# Scientific understanding behind the development of integrated co-benefits strategies

# *Les connaissances scientifiques sous-jacentes aux stratégies visant un double bénéfice*

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**Background paper for the Global Atmospheric Pollution Forum Stockholm Conference on "Air Pollution and Climate Change: Developing a Framework for Integrated Co-benefits Strategies".**

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## Introduction

The aim of the first session of the conference is to review the current scientific understanding of the linkages between air pollution and climate change underpinning the formulation of integrated co-benefits strategies.

As background for this discussion, this note briefly summarises the key areas where air pollutants, greenhouse gases and climate change interact. This is preceded by an overview of current trends in atmospheric emission and followed by a brief outline of methodological approaches to quantifying co-benefits. The conclusion and discussion items presented make suggestions on some possible key scientific issues for consideration at the meeting.

In the development of this background paper there was heavy reliance on some key documents. These are Chapter 2 of the Global Environment Outlook, GEO 4, called "Atmosphere" published by UNEP (Kuylenstierna *et al,* 2007), the review by the UK Air Quality Expert Group called "Air Quality and Climate change: a UK Perspective" published by UK DEFRA (AQEG 2007) and the review by the European Environment Agency on "Air Pollution and Climate Change Policies in Europe" (EEA 2004).

In many cases greenhouse gases (GHGs such as $CO_2$, $CH_4$, $N_2O$) and air pollutants (such as $SO_2$, $NO_x$, PM, $O_3$ VOCs) share the same emission sources and are affected by the same driving forces. Policies and measures that affect one emission will affect the other in some way, either increasing or decreasing its emission. Importantly, once emitted into the atmosphere some substances traditionally termed "air pollutants" also increase radiative forcing, thus contributing to global warming. This includes both primary pollutants such as black carbon and secondary pollutants such as ozone. Other pollutants lead to cooling of the atmosphere (such as sulphate aerosols). Changes to climate such as shifts in rainfall patterns also arise from the presence of particulate matter in the atmosphere (the "Atmospheric Brown Cloud" effect – Ramanathan *et al.,* 2002), alongside the climatic changes induced by global warming. The impacts of climate change and air pollution together with elevated carbon dioxide concentrations often interact, in some cases augmenting each other and in others reducing overall impacts.

## 1. Atmospheric Emissions: driving forces and general trends

Human activities emit a wide range of substances into the atmosphere; these substances have different behaviour and effects (AQEG, 2007). Localised peaks of higher concentration may occur close to the origin of emissions of importance, for example, in urban areas for air quality and possible health effects. Chemical reactions occur in the atmosphere that transforms some pollutants as they disperse leading to secondary pollutants with additional consequences.

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Examples include gases such as $O_3$ and fine particulate matter (PM) comprising substances such as sulphates and nitrates. Pollutants may also be removed from the atmosphere by deposition back to the surface, either directly from surface air, or following absorption into and precipitation in rain. Chemical reactions can occur on a time scale of days and pollutants may travel a few thousand kilometres, so that problems such as acidic deposition or eutrophication (e.g. excess nitrogen in sensitive ecosystems) are transboundary/continental in scale. Unreactive gases however, may persist for tens or even hundreds of years, mixing globally and penetrating the whole troposphere. This leads to accumulation and globally increased concentrations with a slow response to reduction of emissions. Both gases and aerosols can contribute to climate change, through their effect on the balance of incoming and outgoing radiation to and from the Earth and its atmosphere. This effect can be either direct, as is the case for directly emitted greenhouse gases (GHGs) such as $CO_2$ and $CH_4$ and emitted particles (e.g. black carbon), or indirect, through the formation and concentration of GHGs (e.g. ozone) and particles (e.g. sulphate, nitrate and ammonium aerosol) *via* atmospheric chemistry. This range of behaviour is illustrated for some common emitted substances in Table 1.

The linkages between sources of pollutants and greenhouse gases and their effects on receptors are complex as illustrated in Figure 1. Although not illustrated in Figure 1 the same source sectors give rise to $CO_2$ and $N_2O$ affecting climate change.

Atmospheric composition is affected by virtually all human activities. Population increases, income growth and the global liberalization of trade in goods and services all stimulate an increase in energy and transport demand. These are drivers of emissions of substances into the atmosphere. Significant downward pressure on emissions has come from increases in efficiency and/or from implementation of new or improved technology. These drivers are common to both air pollutants and greenhouse gases.

The increasing population on the planet contributes to the scale of activity but, of even greater importance, the continuing expansion of the global economy has led to massive increases in production and consumption, indirectly or directly causing emissions to the atmosphere. In addition, urban populations have risen to include half of humanity (Kuylenstierna *et al,* 2007).

In most cases the same sectors and processes are responsible for releasing emissions of both air pollutants and greenhouse gases. The major sectors are transport (road, rail, aircraft and shipping), electricity and energy supply, major and small industrial sectors, household emissions and land use change and practices. Figure 2a shows the emission of different GHGs in 1990 and 2004 and Figure 2b the sectoral breakdown of GHG emissions.

Table 1.
Contrasting characteristics of some common pollutants (source: AQEG, 2007).

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

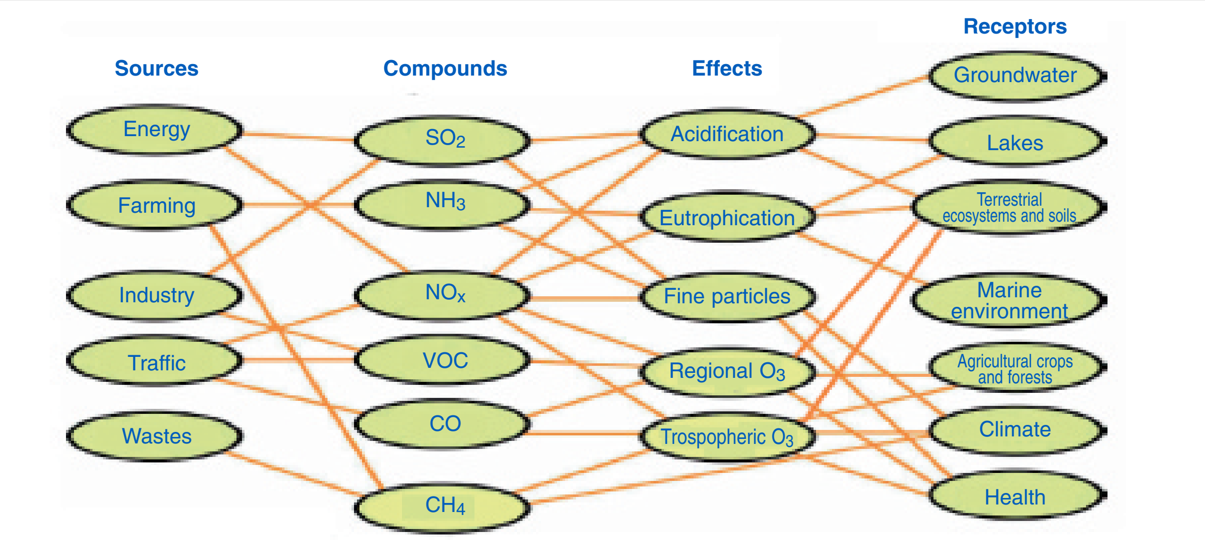


Figure 1.
Examples of some of the potential linkages between regional air quality and climate change issues (from AQEG 2007, after Grennfelt *et al.* (1994)).

