions controls in cities will therefore be offset to some extent by increases in urban O_3 in these areas.

5.2 Environmental impacts

Ozone reduces plant growth and crop and forest yields initially by impacting leaf structure and physiology. It also has potentially long-term effects on ecosystem structure and function and the carbon cycle. Under current O_3 concentrations, significant impacts to crops in Europe and North America have been observed. In the US in the 1980's annual arable crop production losses due to O_3 were estimated to be \$2-4 billion. In the EU in 2000 an estimated €6.7 billion was lost due to arable crop impacts. For the same year, global economic losses from reduced yields were estimated to be \$14-26 billion for rice, soybean, maize and wheat combined.

Global yield losses recently estimated for 2000 for these four crops ranged from 2% for maize to 16% for soybean[12]. However, these global mean estimates conceal large regional differences. Yield losses for wheat and rice in South Asia were particularly affected, as was wheat in sub-saharan Africa. For example, in India, estimated overall yield losses due to ambient O_3 in 2000 were about 6% for rice, 13% for wheat, and 19% for soybean. These estimates are highly uncertain as they are based on North American and European exposure-response relationships, nevertheless, experimental studies in Africa, Latin America, and Asia have demonstrated significant impacts on staple crop yield and quality. For example, experimental studies from specific locations in India and Pakistan reported yield losses due to current ambient O_3 of 10% for rice, 13-47% for wheat, 20% for mung bean, 24% for spinach, 30% for pea, and 45% for carrot. Effects have also been reported on the nutritional quality of crop species. In India for example, reductions in the iron content of spinach, and beta-carotene content of carrot have been observed. Comparisons of experimental results for Asia with exposure-response relationships based on studies in North America suggest that the impacts of O_3 on sensitive crops in South, Eastern, and South-east Asia may in fact be greater than indicated by the global impact assessment with significant implications for local food supply and livelihoods.

Recent global estimates for 2030 showed an increase in global yield losses due to O_3 for wheat and rice, but little change for soybean and maize. This analysis was based on a scenario in which only legislation adopted before 2002 was considered. Under the updated CLE scenario developed for the Royal Society study, the potentially large crop losses in Asia due to O_3 will be less significant supporting the need for the full implementation of current emission controls to reduce the risk to food security in the region.

Non-food crops are also at risk from O_3 pollution. There are no estimates for the economic impacts of O_3 on perennial crops, however moderate exposure has been shown to result in reductions in the proportion of clovers in managed pastures and may affect the forage quality of the crop. Similarly, some of the proposed biofuel crop species (eg willow, poplar) are known to be sensitive to O_3. The sensitivity of other biofuel species (eg palm oil, *Panicum*, *Miscanthus*, *Phalaris*) is not yet known. Significant effects have also been observed on tree growth and rates of photosynthesis - economic losses from the reduced yield of timber for Sweden alone are estimated to be € 56 million per year. Tree species which are fast-growing pioneer species, such as birch, aspen and poplar, may be relatively more sensitive to O_3 compared to climax species such as beech and oak. This may have implications for agro-forestry and biofuel production if climax species are replaced by fast growing plantation species.

Very few assessments of the impact of O_3 on wild plant species have been made and almost none have evaluated species outside of North America and Europe. Available evidence suggests that individual wild plants may be as sensitive to O_3 as the most sensitive crop species. The areas of the world where O_3 may have the greatest potential impact on plant biodiversity were identified by comparing estimates of changes in global plant productivity due to O_3 between 1900 and 2100 with priority conservation areas. The results suggest that the areas of greatest risk may fall in Eastern North America, Central Europe, the Northern half of South America, Central Africa, and South-East Asia. Some of the areas identified as being at high risk from O_3 coincide with those at high risk from increasing nitrogen deposition, including the forests of South-East Asia and South-West China, and the cerrado of Brazil.

