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Air pollution and climate change policies in Europe: exploring linkages and the added value of an integrated approach

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Executive summary

There is an increasing awareness in both the science and policy communities of the importance of addressing the linkages between the traditional air pollutants and greenhouse gases. Many of the traditional air pollutants and greenhouse gases have common sources, their emissions interact in the atmosphere, and separately or jointly they cause a variety of environmental impacts on the local, regional and global scales. Linkages work in two directions: there can be synergies and negative trade-offs. Thus, emission control strategies that simultaneously address air pollutants and greenhouse gases may lead to a more efficient use of the resources on all scales.

This report explores the linkages between air quality and climate change from a European perspective in order to assist the European Environment Agency (EEA) in approaching the issues of air quality and climate change in an integrated way. This report addresses atmospheric linkages, linkages of impacts and possible synergies in emission reductions and emission control strategies. Furthermore, it assesses the relevance and significance of linkages for different control options and defines priority issues for integrated assessment. Finally it proposes preliminary indicators that could be used by the EEA to approach and report on linkages between air quality and climate change in a structured manner.

Atmospheric linkages between air pollution and climate change

- Air pollutants and greenhouse gases interact on various spatial and temporal scales. Many air pollutants contribute to radiative forcing. Examples are nitrogen oxides, carbon oxide and non-methane volatile organic compounds which are precursors to tropospheric ozone (an important greenhouse gas as well as an air pollutant). Another example are aerosols and particulate matter (PM), which can have either a positive or negative forcing effect, dependent on their composition. Both ozone and PM have direct health effects.
- Particularly relevant for the linkages between climate change and air pollution is tropospheric ozone. Climate change, on the one hand, influences ozone concentrations through dynamical and chemical changes in the atmosphere. On the other hand, increasing background ozone concentrations in Europe affect climate change because ozone is a potent greenhouse gas itself and indirectly influences the lifetime of other greenhouse gases such as methane.
- The climatic effects of aerosols are dependent on their composition. Black carbon (soot) enhances warming, while other aerosols constituents (sulphates, nitrates, organic compounds) generally have a cooling effect. The net effect of reducing particulate matter is probably leading to a further enhancement of the greenhouse effect. However, the issue of a net cooling/warming by aerosols critically depends on the highly uncertain effect of black carbon aerosol, which is at present strongly under debate.
- Climate change and stratospheric ozone depletion interact in various ways. *Inter alia*, the disturbance of the atmospheric radiative balance is expected to delay the recovery of the ozone layer by some decades.

Linkages of impacts of air pollution and climate change

- Impacts of climate change and air pollution on humans and ecosystems interact in two ways. On the one hand, climate change can change the effects of **exposure** of humans and ecosystems to air pollution,

and the other way round. On the other hand, climate change can affect the **sensitivity** of humans and ecosystems to specific impacts of air pollution and the other way round.
- The **exposure** of ecosystems to air pollution can change as a result of phenological changes induced by climate change (e.g. changes in the length of the growing season) as well as by changed distribution of air pollutants through changed weather patterns. Their **sensitivity** may change as a result of, *inter alia*, climate-induced changes in ecosystem vitality, soil processes and ecosystem composition.
- The **exposure** of humans to ozone, particulate matter and other pollutants is likely to be affected by climate-induced changes in their local and regional abundance. Insufficient information is available to assess changes in the **sensitivity** of humans to air pollutants because of climate change.
- Because of the long response times involved in impacts of climate change, interactions with regard to impacts are believed to be of lesser significance in the short to medium term than other types of linkages discussed in this report.

Linkages of emission sources and control options
- From a policy perspective, the most important linkages between climate change and air pollution exist at the level of emission sources. Air pollutants and greenhouse gases are often emitted by the same sources and hence changes in the activity levels of these sources affect both types of emissions.
- Technical emission control measures aiming at the reduction of one type of emissions from a particular source may reduce or increase the emissions of other substances. In the energy sector, efficiency improvements and increased usage of natural gas can address both problems (synergies), while desulphurisation of flue gases reduces sulphur emissions but can — to a limited extent — increase carbon dioxide emissions (trade-offs). In agriculture, some specific measures to abate ammonia emissions could enhance nitrous oxide and/or methane emissions, while other types of measures would reduce these.
- Energy scenarios that ignore the linkage between emissions of local and regional air pollutants and greenhouse gases ignore the constraints imposed by concerns about local and regional air pollution on the development of the energy system and thus tend to overestimate the potential growth of greenhouse gas emissions. Similarly, an integrated assessment across economic sectors is important to identify possible situations in which emission reductions in one sector or region of one type of pollutant would lead to increasing emissions in another sector or region.
- Implementing climate policies, e.g. in order to achieve the Kyoto Protocol targets, can significantly reduce the costs of meeting air quality targets. In the same way, meeting stringent air quality targets is at the same point likely to require measures beyond end-of-pipe technological solutions, and require broader structural changes (e.g. in the energy mix), consistent with climate goals.