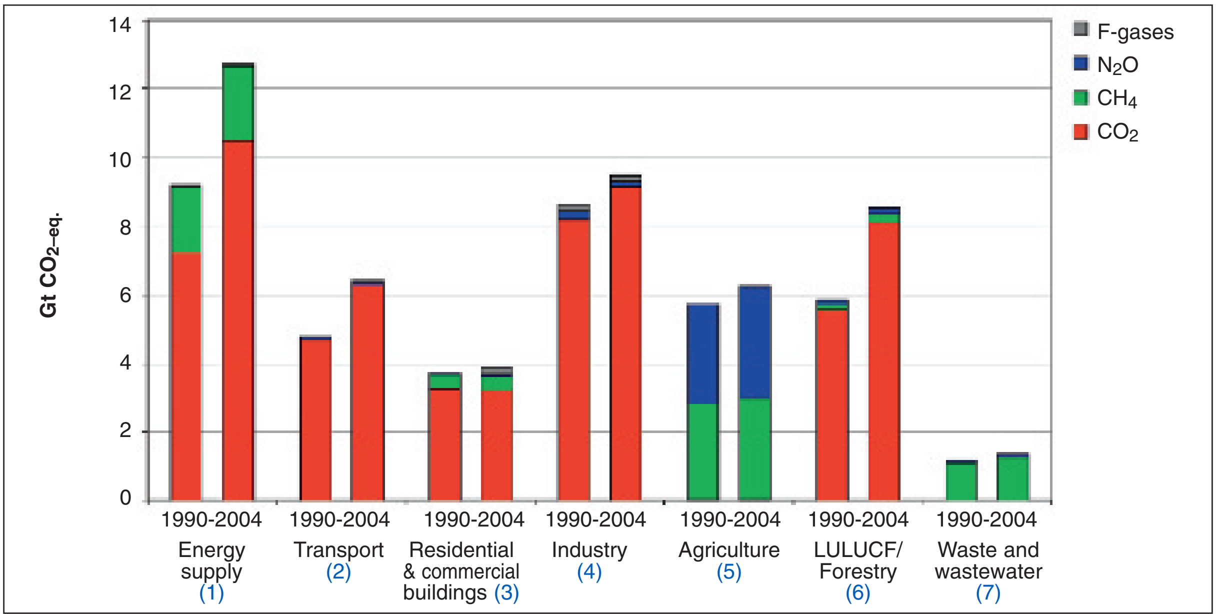


Figure 2a.
GHG emissions by sector in 1990 and 2004 (Source: Barker *et al.*, 2007).

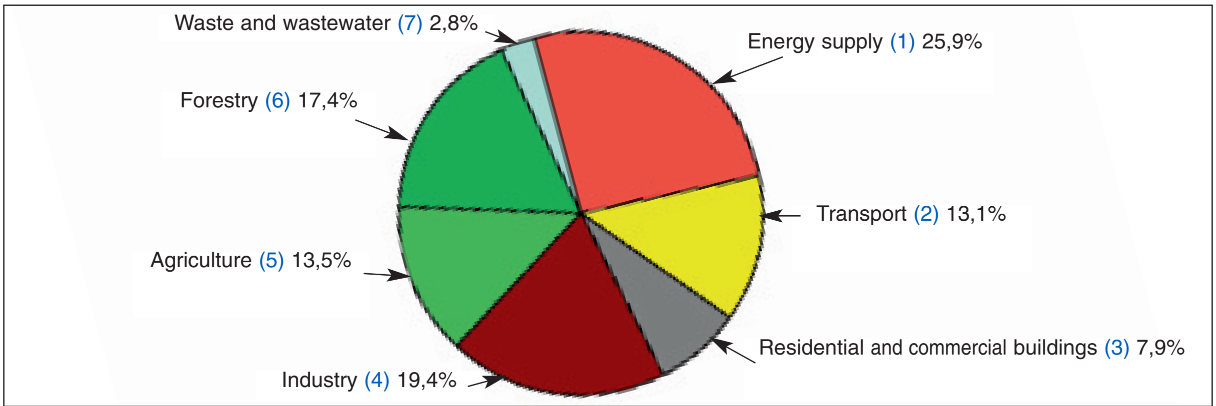


Figure 2b.
GHG emissions by sector in 2004 (Source: Barker *et al.*, 2007).

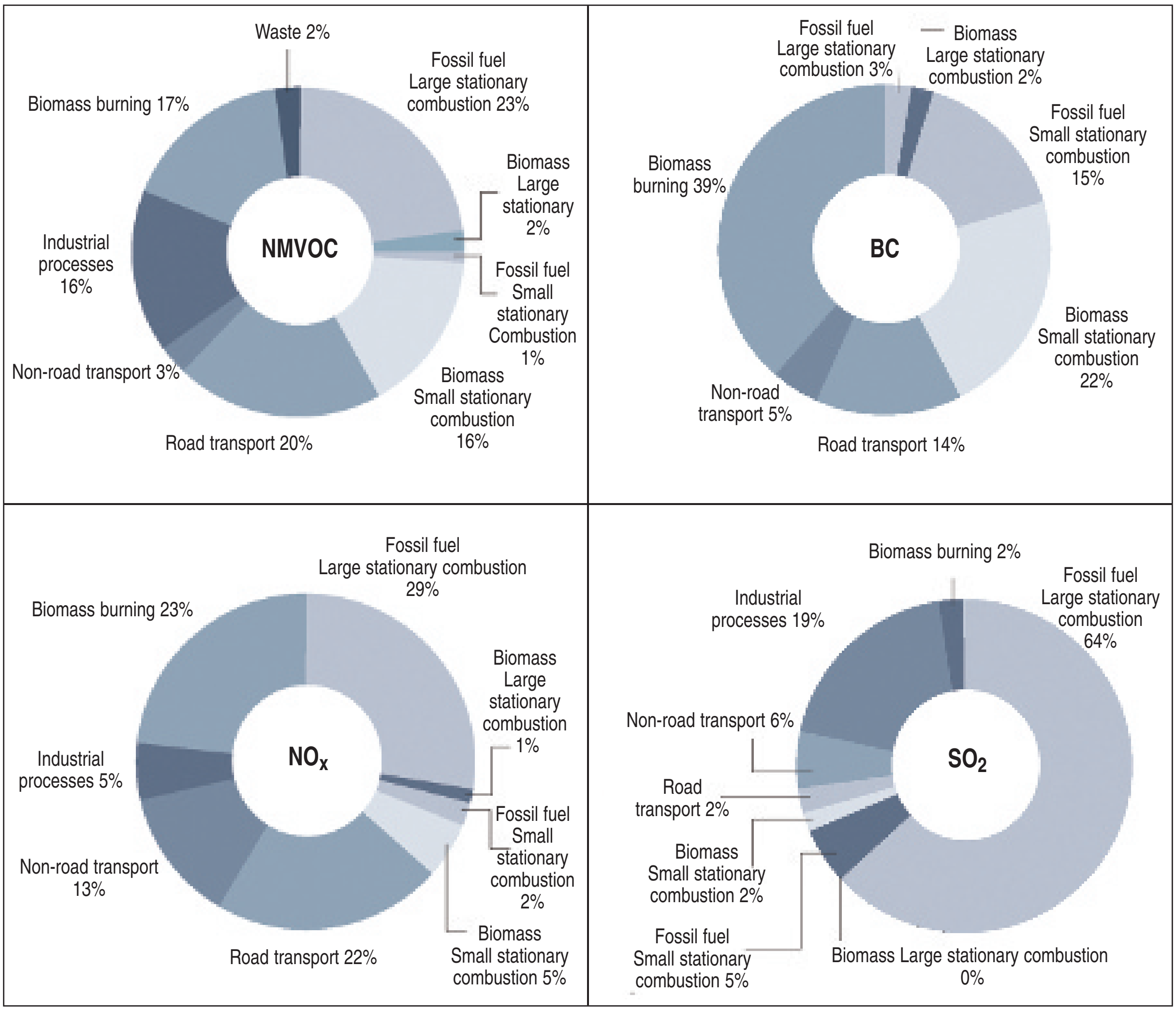


Figure 3.
The relative importance for global emissions for selected pollutants (non-methane volatile organic compounds, black carbon, sulphur dioxide and nitrogen oxides) of different sectors and fuel types for the year 2000.
(Source redrawn from EDGAR data based on Olivier *et al.*, 2005 and Bond *et al.* (2004).