5.3 Impacts on climate

In addition to being an important air pollutant, O_3 is a greenhouse gas. Future changes in O_3 concentrations will impact the climate system although to what extent is uncertain. The IPCC estimates that increases in tropospheric O_3 since the industrial revolution now mean that O_3 is third only to CO_2 and CH_4 in terms of global radiative forcing.

In addition to this direct climate effect, O_3 has an indirect effect. Reductions in the land carbon sink may occur due to the impacts of O_3 on plant growth and physiology. Increases in atmospheric CO_2 may increase plant productivity enhancing carbon sequestration, but this is likely to be offset by the impacts of O_3. The implications of these interactions for future climate are uncertain. However, the results from the longest field experiment of the combined effects of O_3 and elevated CO_2 concentrations suggest that O_3 reduces or removes the positive effects of elevated CO_2 on plant growth and soil carbon accumulation.

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[12] Using seasonal mean O_3 concentrations.

A recent study into this effect using a high emission (A2) scenario predicted that between 1990-2100 the impacts of O_3 would result in a 17% reduction in the terrestrial carbon storage projected to occur from increasing CO_2 concentrations. This resulted in an additional radiative forcing effect only slightly lower than the direct forcing effect of O_3, and an overall increase in total radiative forcing by at least 70% due to O_3. Under the more moderate B2 scenario, the effects of O_3 on land carbon storage would be reduced, and the direct radiative forcing due to O_3 would also decrease. Ozone feedback effects could therefore significantly amplify the radiative forcing leading to O_3 being a more significant driver of climate change in the future. Global modelling studies such as these are uncertain. However, other studies using different model approaches also suggest that there is a significant, and previously neglected, indirect effect of O_3 via the land carbon sink.

Ozone precursors also have climate impacts, both positive and negative. For example increasing NO_X emissions tend to increase levels of the hydroxyl radical (OH), reducing the lifetime of CH_4, which depending on the location and season, may reduce the positive radiative forcing of CH_4. Carbon monoxide, CH_4 and VOC emissions however, tend to reduce OH levels, increasing the lifetime of CH_4 producing additional positive radiative forcing. Controls on O_3 precursors could therefore have climate effects in addition to the direct and indirect impacts of O_3.

6 Uncertainties

Future projections of emissions are limited by the uncertainties inherent in the assumptions on which the analysis is based, in particular the socioeconomic pathways followed and the rate at which technological advances occur and are implemented. In this study important assumptions included the rate of economic growth in developing countries, particularly China, future coal use, growth rates in shipping emissions, the effect of a major shift in land use, for example for biofuel production, and the level of implementation of air pollution and climate change controls.

7 Controlling ozone

Ozone is a secondary pollutant and cannot therefore be directly controlled. Instead efforts must be focused on controlling the emissions of the precursors that lead to O_3 formation. There is a huge range of sources of emissions; those that originate from natural sources are not easily controllable, while anthropogenic sources include a wide range of sectors, some of which are easier to control than others.

7.1 What control measures exist already?

Ozone control has historically been at the country or, as in the EU, at the regional level, and has focused on controlling high O_3 peaks as these were the periods during which the impacts of O_3 were considered to be greatest. The USA and Japan have had O_3 control programmes in place since the 1960s, and the EU since the 1970s. Mechanisms for reducing O_3 pollution and impacts include limiting emissions of O_3 precursors, standards and guidelines that define air quality targets, alarm thresholds to advise sensitive sectors of the population to move indoors, and O_3 alarm plans to restrict emissions associated with land transport and industry during peak O_3 episodes.

No global framework exists for the direct management of O_3 and O_3 precursors, although as a greenhouse gas O_3 does fall under the umbrella of the United Nations Framework Convention on Climate Change (UNFCCC). The Kyoto Protocol however focuses on the basket of long-lived greenhouse gases[13] and does not include O_3. At the global level, the WHO is the only international body to address O_3. Guidelines aimed at reducing the human health impacts of the most common air pollutants, including O_3 are issued for policy-makers. The only international mechanisms for the control of O_3 are regional in scope. Of these, the Gothenburg Protocol of the UNECE Convention on Long Range Transboundary Air Pollution (CLRTAP), and the EU air quality framework are the most comprehensive and well established.