Policy practices and opportunities
- Opportunities for synergies and avoiding trade-offs have been integrated into international air quality policies or policy negotiations in Europe, such as the 'Clean Air For Europe' programme (CAFE) where the links between air pollution and climate change are an integral part of the analysis which will lead to the adoption of the Thematic Strategy on Air Pollution in mid 2005. Neither the Convention on Long Range Transboundary Air Pollution of the United Nations Economic Commission for Europe (UNECE CLRTAP), nor the current climate negotiations under United Nations Framework Convention on Climate Change (UNFCCC) address

these issues on policy level. At the technical assessment level however, the opportunities are increasingly noted (Intergovernmental Panel on Climate Change — IPCC, UNECE Task Force on Integrated Assessment Modelling — TFIAM).

- Linkages can be taken into account when designing different types of policies such as economic instruments, regulatory policies, voluntary agreements, and awareness and education strategies. Policies targeting activities that release air pollutants and greenhouse gases (e.g. combustion of fossil fuels, intensive agriculture) rather than the emissions of one specific substance (like carbon dioxide, sulphur dioxide, or ammonia) have a larger potential for capturing possible synergies.
- Climate change policies, if developed independently from air pollution policy, will either constrain or reinforce air pollution policies, depending on the choice and design of the policy instruments, and the other way around. From an economic perspective, policies that may not be regarded as cost-effective from a climate change or an air pollution perspective alone may be found to be cost-effective if both aspects are considered.
- If climate change considerations were to be taken into account when designing policies and measures to abate local and regional air pollution (and vice versa), the cost-benefit equation and thus the relative priorities of policy options could change considerably; there is as yet no agreed operational framework to evaluate the importance of climate change versus air pollution.

Integrated assessment

- The complex atmospheric interactions between air pollution and climate change are presently not understood sufficiently well to allow their quantitative incorporation in integrated assessment modelling. Instead, these interactions should be taken into account in integrated assessment of the two issues in a qualitative fashion. The same counts for interactions between impacts of air pollution and climate change.
- Sufficient knowledge is available to include quantitatively many of the linkages at the level of emission sources and control strategies in integrated assessment and integrated assessment modelling in the near future.
- It is important to take into account the linkages between climate change and air pollution both in cost-effectiveness analysis (how to reach adopted environmental quality goals in the cheapest manner) and cost-benefit analysis (what is the economically optimal level of abatement?).
- Choice and design of policies and measures to address climate change can affect the spatial and temporal distribution of emissions and hence their effectiveness in terms of air pollution. This needs to be taken into account in integrated assessment studies.
- The experience acquired with a framework of models in previous European integrated assessment studies provides a good basis for future activities to include both air pollution and climate change. While components of this framework focusing on the two issues can be further improved to include linkages, a 'soft link' rather than a 'hard link' between the components appears to be appropriate because of the disparate characteristics of the problems in terms of time, space, and complexity.

In conclusion, there are various options to address the linkages between climate change and air pollution in different EEA reporting activities. An immediate short-term example is the *State of the environment and outlook report* (SoEOR2005). For effective communication of information about the links to policy-makers and the public, translation into indicators is required. We have given some preliminary suggestions for the development and implementation of such indicators. Some of these can be implemented at short notice, using the integrated assessment framework with associated models and information systems available to the EEA. Other indicators require further reflection, discussion with external experts, and elaboration.

1. Introduction

1.1. Aims and scope of the report

This report explores the linkages between air quality and climate change from a European perspective in order to assist the European Environment Agency (EEA) in approaching the issues of air quality and climate change in an integrated way. The report addresses the linkages between air pollution and climate change by:

(1) collecting and summarising existing information from the literature on linkages between air pollution and climate change;
(2) identifying gaps in current knowledge on linkages between air pollution and climate change;
(3) assessing the relevance and significance of linkages for different control options;
(4) prioritising issues for integrated assessment;
(5) proposing preliminary indicators for the EEA for reporting on linkages.