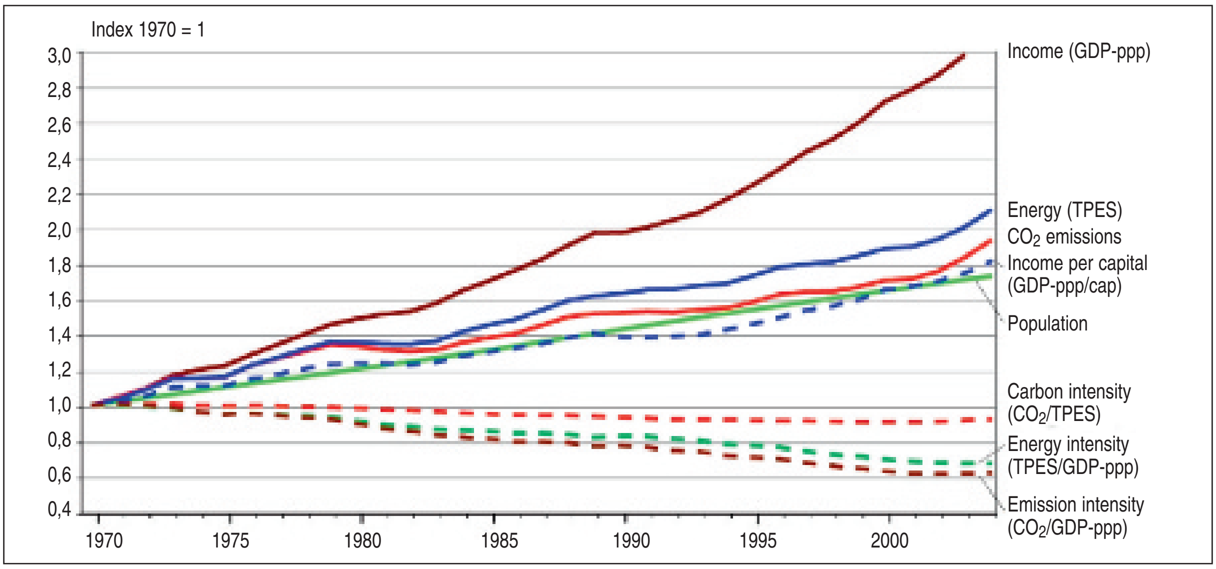


Figure 4.
Relative development of income, population, energy and $CO_2$ emissions, 1970-2004 (IPCC 2007b).

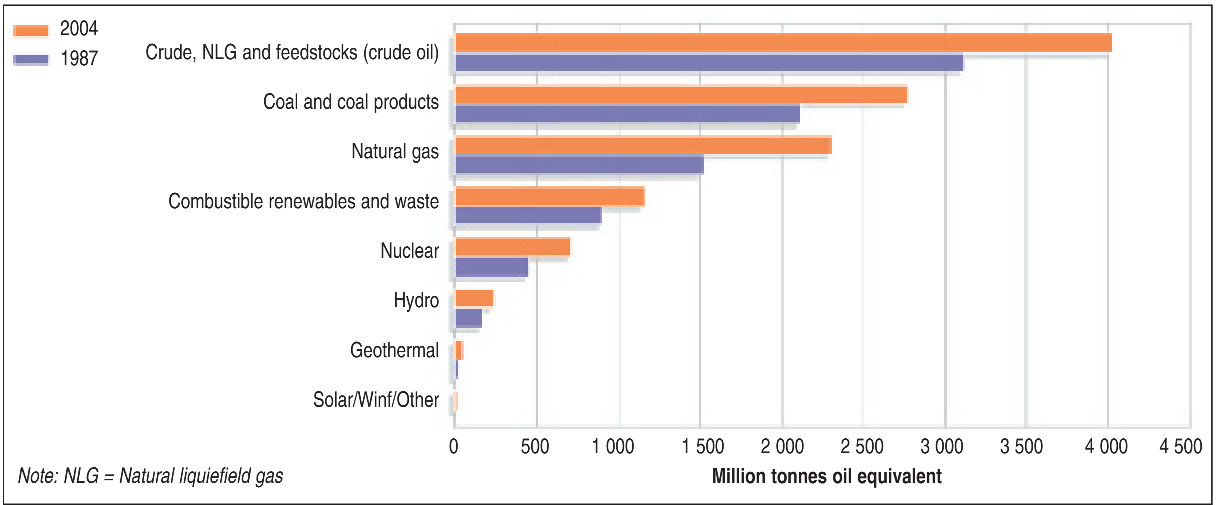


Figure 5.
Total Primary Energy supply by energy source (source IEA 2007 in GEO Data Portal).

Figure 3 shows the importance of different sectors and fuels for air pollutant emission, globally. Clearly the main sources of GHGs and air pollutants are the same: fossil fuel combustion in the energy sector and in transport, industrial processes, land use change/ practices and other biomass burning.

### 1.1. Emissions from energy use

Energy use, especially from the use of fossil fuel, is a driver of most air pollutants and GHG emissions. This has been partly decoupled from the growth of GDP (see Figure 4), due to increased efficiency in energy and electricity production, improved production processes and a reduction in material intensity, but it should also be noted that the declining trends in energy intensity seem to have flattened out during the last years covered in Figure 4.

The global primary energy supply has increased by 4 per cent/year between 1987 and 2004 (from IEA 2007 in GEO Data Portal) and fossil fuel still supply over 80 per cent of our energy needs (Figure 5). The developed world is still the main *per capita* user of fossil fuel and the main emitter of greenhouse gases. However, in many developing countries the use of long-lived, outdated and polluting technology exposes vulnerable communities to the adverse health effects caused by air pollution and at the same time this inefficiency leads to high emissions of GHG per unit of production.

Atmospheric emissions from large stationary sources in developed countries have been reduced by using cleaner fuels, end-of-pipe controls, relocating or shutting down high-emitting sources and promoting more efficient energy use. In many developing countries such measures have not been fully implemented, but if implemented have the potential to rapidly reduce emissions. Industrial sources that use obsolete technology, lack emission controls and are not subject to effective enforcement measures, contribute significantly to the emission load.

Among the factors that define the level of emissions from the energy sector are fuel quality, technology, emission control measures, and operation and maintenance practices. Energy efficiency improvements and energy conservation are given high priority in the energy development strategies of many countries, including developing countries. High efficiency and clean technology will be crucial to achieve a low-emission development path for both GHGs and traditional air pollutants, combined with security of supply.

### 1.2. Transport sector emissions

The high growth in passenger car sales reveals that people put a high preference on car ownership as they become more affluent. Atmospheric emissions from the transport sector depend upon several factors, such as vehicle fleet size, age, technology, fuel quality, vehicle kilometres travelled and driving modes. Shifting from public transport systems to private car use increases congestion and atmospheric emissions. Poor urban land-use planning, which leads to high levels of urban sprawl (spreading the urban population over a larger area), results in more car travel and higher energy consumption. Road transport in Europe (EU27) is responsible for 40% of the $NO_x$, 18% of the total $PM_{2.5}$ emission and 18% of the VOC emission (EEA 2004). At the same time road transport in the EU15 is responsible for 19% of the total GHG emission (EEA 2004).