The Gothenburg Protocol provides a multi-pollutant[14], multi-effect strategy for managing air pollution, and recognises the effects of control measures across the spectrum of pollutants, and potential interactions between pollutants. National limits for European countries are based on scientific assessments of the thresholds of effects on natural ecosystems and human health, and the relative cost effectiveness of abatement options.

In the EU the Clean Air for Europe (CAFE) Strategy specifies EU air pollution objectives and proposes measures to achieve them by 2020. The Directive on Ambient Air Quality and Clean Air for Europe integrates previous Directives concerned with ambient air quality, and sets limit values for air pollutants[15], target values and objectives for protecting vegetation, and provides for information exchange between member states. It also contains target values and long-term objectives for the concentration of O_3 in ambient air, and objectives for fine particles ($PM_{2.5}$). National targets for emissions are set in the National Emissions Ceilings (NEC) Directive. Due to be revised in 2008/2009 this sets national targets[16] to reduce acidification, O_3 and eutrophication. Also relevant for O_3 control is the Integrated Pollution, Prevention and Control (IPPC) Directive which requires that stationary sources of pollutants from new and existing industrial and

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[13] CO_2, CH_4, nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6).

[14] For anthropogenic emissions of NO_X, VOC, ammonia and sulphur.

[15] SO_2, NO_2, NO_X, PM, Pb, Benzene, CO.

[16] for SO_2, NO_X, VOC, $PM_{2.5}$ and ammonia.

agricultural sources with high polluting potential be permitted only where certain environmental conditions are met. This includes sources associated with the energy industries, production and processing of metals, mineral industry, chemical industry, waste management, and livestock farming.

Other regions, in particular Asia, Africa, and Latin America, are starting to take a more regional approach to managing air quality. None are yet focused specifically on reducing O_3 pollution, however O_3 levels may be affected as a consequence of the controls in place. For example the South Asian countries signed the 1998 Malé Declaration on control and prevention of air pollution and its likely trans-boundary effects for South Asia. In 2002, the Environment Ministers of the Association of Southeast Asian Nations (ASEAN) group signed a legally binding agreement on trans-boundary haze pollution resulting from land and forest fires, and in the African region, the Air Pollution Information Network for Africa (APINA) aims to improve capacity in African countries to monitor and manage air pollution problems. Additional regional networks, designed to facilitate cooperation in management of urban air quality management, are also in place. For example, the Clean Air Initiative for Asian Cities (CAIA) is a regional-wide network which aims to improve air quality in cities by improving awareness, supporting the development and implementation of air quality standards and policies, and strengthening capacity. Equivalent networks now exist in Latin America and the Caribbean.

In the UK, the regulatory framework is guided by the obligations established in the CLRTAP and by the EU. The UK Air Quality Strategy for England, Scotland and Wales provides the framework for managing ambient air quality in the UK.

7.2 What further measures are needed?

The Royal Society study results highlight the need for a globally coordinated approach to O_3 management. Ozone is a global pollutant and until policy frameworks are implemented to address the transboundary nature of O_3, national and even regional level controls are unlikely to achieve their policy objectives. Controls must be targeted at reducing both peak and background O_3, and must address the local, regional, and hemispheric scales of variability in O_3 sources and sinks.

In large urban areas O_3 formation is VOC limited and VOC emission controls can therefore be an effective option for limiting the increases in O_3 formation that occur in such areas from NO_X emission controls. In the UK, in contrast to much of continental Europe, regional scale O_3 formation is VOC limited and VOC emission reductions could also provide a useful contribution for controlling O_3. Appropriate VOC emission control measures should therefore be included in regional and urban air quality strategies.