Air transport is one the fastest rising transport modes, with an 80 per cent increase in kilometres flown between 1990 and 2003 (UNSD 2007 in GEO Data Portal). This dramatic increase was driven by growing affluence, more airports, the rise in low-cost airlines and the promotion of overseas tourism. Economic efficiency is driving improvements in energy efficiency, and new commercial aircraft are claimed to use up to 20 per cent less fuel than those sold 10 years ago (IATA 2007). The aviation industry

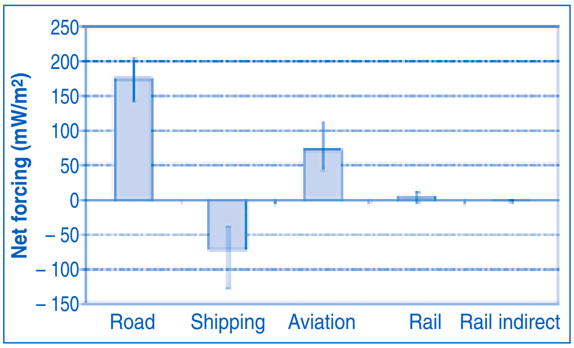


Figure 6.
The net radiative forcing in 2000 from different transport sub-sectors globally. The negative forcing from shipping is a reflection of the sulphur emissions (Fuglestvedt *et al* 2008).

gives rise to both air pollutants and GHGs. The principal aviation pollutants include $NO_x$, $SO_2$, CO, PM and VOCs, and the main GHGs are $CO_2$, $CH_4$ and $O_3$. Aviation emissions account for around 3.5 per cent of man's contribution to global warming from fossil fuel use. By 2050, this percentage could grow to between 4 per cent and 15 per cent (IPCC, 1999). In addition, the impact of all aircraft emissions at altitude is three times more damaging than $CO_2$ emitted at ground level.

Shipping has also grown remarkably over recent decades, mirroring the increase in global trade. It has risen from 4 billion tonnes in 1990 to 7.1 billion tonnes total goods loaded in 2005 (UNCTAD 2006). Improvements in the environmental performance of the shipping industry have been less pronounced than for air transport. The pollutant emissions from shipping are regionally very significant especially close to key shipping lanes and in ports across the world. Globally shipping is responsible for 56% of sulphur emissions from the transport sector [Fugelstvedt *et al,* 2008]. The application of pollution control equipment in shipping has been lacking, causing high levels of emission. The cooling caused by $SO_2$ emissions from ships probably more than compensates for the warming caused by GHG emissions (Figure 6).

### 1.3. Industrial processes

Manufacturing processes can also cause direct emissions, such as $CO_2$, $SO_2$ and particulate matter from steel and cement production, $SO_2$ from copper, lead, nickel and zinc production, $NO_x$ from nitric acid production, CFCs from refrigeration and air conditioning, $SF_6$ from electricity equipment use, and perfluorocarbons (PFCs) from the electronic industry and aluminium production. CFCs, $SF_6$ and PFCs are important GHGs. The emissions depend mainly on the fuel used and the pollutants or the technology applied. CFC are not Kyoto GHGs as they are covered by the Montreal Protocol on stratospheric ozone depletion but HFCs are covered by the IPCC (2006) guidelines.

### 1.4. Biomass and land use practices

In rural areas, customary land-use practices also drive atmospheric emissions. The clearance of forested land, and its subsequent use for cattle and crop production, releases carbon stored in the trees and soils, and depletes its potential as a $CO_2$ sink. It may also increase methane, ammonia and nitrogen oxide emissions. Deforestation is known to have contributed about 20 per cent to annual atmospheric emissions of $CO_2$ during the 1990s [IPCC 2007 *WG1*]. Normal agricultural land-use practices, such as burning crop residues and other intentional fires, increase emissions of $CO_2$, particulate matter and other pollutants. Wildfires and forest fires used for land clearance also release very high levels of particulates.

Normal agricultural practice leads to emission of various pollutants and greenhouse gases such as $CO_2$, particulate matter, $NH_3$, $NO_x$, $SO_x$, and VOCs. Black carbon emitted, for example, from vegetation burning contributes to global warming, but the organic or white carbon leads to surface cooling. An equivalent amount as the $CO_2$ emitted would be absorbed during the growth of crops in the following year. Therefore, this regular burning is mainly an air pollutant and aerosol issue and contributes to the "River of Smoke" across southern Africa. Land use change is another matter. Deforestation changing forests to grasslands leads to a large proportion of the $CO_2$ emitted annually to the atmosphere. It is also responsible for high levels of pollution in many areas in Asia, Africa and Latin America. Examples are the plumes from the burning of Amazonian rainforest across large swathes of South America and the Indonesian forest fires leading to transboundary pollution by particulate matter in SE Asia, itself giving rise to significant health impacts many hundreds of kilometres away from the fires themselves.

### 1.5. Domestic sector

The domestic sector is responsible for much of the demand for goods and services such as electricity that drive up emissions of both GHGs and air pollutants. Practices in the home also give rise to emissions and indoor air pollution. This is a particular issue in poor households of Africa and Asia where biomass and/or coal are used for cooking, often using primitive means and with poor ventilation. This indoor air pollution is particularly important for health impacts on women and children in each house but also can lead to significant levels of outdoor air pollution. The black carbon emitted from these sources is significant in part of the world such as S Asia. Burning the biomass also gives rise to organic carbon emissions which have a cooling effect and the net impact will be dependant on relative emissions and concentrations in the atmosphere.

### 1.6. Increasing urbanisation

Emissions in densely populated areas tend to be higher due to the total level of emission-related activity, even though the per capita emissions are reduced by higher efficiency and shorter travel distances using personal transport. In combination with low dispersion conditions, this results in exposure of large populations to poor air quality. Urbanization, seen in such forms as urban population growth in Latin America, Asia and Africa, and urban sprawl in North America and Europe, is continuing as a result of a combination of social and economic drivers. Urban areas concentrate energy demands for transport, heating, cooking, air conditioning, lighting and housing. Moreover, cities create heat islands that alter regional meteorological conditions and affect atmospheric chemistry and climate.

### 1.7. Technology development

Technological innovation, coupled with technology transfer and deployment, is essential for reducing emissions. A broad portfolio of technologies is necessary, as no single technology will be adequate to achieve the desired level of emissions. Desulphurization technologies, low nitrogen combustors and end-of-pipe particulate capture devices are examples of technologies that have contributed considerably to $SO_2$, $NO_x$ and PM emission reduction. However, some technologies, such as flue gas desulphurisation, while effectively reducing sulphur emissions by more than 90%, also lead to increased $CO_2$ emissions per unit electricity produced. A further factor to consider is that reduced sulphur emissions also result in a reduction in the cooling effect of sulphate aerosol formation. A number of technologies may play key roles in reducing GHG emissions. They include those for improved energy efficiency, renewable energy, integrated gasification combined cycle (IGCC), clean coal, nuclear power and carbon sequestration.

## 2. Greenhouse gases and air pollutants in the atmosphere

The greatest direct human pressure on the climate system arises from the emission of greenhouse gases, chief of which is $CO_2$, mainly originating from fossil fuel consumption. The unprecedented recent rise has resulted in a current level of 380 parts per million, much higher than the pre-industrial (18th century) level of 280 ppm. There has also been a sharp rise in the amount of methane, another major greenhouse gas, with an atmospheric level 150 per cent above that of the 19th century [Siegenthaler *et al.*, 2005, Spahni *et al.*, 2005]. Examination of ice cores has revealed that levels of $CO_2$ and methane are now far outside their ranges of natural variability over the preceding 500 000 years [Siegenthaler *et al.*, 2005]. The potential negative impact of different substances on the global climate is measured by its Global Warming Potential (GWP). These are defined as the ratio of the time integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of a reference gas normally $CO_2$ [Ramaswamy *et al.* 2001 quoted in AQEG 2007]. Examples of GWP over a 100 year time horizon are 1 for $CO_2$ (by definition), 23 for methane and 296 for nitrous oxide (as quoted in AQEG 2007).

Once emitted, some atmospheric pollutants affect the planet's heat balance contributing to radiative forcing in direct and indirect ways [EEA 2004]. They include industrial gases, such as sulphur hexafluoride, hydrofluorocarbons and perfluorocarbons; several ozone-depleting gases that are regulated under the Montreal Protocol; tropospheric ozone; nitrous oxide; particulates; and sulphur- and carbon-based aerosols from burning fossil fuels and biomass.

Aerosols, small particles suspended in the air, play a substantial role in the radiation balance of the earth, mostly through scattering and absorption process [EEA 2004]. They produce brighter clouds that are less efficient at releasing precipitation and lead to large reductions in the amount of solar irradiance reaching the Earth's surface, a corresponding increase in solar heating of the atmosphere, changes in the atmospheric temperature structure, suppression of rainfall, and less efficient removal of pollutants. This has direct implications to availability and quality of freshwater [Ramantahan *et al.,* 2001]. Sulphate aerosols, formed from the oxidation of $SO_2$ in the atmosphere, reflect radiation from the sun and give rise to a cooling effect, masking much of the current warming effect. Organic aerosols also cool but black carbon heats the atmosphere through absorption of radiation [EEA 2004]. Combustion processes are the largest source for black carbon [Penner *et al.,* 1993 in EEA 2004] whilst organic carbon is the single most important component of biomass burning aerosols [Andreae *et al.,* 1988 in EEA 2004]. As elemental carbon aerosols (soot or "black carbon") contribute to global warming while also contributing to local air pollution, removing such pollutants will be beneficial both with respect to climate change and health effects.

The aerosol direct radiative effect has been approximately quantified for sulphate aerosol, biomass burning aerosol, fossil-fuel organic and fossil-fuel BC aerosols, and mineral dust [Penner *et al.,* 2001]. In addition, the radiative forcing due to nitrate aerosol has recently been quantified, as has the effect of BC deposition onto snow surfaces. However, considerable uncertainty still exists with regard to the magnitude (and even sometimes the sign) of the radiative forcing due to aerosols. IPCC in 2007 reported that the anthropogenic contributions to aerosols together produced a net cooling effect (Figure 7) and observations and model calculations have shown that the aerosols in the atmosphere are delaying the global warming expected from the increase in greenhouse gases.

Whilst most studies have characterised carbon from biomass burning as "black" or "organic", analysis of aerosols over Asia suggest that some particles belong to a category of "brown carbon" which makes a contribution to radiative forcing [Duncan *et al.,* 2008] which is a ubiquitous and previously unidentified component of the organic aerosol which has recently come in to the forefront of atmospheric research [Lukács *et al.,* 2007]. This highlights the uncertainties concerning the aerosol impact on radiative forcing. This uncertainty is clear in the debate concerning solid fuel use in developing countries, which is a major source of carbonaceous aerosols and other air pollutants affecting climate.

The radiative forcing attributable to household fuel combustion in Asia has been quantified by Aunan *et al.* (in press) in terms of current global annual mean radiative forcing and future global integrated radiative forcing for a one-year pulse of emissions (2000) over two time horizons (100 and 20 yr). They find that the radiative forcing from the Kyoto gases, $CO_2$ and $CH_4$, is probably counteracted by co-emitted species. Despite the significant emissions of black carbon aerosols (BC), short-lived (non-Kyoto) components from household fuel use overall seem to exert a net negative radiative forcing because of the strong influence of reflective aerosols. Net radiative forcing (current and future integrated) from regional biomass burning is close to zero if the issue of land use change and forestry is not accounted for, since the positive and negative radiative forcing values essentially cancel each other out. For household fossil fuels the net radiative forcing from short-lived species is near zero, thus reduction of household coal burning will have little short-term impact on global climate, but will mitigate global warming over time through $CO_2$ and $CH_4$ reduction (Aunan *et al.* in press).

Ozone formation is affected by the climate, especially temperature, as well as irradience levels, both of which are affected by global climate change. Ozone is

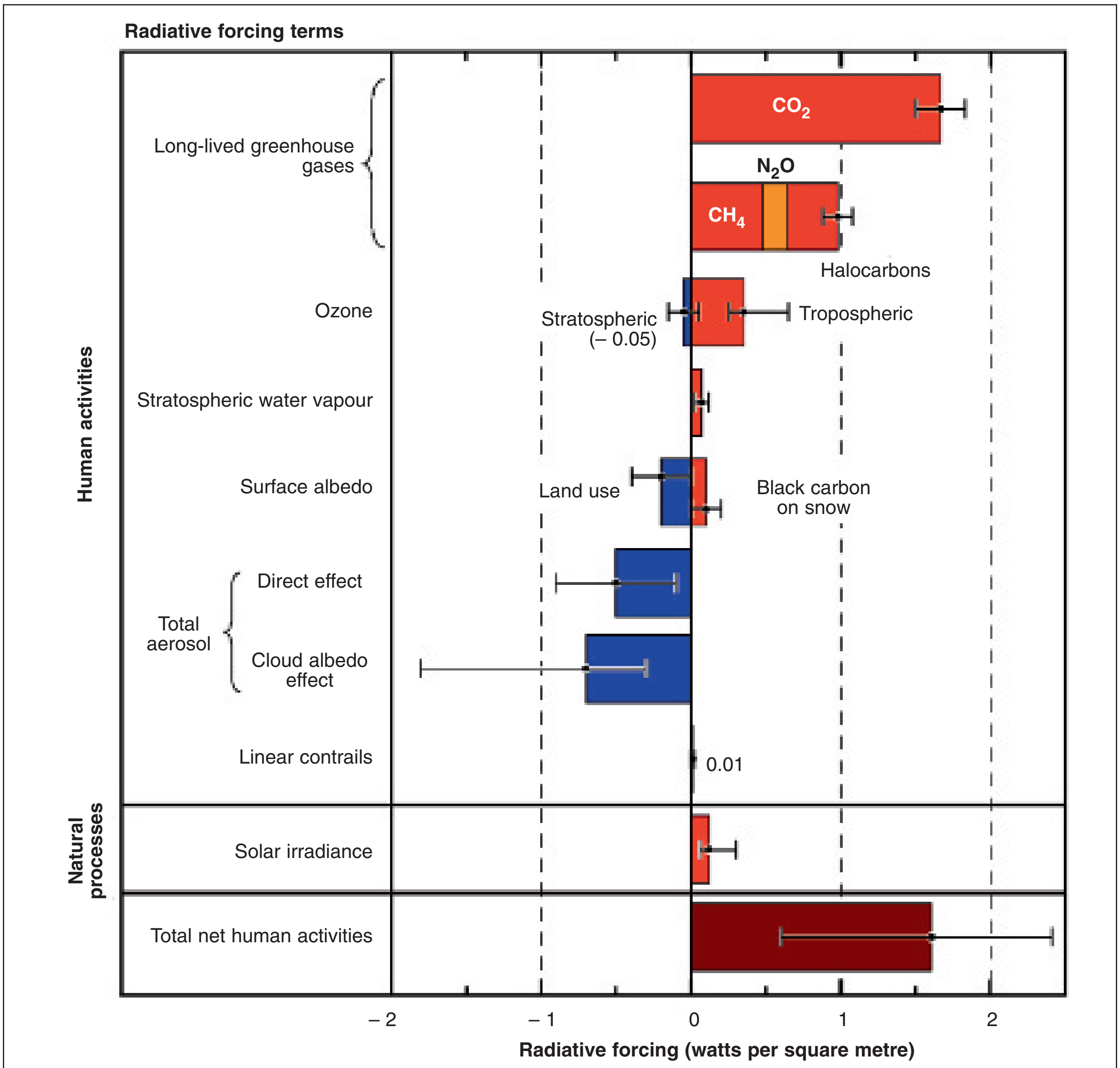


Figure 7.
Summary of the principal components of the radiative forcing of climate change (Source: Forster *et al.,* 2007).