Recommendation 1:

Options for an international mechanism to provide a globally coordinated approach to air pollution issues, and O_3 specifically, should be identified and evaluated. This should be led by a United Nations body such as the UNECE, or the United Nations Environment Programme (UNEP), and should build on ongoing activities such as the European Monitoring and Evaluation programme (EMEP) - including its Task Force on Hemispheric Transport of Air Pollution, and work of the Global Atmospheric Pollution Forum.

Recommendation 2:

2.1 The UNECE, European Commission and all national governments to target emission control measures to reduce peak and background O_3 concentrations taking into account the relative importance of different emission sources at the local, regional and global scale as appropriate;

2.2 Decision making bodies responsible for local air quality to implement VOC emission controls in large urban areas where NO_X emission controls are contributing to increasing local O_3 concentrations;

2.3 UK Government to implement regional scale VOC emission controls as part of the national strategy for controlling O_3.

Future O_3 concentrations will be determined mainly by emissions of O_3 precursors and it is the extent to which emission controls are implemented over the next few decades that will determine how big a pollution problem O_3 is beyond 2050. The global modelling analysis shows that it is the changes in anthropogenic emissions, mainly of NO_X, but also of CH_4, CO, and nmVOC that will be the primary influence on ground-level O_3 concentrations in 2050. Existing emissions controls must therefore be implemented as a priority.

As climate change will exacerbate the future increases in O_3 projected in Asia, Africa and Latin America due to increases in precursor emissions, a key policy objective should be to reduce emissions in the most vulnerable regions as rapidly as possible to avoid being in a situation where the impacts of climate change and high O_3 coincide.

Recommendation 3:

All national governments to implement current O_3 precursor emission reduction legislation as a matter of priority. Further measures to reduce precursor emissions are required, in particular:

3.1 NO_X controls need to be strengthened for mobile sources in countries outside the EU and Japan. NO_X controls for large stationary sources should be strengthened worldwide;

3.2 *Action is needed to reduce NO_X and CO emissions from biomass burning, particularly in Latin America, Africa and Asia where emissions are currently greatest;*

3.3 *International support should be provided by the International Energy Agency (IEA) and United Nations Development Programme (UNDP) for the implementation of low-cost CH_4 emission reduction technologies in the agriculture and energy sectors in the Asian, Latin American and African regions.*

The future effects of climate change will mean that in urban areas in many countries, emission reductions will need to be strengthened and exposure management plans reviewed, to take into account the combined effects of climate change and reduced NO_X titration, and the projected increases in frequency and magnitude of conditions conducive to high O_3 events.

As O_3 is an important greenhouse gas, greater harmonisation between the international and regional climate and O_3 regulatory frameworks should be a priority. The CLRTAP, and the EU, and the CLRTAP and UNFCCC could work together to define coordinated long term goals (to 2050) for the reduction of emissions, and greenhouse gases (including O_3). This should include consideration of the potential contribution of reducing CH_4 emissions and emissions from biomass burning including deforestation and forest degradation, to meet both O_3 and climate change objectives. Similarly, the European Commission in its work to revise the NEC Directive, and the development of climate change adaptation and mitigation strategies should ensure that the scientific and policy interpretation of scientific data and modelling results are harmonised to support and reinforce the work of the CLRTAP. As co-benefits will not always be possible it is important that impact assessment processes are designed to enable the early identification of areas where climate change emission reduction strategies may undermine O_3 objectives (and vice versa) (eg biofuels) and that appropriate action is taken to minimise such impacts.

Recommendation 4:

Improved coordination of O_3 and climate change policy and research frameworks is required and should include:

4.1 *The UNECE, EU, and national governments to review the potential impacts of climate change on the achievement of medium (eg 2020) and long-term (eg 2050 and beyond) O_3 policy objectives and revise air quality management strategies appropriately;*

4.2 *An investigation into the policy interactions to be led by the UNFCCC secretariat together with the Executive Body of the CLRTAP. This should evaluate the mechanisms by which the objectives and targets of UNFCCC and CLRTAP (and other regional air pollution bodies) could be better harmonised, and should include a review of the linkages between current and future policy and technological controls on greenhouse gases and other air pollutants over the period 2010–2050 and to 2100;*