a potent pollutant affecting vegetation, crop yields and human health and it is also the third most important greenhouse gas (see Figure 7). Methane is an important compound for the formation of ozone and, of course is the second most important greenhouse gas. Any reduction in ozone concentrations will result in reduced pollutant impact and warming.

Many air pollutants can be seen as short-lived "greenhouse gases" (or rather compounds) and control of these compounds will therefore result in a faster response of the climate system than the control of traditional greenhouse gases that tend to be long-lived (e.g. about 20% of $CO_2$ remains in the atmosphere after a millennium [IPCC 2007; *WGI]*. However, the net radiative effects of air pollutants are hard to estimate as they tend to vary greatly in space and time [EEA 2004].

The interrelations between pollutant gases and GHGs in the atmosphere tend to be quite complex with, for example, an increase in $NO_x$ concentration leading to a decreased lifetime of $CH_4$ and HFCs *(via* OH) and thus to reduced radiative forcing [EEA 2004]. At the same time the increased $NO_x$ will lead to increased ozone formation, leading to increased radiative forcing. Increased $NO_x$ will lead to increased N deposition fertilising vegetation growth and thus absorbing more $CO_2$ and sequestering more carbon, but once in the nitrogen cycle of the ecosystem, may in some circumstances be remitted as $N_2O$, a potent greenhouse gas [EEA 2004].

The global system response to increased radiative forcing will be experienced through changes in surface and atmospheric temperatures, changes in winds and the global circulation, clouds and precipitation, ice cover and ocean currents. The changing weather patterns brought about by climate change will alter the chemical transformation and transport of pollutants in the atmosphere. This in turn will lead to changes in the exposure of sensitive receptors such as people, ecosystems, crops and man-made materials. For example, it is highly unlikely that the frequency of wintertime pollution events in the UK will remain unchanged as a result of climate change, as the likelihood of stable, calm and cold conditions become less likely [AQEG, 2007]. It is also highly unlikely that the frequency of summertime pollution events in Europe will also remain unchanged as a result of climate change. The intense $O_3$ episodes in the UK during 1976 and in France and Switzerland during 2003 were brought on by sustained high temperature and drought conditions. Such conditions favour $O_3$ production and minimise $O_3$ destruction through the uptake by vegetation at the earth's surface. These conditions are anticipated to become more frequent in some parts of the world as a result of global warming. Climate change may well make local and regional $O_3$ air quality goals become more difficult to achieve in the future [Anderson *et al.,* quoted in AQEG 2007].

## 3. Interactions between climate change and air pollution on impacts

### Crops and vegetation

Ozone ($O_3$) is the main atmospheric pollutant affecting crop yields globally [Emberson *et al.,* 2003] and is also the third most important GHG [IPCC, 2007]. Economic losses resulting from $O_3$ induced crop yield losses have been estimated for different regions around the globe: for the US, economic losses of $3 billion per year were estimated for 9 arable crops [Adams *et al.,* 1989]; in Europe estimates were in the order of $8 billion for 20 arable crops [Holland *et al.,* 2000] and in East Asia, losses of US$ 5 billion based on 4 crops have been estimated [Wang & Mauzerall, 2004]. These studies emphasise the current-day scale of economic losses due to $O_3$, a strong indication that efforts to control $O_3$ precursors will have immediate economic benefits through improved crop productivity as well as reducing the role that $O_3$ plays as a GHG.

The fact that crop productivity is threatened from both air pollutant and climate change provides an opportunity to investigate potential co-benefits that may be realised from ozone concentration reductions in relation to climatic changes and identify the complex interactions between these stresses in relation to crop impacts. In an attempt to define the scope of these interactions it is useful to categorise the possible effects according to direct (resulting from contact with the pollutant) and indirect (resulting from environmental change) effects. For example, elevated $CO_2$ and $O_3$ directly affect crop productivity through impacts on photosynthesis; indirect impacts can manifest themselves through shifts in nutrient cycling, crop–weed interactions, insect pest occurrence, and plant diseases [Fuhrer, 2003]. In terms of direct effects, some crops are expected to benefit from elevated $CO_2$ through the "$CO_2$ fertilization" effect and associated gains in photosynthetic efficiency. In contrast, elevated $O_3$ will reduce photosynthesis. In combination the situation is complicated by the fact that elevated $CO_2$ leads to a reduction in stomatal conductance and hence gas exchange, resulting in a reduced $O_3$ dose and subsequent $O_3$ damage. Evidence also suggests that many of the beneficial effects of elevated $CO_2$ alone may be lost in a warmer climate due to factors such as accelerated plant development, decreased water- and nitrogen- use efficiency. As such, it tends to be assumed that agroecosystem responses to climate change will be dominated by those caused directly or indirectly by shifts in climate rather than elevated $CO_2$ concentrations. Such changes in environmental systems will also affect $O_3$ influence both by altering physiologically-determined $O_3$ dose as well as the consequences of such dose resulting in $O_3$ damage. For example, $O_3$ is a photo-chemical pollutant and as such tends to be associated with hot dry conditions, conditions that also lead to reduced soil water and drought which would limit $O_3$ uptake but also affect water use efficiency. $O_3$ has also been shown to affect plant susceptibility to pests and diseases which will also be mediated by climate change.

As well as indirect and direct effects there are also feedback effects that are important to consider. A recent study by Sitch and others (2007) estimated the impact of projected changes in $O_3$ levels on the land-carbon sink. The study found a significant suppression of the global terrestrial carbon sequestration as increases in $O_3$ concentrations decreased plant productivity. In consequence, more $CO_2$ accumulates in the atmosphere suggesting that indirect radiative forcing by $O_3$ effects on plants could contribute more to global warming than the direct radiative forcing due to tropospheric $O_3$ increases. A similar study was conducted for China for grassland ecosystems [Ren and others 2007] found that surface $O_3$ (in combination with climate and $CO_2$) played a significant role in limiting net primary productivity (NPP), and that an improvement in air quality could significantly increase productivity and carbon storage in China's grassland ecosystems.

### 3.1. Health

Health is impacted by both climate change and air pollutants. The WHO has estimated that warming and precipitation trends due to anthropogenic climate change over the past 30 years already claim over 150,000 lives annually. Many prevalent human diseases are linked to climate fluctuations, from cardio-vascular mortality and respiratory illnesses due to heatwaves, to altered transmission of infectious diseases and malnutrition due to crop failures [Patz *et al.,* 2005]. Climate change may affect exposures to air pollutants by affecting weather, anthropogenic and biogenic emissions, and by changing the distribution of airborne allergens [Bernard *et al.,* 2001].

The most important pollutant affecting human health is particulate matter (PM). Airborne PM is a complex mixture of particles with components having diverse chemical and physical characteristics. Particles are generally classified by their aerodynamic diameter since size is a critical determinant of the site of deposition within the respiratory tract. $PM_{10}$ are particles less than 10 microns in aerodynamic diameter. They can further be divided into coarse particles (from 2.5 to 10 $\mu$m), fine particles ($PM_{2.5}$, less than 2.5 $\mu$m) and ultrafine (UF) particles (particles of diameter less than 0.1 $\mu$m). $PM_{10}$ includes inhalable particles which can penetrate to the thoracic region. $PM_{2.5}$ has high probability of deposition in the airways and alveoli. Particles with different aerodynamic diameters differ in their overall contributions to airborne particle mass and in their origin, physical characteristics, chemical composition, and health effects. WHO estimates that outdoor air pollution of particulate matter leads to approximately 800,000 premature deaths per year and indoor air pollution to about double that number. The economic cost of these health impacts is considerable. According to a World Bank report [World Bank 2007] using conservative estimates, the economic burden of premature mortality and morbidity associated with air pollution in China was 157.3 billion Yuan (approx $23 billion) in 2003, or 1.16 percent of GDP. This assumes that premature deaths are valued using the present value of per capita GDP over the remainder of the individual's lifetime. If a premature death is valued using a value reflecting people's willingness to pay to avoid mortality risks, the damages associated with air pollution are 3.8 percent of GDP. In Europe, the EU has assessed that there would be cost savings due to health benefits from alternative scenarios, outlining different ambition levels for the reduction of ozone and fine particles in 2020, ranging from €37 to €160 billion/year [AEAT, 2005].

The most important compounds in fine particulate matter (usefully characterised by PM less than 2.5 $\mu$m) are sulphates and black carbon. Sulphates cool the atmosphere and black carbon warms it. Fine PM gets deep into lungs and can cause pulmonary and cardiovascular diseases, exacerbate asthma attacks, increase workdays lost, and can cause premature mortality of vulnerable people. There is great pressure to reduce health impacts from particulate matter. This will imply a reduction in sulphate concentrations and so weaken the cooling influence that is so far reducing the full impact of global warming, thus providing an additional impetus to reduce GHG emissions. For black carbon there is a double benefit in terms of health improvement and reduced radiative forcing.

Ozone also has important health impacts such as respiratory symptoms, pulmonary function changes, increased airway responsiveness and airway inflammation, change of pulmonary defence mechanisms, disruption of the normal function of the airways and pulmonary immune system, increased daily mortality, independent of the effects of PM. Increased school and work absenteeism, increased hospital or emergency room admissions for asthma, respiratory infections, and exacerbation of chronic airway diseases may result. Epidemiological evidence of the chronic effects of $O_3$ is less conclusive.

### 3.2. Ecosystems

The main ecosystem impacts from traditional air pollution are related to biodiversity changes from eutrophication by N deposition, acidification by S- and N- compounds (including ammonium) and impacts of ozone. There are also changes in net primary productivity of ecosystems by ozone concentrations and reductions in productivity and fish populations due to lake and stream acidification. Climate changes also affect plant and animal distributions from changes in temperature, frosts, rainfall patterns and soil water availability.

It is likely that the impacts, particularly of nitrogen and climate change will interact in ways that will be complex and difficult to predict. The increased nitrogen deposition enhances the growth-rates of nitrogen-limited forests and this is thought to have led to increased uptake of $CO_2$ in boreal forests [Schimel,1995 in AQEG 2007], but the long-term effects of increased nitrogen deposition may be deleterious, due to interactions with pathogens and pests, changes in soil nitrogen levels influencing mineralization and leaching of nitrogen from the soil, and release of soil carbon as $CO_2$. There is therefore a need for careful evaluation of the impact of enhanced N deposition on the strength of forests as a sink for $CO_2$ [AQEG, 2007]. There is also a risk that the enhanced N deposition will lead to increased $N_2O$ emission from soils, which is a very potent GHG [AQEG, 2007].

Regional acidification will also be influenced by climate change due to changes in weather patterns and intensity of rainfall [AQEG, 2007], due to changes in run-off and evaporation as well as N cycle changes in sensitive catchments and frequency of drought events.

Since $CO_2$ dissolved in water gives rise to carbonic acid, increased $CO_2$ levels will make the oceans more acidic. The uptake of anthropogenic carbon since 1750 has led an average decrease in pH of 0.1 units. Increasing atmospheric $CO_2$ concentrations lead to further acidification. Projections based on SRES scenarios give a reduction in average global surface ocean pH of between 0.14 and 0.35 units over the 21st century. While the effects of observed ocean acidification on the marine biosphere are as yet undocumented, the progressive acidification of oceans is expected to have negative impacts on marine shell-forming organisms (e.g. corals) and their dependent species [IPCC 2007: *WGI SPM; WGII SPM]*.

### 3.3. Corrosion of materials

The action of sulphur dioxide, ozone and nitric acid on corrosion of materials such as steel and stone in cars, buildings and monuments is substantially affected by temperature, rainfall and humidity and therefore there is a clear interaction between air pollutant impacts and climate change on corrosion.

The EU Noah's Ark project on global climate change impact on built heritage and cultural landscapes considers that climate change over the next 100 years will likely have a range of direct and indirect effects on the natural and material environment, including the historic built environment. Important changes will include alterations in temperature, precipitation, extreme climatic events, soil conditions, groundwater and sea level. Some processes of building decay will be accelerated or worsened by climate change, while others will be delayed. For example, the likely reduction in freeze-thaw cycles across much of Europe in the future will lower the potential for frost shattering of porous building stone. On the other hand, it is likely that northern climates may have been so cold in past centuries that they experienced fewer freeze thaw cycles, thus in the future freeze-thaw events may be more frequent.

Pollution and climatic parameters have a direct effect on several materials independent of each other but it is also very common that pollutants and climate act together. In developing future policy for protection of our cultural heritage, it is therefore important to consider effects of pollution and global climate change in a common framework.

Research to date has shown that the cost savings of mitigation measures that reduce corrosion impacts are potentially very large and may compensate for a considerable proportion of abatement. For example, estimated annual cost savings associated with the implementation of the Second Sulphur Protocol under the Convention on Long-range Transboundary Air Pollution for urban and rural areas in western and Eastern Europe combined was in the order of 9,500 Million USD [Cowell and Apsimon, 1996].

## 4. Methodological approaches to quantify co-benefits

Various methodologies have been used to quantify the co-benefits of using policies, measures or technologies that reduce traditional air pollution and greenhouse gases together. These essentially work out the reduced impacts from the implementation of measures on emissions and quantify these in economic terms to allow comparison between different measures. This is a cost-benefit approach as outlined in Figure 8. A cost effectiveness approach may also be used where it is advantageous to avoid costing the impacts but where comparison of changes in the emissions and common impacts is enough. The main impacts investigated in these studies are related to health impacts by particulate matter (generally resulting in the largest economic benefits), crop yield reductions by ozone (also resulting in high economic losses) and to some extent the corrosion of materials. Ecosystem impacts are inherently difficult to assess, and assessment of economic consequences are particularly difficult and have so far rarely been included in a cost-benefit analyses.

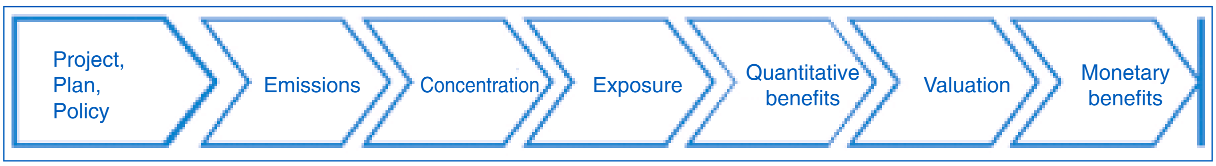


Figure 8.
A flow chart of co-benefit estimates

The evaluation of the co-benefits of measures to reduce both GHGs and air pollutants requires an interdisciplinary approach including emission estimation, technology assessment, dispersion modelling, impact estimation and economic evaluation.