4.3 *A review by the European Commission of how EU policy (such as the NEC Directive, and climate change adaptation and mitigation policies) can be better integrated with the objectives of the CLRTAP;*

4.4 *A study into the biogeochemical interactions between climate change, tropospheric O_3 and other pollutants to be undertaken by the IPCC and CLRTAP.*

Measures required to protect human health

As O_3 is known to have effects on human health and the environment at ambient concentrations, even with the full implementation of current controls, O_3 impacts will continue and may increase in some regions. As the total health impact is now known to be driven more by baseline concentrations than occasional high O_3 episodes, policy objectives should be targeted to reducing both (see recommendation 2.1).

In many countries around the world, information regarding the impact of O_3 to human health is not routinely collected and there is little baseline health data against which policy targets can be set and monitored. Success in achieving reductions in health impacts will be limited unless there is a rapid increase in the capacity of countries for monitoring, impact assessment and management of O_3, particularly in those regions where O_3 emission precursors are projected to increase in forthcoming decades.

The human health benefits obtained from reducing NO_X emissions mean that the implementation of NO_X controls is likely to continue for the foreseeable future in many urban centres and further increases in urban O_3 can be anticipated.

Recommendation 5:

Ozone regulatory frameworks to be strengthened to protect human health from background O_3 exposure:

5.1 *The WHO, US Environmental Protection Agency (EPA), UNECE and European Commission to examine the importance of background O_3 effects on human health, and to strengthen guidelines and standards appropriately;*

5.2 *The WHO and other appropriate regional organisations to ensure countries that would like to develop strategies to achieve reductions in the human health impacts of O_3 receive sufficient financial and information support to do so;*

5.3 *That existing systems for alerting the public when O_3 concentrations exceed certain levels be strengthened.*

Further measures required for the environment

Consideration of the environmental impacts of O_3 has historically been mainly confined to important crop and forest species in North America and Europe. However, this Royal

Society study emphasises the potential importance of O_3 for plant species in other regions, particularly in the context of increasing global food insecurity, climate change and carbon sequestration and biodiversity loss. Improving the capacity to assess O_3 impacts in other regions is therefore an important priority.

Assessments of the impacts of O_3 on vegetation vary depending on the exposure index used. The flux-based approach provides a stronger mechanistic basis for assessing O_3 impacts but can only be applied to a small number of species. Broader application of this method would improve impact assessments and future decision making.

In terms of food security, the greatest impacts of O_3 are expected to fall in the early half of the century before the implementation of emission controls takes effect. In rapidly developing regions such as South Asia O_3 could present a significant threat to national food security. These impacts could partly be mitigated by measures to reduce the sensitivity of local cropping systems. A high priority for the immediate future will be to integrate O_3 tolerance into national breeding and selection programmes, and into research programmes, and to increase tolerance to O_3 alongside other climate related stressors such as drought and high temperatures. More generally, better understanding of the implications of O_3 for food security is required.

Few studies have assessed the long-term effects of O_3 on biodiversity or ecosystem services. The initial assessment undertaken in this study suggests that O_3 may be important in major eco-regions of high conservation priority, in Latin America, Asia and Africa, as well as in parts of Europe and North America. The long-term effects of O_3 on biodiversity are particularly uncertain at lower latitudes where almost no research has been undertaken.