Analyses may be carried out by Bottom-up (B-U) or Top-down (T-D) methods. B-U methods are often used to analyse specific projects on a fairly small scale while T-D models focus on the overall macro-economic effect of measures and are suited to analyse options such as carbon taxes or non-price policies (market reforms, information, capacity building).

Figure 9 illustrates steps in a B-U analysis. To calculate the net benefits using a bottom up analysis, it is necessary to know: i. how the measures affect the emissions ii. how the exposure of humans and the environment changes iii. changes in the effects due to changed exposure (exposure-response or dose-response functions) iv. size of non-emission effects v. the economic values of the changes vi. costs of the measure.

There are large uncertainties in all steps, especially in exposure-response functions and monetization. Exposure-response functions for mortality and morbidity of PM in air have been developed from many studies, but there are few studies of long-term effects in developing countries. Monetization of these effects is mostly based on willingness-to-pay (WTP) studies. The number of such studies in developing countries is unfortunately very low. The human capital method, which is popular in the Chinese research and policy community, equates a statistical life lost to potential earnings lost by the diseased. This approach results in lower values for health damage than the WTP approach.

Despite the uncertainties, cost benefit analyses give useful information. As an example of the work that has been undertaken Aunan *et al.* (2004) made a cost-benefit analysis of six measures that would reduce emissions of $CO_2$ and particles in Shanxi Province, China. Only reduced health damage due to improved air quality was included as co-benefit. Three of the measures were found to have negative costs due to improved fuel economy. Using the best estimates of health benefits, all six measures became highly profitable in a socio-economic sense. Even with a low estimate of health effects, the net costs were negative or nearly zero.

## 5. Conclusions

Given that tropospheric ozone contributes to radiative forcing, crop yield losses, health and corrosion impacts, as well as reduction in net primary productivity, reducing the uptake of $CO_2$ by vegetation, there is a clear argument that all measures to reduce ozone will be a benefit for the global climate, crop yields and human health.

Methane is an ozone precursor as well as the second most important GHG. Therefore, reducing methane emissions will have a beneficial effect on radiative forcing and ozone formation, which would become apparent within a fairly short time scale given the relatively short residence time of methane in the atmosphere.

Reducing another ozone precursor, $NO_x$, without supplementary reductions in CO, $CH_4$ and VOCs, will not have such clear benefits as this will lead to reduced OH in the atmosphere which may exacerbate the build-up in global $CH_4$ concentrations.

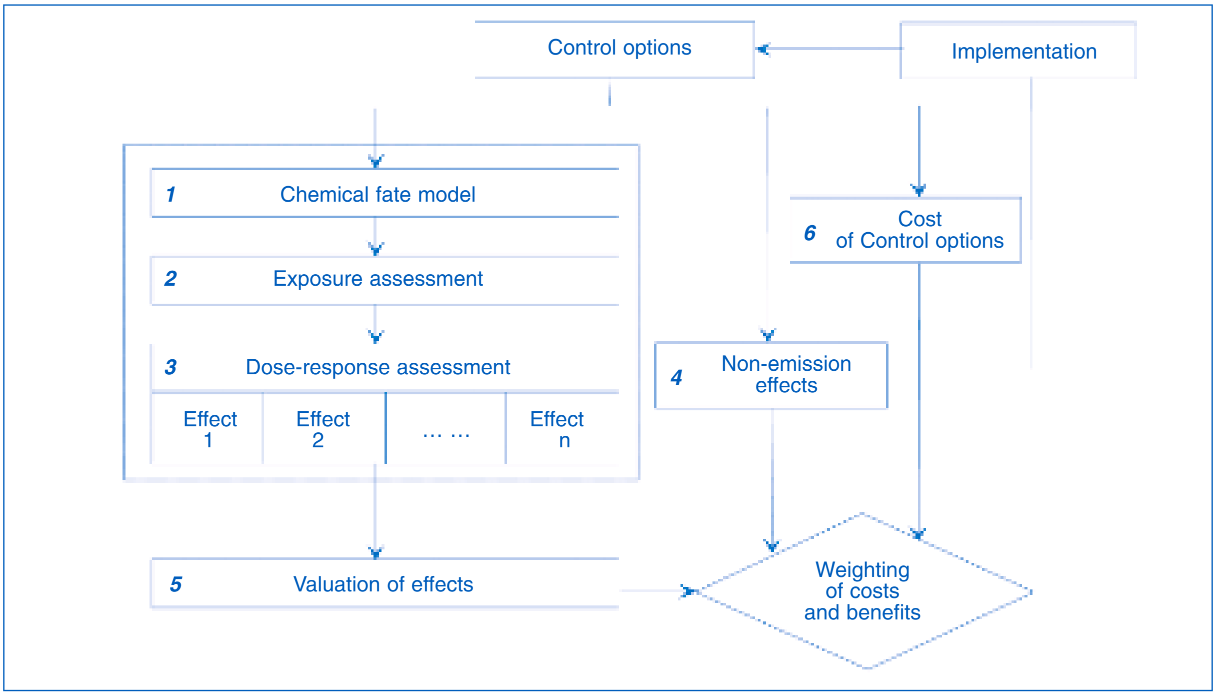


Figure 9.
The steps required in a bottom up analysis of co-benefits.

There are considerable uncertainties concerning the impact of aerosols on net radiative forcing, but the impacts on human health are pressing. There is therefore intense pressure to reduce particulate matter concentrations, including sulphate, black and organic carbon components. The reduction of sulphate from human health demands (and indeed from demands for reduced ecosystem acidification and corrosion of materials) will mean that there will be a reduction in the cooling effect that these have afforded the earth, thus putting increased pressure on the need for abatement of the GHGs.

The reduction in black carbon from some sources (e.g. diesel vehicles) will result in reductions in both radiative forcing and human health impacts. Because of the short atmospheric lifetime of BC, the impact of emission reductions is more or less instantaneous. This is therefore a very important consideration in the evaluation of the impact of diesel *versus* petrol car usage, which cannot be based on $CO_2$ emissions alone, and a holistic full life cycle perspective for all radiative forcing components must be taken into account when evaluating competing technologies [AQEG, 2007].

There is uncertainty on the net effect on radiative forcing from the burning of biomass due to the balance of emissions of black carbon (warming effect) and organic carbon (cooling effect) from these sources. However, the imperative to reduce health impacts, especially of the poor will entail pressure to reduce emissions from these sources.

## 6. Discussion Points

This background paper makes clear the extensive and profound scientific interactions between air pollutants and climate change. However, for the purposes of considering the long-term development of co-benefit strategies, there remain a number of important issues on which discussion in the first session could focus:

- Is there now an overall consensus on the scale of the contribution of air pollutants to climate change? Is it sufficient for long-term policy development?
- Is there a general scientific consensus on which pollutants we need to include for co-benefit policy purposes – ozone, methane, black carbon, sulphate, nitrate and ammonium aerosols and others?
- What are the critical uncertainties that must be addressed?
- What should future research priorities be? What areas are high priority for research? Life cycle analysis for biofuels, etc? Integration of short-term and long-term effects? Common metrics between air pollutants and greenhouse gases? Others?
- What are the implications of these priorities for short-term and long-term strategies integrating pollution and climate change?

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