Recommendation 6:

6.1 *Application of the flux-based O_3 exposure metric to a wide range of staple crops, food species, and wild species of conservation importance, and use of this information to assist assessments of current and future O_3 impacts in Europe and other regions with high O_3 exposures. To be led by the UNECE International Cooperative Programmes for vegetation and forests, and the Global Atmosphere Pollution Forum;*

6.2 *That the Food and Agriculture Organisation (FAO) initiate an assessment of the impacts of O_3 on food and non-food crops and the implications for global and national food security, and to identify and disseminate policies to reduce these impacts. Regions vulnerable to food shortages, and identified in this study as vulnerable to increasing O_3 concentrations, should be the priority for assessment. The potential combined impacts of climate change and O_3 on economically important crops should also be considered;*

6.3 *That the Convention on Biological Diversity (CBD) secretariat undertake an assessment of the impacts of O_3 and other air pollutants on biodiversity and natural ecosystems; this should include an assessment of data requirements for an assessment of impacts to wild species of high conservation value in the major eco-regions in Latin America, Asia, Africa, and vulnerable regions of Europe and North America.*

Ozone policy requirements

Rapid, unregulated growth in emissions from poorly regulated sectors will undermine global efforts to reduce tropospheric O_3. Although land based emissions have been reduced in many countries, emissions from international aviation and shipping are rapidly increasing. Aviation emissions contribute an estimated 2% and international shipping an estimated 15% of global NO_x emissions respectively, and emissions are projected to increase as a result of expected growth in volume. The International Maritime Organisation (IMO) and the International Civil Aviation Organisation (ICAO) should act to regulate NO_X, CO, and VOC emissions as far as is technically feasible, and to implement agreed emission controls. To ensure that emission reduction policies for these sectors are compatible, links should be formally established between the IMO, UNECE and UNFCCC to enable the joint consideration of air quality and climate change impacts with the objective of reviewing the state of play and identifying priorities for future work.

Improving the integration of O_3 policy with policies aimed at reducing other air pollutants, and mainstreaming of air quality policy into other policy areas such as food, climate and energy policy could provide an important contribution to the delivery of the emissions reductions required to avoid a high O_3 future. Similarly, integrated assessment models such as the IIASA RAINS[17] and GAINS[18] models are useful tools for improving policy integration and could be used in regions where the development of environmental policies is still in its early stages, particularly in the developing regions where economic growth is the over-riding policy priority.

Unless there is a substantial increase in the capacity of many countries outside Europe, North America, and Japan to assess the science and to manage O_3, the success of current efforts to control O_3 will be limited. New regionally focused frameworks are necessary where they are not already in place and should be designed on the basis of best practice and the experiences of other regions in developing air pollution control frameworks. The linkages between polluting sectors need to be strengthened, and emission controls set to take into account the cumulative effects of emissions from these sectors. Capacity building will be fundamental particularly in those regions where there are limited O_3 controls in place. Innovation and technology transfer will play a crucial role.

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[17] Regional Air Pollution Information and Simulation Model.

[18] Greenhouse Gas Air Pollution Interactions and Synergies Model.

Priorities for capacity building in regions will limited O_3 controls in place include:

- The development of approaches for preparing national air pollutant emission inventories using a simplified and user-friendly framework that is suitable for use in different developing and rapidly industrialising countries and which is compatible with other major international emissions inventory initiatives;
- The development and use of passive monitoring systems in rural areas to complement the more detailed monitoring which tends to be focussed in major urban centres;
- The development of effective and well-parameterised regional photochemical models for application in South and South-east Asia, Africa and Latin America;
- The establishment of programmes for monitoring O_3 impacts to human health and the environment. An initial emphasis should be placed on identification of vulnerable ecosystems sensitive forest and crop species;
- Identification of best available technologies and prevention strategies for newly built facilities and identification of technologies and strategies that can cost effectively address air pollution and greenhouse gases. The establishment of technical and legal support structures for the development and preparation of new protocols and agreements;
- Strengthened partnership programmes for scientific, political and economic research, and policy development;
- Support for national legislation and development of administrative and technological systems to control precursor emissions in developing countries.

Recommendation 7:

7.1 *All significant sources of anthropogenic emissions must be added to the current mix of abatement measures. The IMO and ICAO must agree to regulate NO_x, CO and VOC emissions from international shipping and international aviation respectively as far as technically feasible, to implement agreed emissions controls, and to continue research into the development of emission reduction technologies for these sectors;*

7.2 *Formal links between the IMO, UNECE and UNFCCC should be established to ensure that the emission reduction policies for shipping and land-based transport emissions are compatible, so that climate change and air quality impacts are considered together. A body similar to the Joint Liaison Group of the Rio Conventions should be convened with the objective of reviewing the state of play and identifying priorities for future work;*

7.3 *UNECE and European Commission to review opportunities for improving O_3 policy integration into other relevant policy areas including energy, climate, food, development and biodiversity policy; this should include a review of how long-term (2050) targets for air pollutants and greenhouse gases should be defined so as to maximise benefits for air quality and climate policy objectives;*

7.4 *Integrated assessment frameworks and other policy options to be further developed and applied in regions where they are not yet in place, for example in Latin America, Africa and across Asia. This should be coordinated by the UNECE;*

7.5 *The CLRTAP to strengthen existing capacity building programmes to focus on the Eastern Europe, Caucasus and Central Asia region, and rapidly developing regions. This should be developed in coordination with the relevant regional development agencies and national aid programmes for developing countries. Programmes should include:*

   - *Assessment of the economic, human health and environmental impacts of O_3 and other air pollutants in countries in Asia, Latin America and Africa;*
   - *Analysis of the economic benefits of O_3 precursor controls in these regions;*
   - *Guidance for the development of national emission inventory programmes, implementation of monitoring networks, and the development of regional photo-chemical models.*

Science and research gaps

Despite rapid improvements over recent years in knowledge of O_3 production and destruction processes and impacts on human health and the environment, many gaps remain. Assessments are limited by the quality of emission inventory data, which are not globally available or standardised. Understanding of the biogeochemistry and physiological processes of natural emissions is not as advanced as for anthropogenic emissions and uncertainties remain regarding how drivers and emissions will change in the future.

Modelling techniques have been developed that have enabled the simulation of the combined effects of changes in climate and emissions on future O_3 concentrations. However, understanding of some of the basic processes and feedbacks between atmospheric chemistry, climate and ecosystems, is still developing, and limits in computing power mean that it is not yet possible to capture all of the important climate sensitive processes which affect O_3 production, destruction and transport at appropriate scales. Uncertainties in the emission scenarios, and poorly constrained processes within the models, are important determinants of the accuracy of future projections.

Human health impact assessments are limited by a lack of accurate baseline data in many countries, and are complicated by uncertainty regarding whether there is a threshold of effects for O_3 in humans. Information regarding the chronic impacts of O_3 is insufficient for reliable health assessments, and although the impacts of acute effects are better understood, the mechanism by which mortality is affected is unclear.

Understanding of environmental impacts is based largely on plant species of economic value, with very little research conducted on wild species, or the ecological impacts of O_3, particularly outside of Europe and North America. The interactions between CO_2, climate change, and O_3 impacts to vegetation require investigation and the combined implications for food security, of O_3 and climate change need to be evaluated.

Recommendation 8:

Significant new investment in tropospheric O_3 research is required by national governments and international agencies to improve the evidence base. This will require international cooperation and should as a priority:

8.1 Address the gaps in understanding of natural emissions and the influence of land use, climate and other global change parameters on emissions; in particular of nmVOC, NO_X from soils and CH_4. This should be led by the UNECE in collaboration with the International Geosphere–Biosphere Programme;

8.2 Review anthropogenic and natural emission inventories, identify what is needed to improve modelling projections and impact assessments, particularly in developing countries, and enhance infrastructure and capacity as necessary. These activities should be regionally coordinated but led by the UNECE;

8.3 The IEA and UNDP to enhance implementation of low-cost technologies for reducing emissions in regions where emissions are projected to rapidly increase and in sectors projected to be important contributors to emissions in the future;

8.4 Focus on the urgent need to substantially increase computing power to enable the development of higher resolution, more complex models to improve the simulation of relevant climate, O_3 and ecological processes at spatial and temporal scales that resolve the time and space variability of the most important processes;

8.5 Strengthen and encourage current initiatives to measure and monitor the regional and global health burdens of O_3. This will require targeted research studies on the toxicology of O_3 and, in particular, the effects of chronic exposure; increased epidemiological research of acute and chronic effects in developing countries, and on chronic effects in other regions; and improved monitoring of ambient O_3 where required;

8.6 Establish long-term field studies for the assessment of the combined effects of O_3, elevated CO_2, climate change and other environmental stressors both on species of economic importance and on a range of natural and semi-natural ecosystems to improve the evidence base of effects on O_3, plant productivity, the ability of ecosystems to sequester carbon, important crop and forest species and biodiversity;

8.7 Initiate research into the effects of O_3 on important species for conservation, including the combined effects of O_3 and other environmental stressors. This research should focus on eco-regions and biodiversity hotspots where future O_3 concentrations represent the greatest threat. The results of this work should be provided to the CBD for their consideration as a new and emerging issue of relevance to biodiversity.

8 Membership of working group

Chair

Professor David Fowler CBE FRS	UK Centre for Ecology and Hydrology, UK

Members

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9 Relevant Royal Society policy reports, statements and responses

Royal Society activities on reducing the risk of the misuse of scientific research
(6 pages, 21 Aug 2008, 17/08)

Joint science academies' statement: Climate change adaptation and the transition to a low carbon society
(2 pages, 10 Jun 2008)

Letter to Secretary of State on Carbon Capture and Storage
(2 pages, 3 April 2008)

Royal Society submission to the Efra committee call for views on Defra's scientific infrastructure
(2 pages, 27 March 2008, 13/08)

Royal Society submission to DIUS UK science and innovation strategy
(12 pages, 29 February 2008, 08/08)

Sustainable biofuels: prospects and challenges
(90 pages, 14 January 2008, 01/08)

Biodiversity – Climate Interactions: Report of a meeting held at the Royal Society
(65 pages, 6 Dec 2007, 30/07)

Joint statement by NASAC to the G8 on sustainability, energy efficiency and climate change
(2 pages, 29 Nov 2007, 28/07)

Response to IMOSEB consultation
(3 pages, 5 Dec 2007, 27/07)

Response to the UK Climate Change Bill Consultation
(7 pages, June 2007, 18/07)

Joint science academies' statement: sustainability, energy efficiency and climate protection
(2 pages, May 2007, 14/07)

Letter to Secretary of State for Trade and Industry regarding cuts to the Research Councils' budgets
(1 page, March 2007, 09/07)

Response to the Office of Science and Innovation's review of science in the Home Office
(2 pages, March 2007 05/07)

Submission to House of Lords S&T Select Committee inquiry on radioactive waste management
(1 page, February 2007, 08/07)

Submission to the STEM Taskforce Science and Society inquiry
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Response to the Environmental Audit Committee's inquiry into the Millennium Ecosystem Assessment
(5 pages, December 2006, 30/06)

Report of a Royal Society policy seminar on the scientific understanding of obesity
(11 pages, February 2006, 03/06)

Submission to the House of Commons Science & Technology Select Committee inquiry on scientific advice, risk and evidence
(10 pages, January 2006, 02/06)

Response to the Stern Review on the economics of climate change
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Response to the House of Commons Science & Technology Select Committee inquiry into carbon capture & storage technology
(3 pages, October 2005, 22/05)

Response to the House of Commons Environmental Audit Committee inquiry 'Keeping the lights on: nuclear, renewables and climate change
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Ocean acidification due to increasing atmospheric carbon dioxide
(60 pages, June 2005, 12/05)

Food crops in a changing climate: report of a Royal Society discussion meeting
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Joint science academies' statement: Global response to climate change
(2 pages, June 2005, 08/05)

Response to Defra review of the UK Climate Change Programme
(6 pages, May 2005, 02/05)

Response to the House of Lords Science & Technology Committee inquiry into how the UK will meet its greener energy targets
(7 pages, November 2003, 22/03)

Environmental effects of marine fisheries
(13 pages, October 2003, 18/03)

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