1.2. Rationale

Air pollution abatement policies in Europe have resulted in a number of protocols (Convention on Long-Range Transboundary Air Pollution (CLRTAP) of the United Nations Economic Commission for Europe — UNECE CLRTAP) and directives (EU). These policies have increasingly been designed to be cost-effective, i.e. meeting environmental requirements at minimum emission abatement costs. However, reaching cost-effectiveness also depends on externalities in other areas, such as climate change. There is an increasing awareness in both the science and policy communities of the importance of addressing the linkages between the traditional air pollutants and greenhouse gases. Many of the traditional air pollutants and greenhouse gases have common sources, their emissions interact in the atmosphere, and separately or jointly they cause a variety of environmental impacts on the local, regional and global scales. Linkages work in two directions: there can be synergies and negative trade-offs. Thus, emission control strategies that simultaneously address air pollutants and greenhouse gases may lead to a more efficient use of the resources on all scales. The EEA seeks to address these linkages in an integrated manner in its reporting, scenario development and indicator development.

The increasing awareness of the importance of addressing the linkages between the various environmental problems is reflected by a number of workshops that were organised around this topic in recent years (see Annex 8). The UNECE CLRTAP Task Force on Integrated Assessment Modelling (TFIAM), together with the European Topic Centre on Air and Climate Change (ETC-ACC) of the EEA, held a workshop on the linkages between air pollution and climate change at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria (27 to 29 January 2003), to explore future directions for integrated assessment modelling under CLRTAP. The workshop reviewed the present scientific activities that investigate linkages between air pollution and climate change, pointing out the need for a systematic analysis of the synergies and trade-offs throughout the full DPSIR (drivers, pressures, state, impacts, responses) chain.

This report takes the insights from this workshop into account. It addresses several aspects of the linkages between local and regional air pollution and stratospheric ozone depletion and climate change. It addresses atmospheric linkages, linkages of impacts and possible synergies in emission reductions and emission control

Box 1.1 Terminology (W.Tuinstra)

In this report we use the term **linkages** when referring to the connection between air pollution and climate change. We consider linkages in the broadest sense, ranging from atmospheric linkages to linkages in emission control and policies. Different terms to refer to these linkages exist in the literature, reflecting different disciplinary or policy perspectives. Below we provide an overview. However, sometimes the terms are used interchangeably in practice, and thus ambiguity exists.

In the field of climate change the term **ancillary benefits** or **secondary benefits** is often used by economists to refer to monetised benefits **incidentally** resulting from mitigation of greenhouse gas emissions, the primary benefits being the reduction of climate change.

The term ancillary benefits may also be used in a more general sense to indicate incidental benefits resulting from the mitigation of a certain environmental problem other than the abatement of the environmental problem itself. Thus, air pollution mitigation may have ancillary benefits in the area of climate change mitigation and the other way around or in other (non-environmental) policy areas. Ancillary effects may also be negative, thus being ancillary costs. The term ancillary benefits and costs is used in the literature mostly to indicate incidental monetised effects, thus referring to the monetised value gained or lost to society by a positive or negative physical or social effect. However, the term is also used to describe physical impacts, such as reduced health risks.

According to Davis *et al.* (2000) the term **co-benefits** (sometimes also referred to as **multiple benefits**) refers to (possibly monetised) **intentional** effects of the combination of policy objectives (e.g. mitigating air pollution and climate change) looking at the costs and benefits from an integrated perspective.

Other terms to indicate linkages between different environmental problems or other issues are **side effects, knock-on effects, spin-off** and **synergies.** Synergies implicate intentional (not monetised) effects and often refer to policies or reduction strategies from an integrated perspective.

strategies. Furthermore, it proposes preliminary indicators that could be used by the EEA to approach and report on linkages between air quality and climate change in a structured manner.

This report does not address co-benefits for other social, economic and environmental issues, such as waste disposal, traffic congestion, energy security and employment. In Box 1.1 we provide some definitions of the terms used.

1.3. The issues

1.3.1. Regional and local issues

Regional and local issues considered in this report are acidification, tropospheric ozone, urban air pollution and eutrophication.

Acidification has been recognised as a major environmental problem since the early 1970s. The main acidifying compounds are sulphur dioxide (SO_2), nitrogen oxides (NO_x) and ammonia (NH_3), which are mainly emitted during fossil fuel combustion (SO_2 and NO_x) and agricultural production (NH_3). Once in the atmosphere, these pollutants are transformed, transported through the atmosphere and subsequently deposited on the earth's surface. Acidifying deposition may be harmful to ecosystems of soil, water and forests and may also cause corrosion of metals and damage to buildings and monuments. Because of the long-distance atmospheric transport, acidifying deposition and its environmental impact in one country originates to a large extent from emissions in other countries.

Tropospheric ozone or ground level ozone formation is another transboundary air pollution problem that can have negative impacts on human health, agricultural crops and vegetation. NO_x, volatile organic compounds (VOCs), CO and CH_4

contribute together to the formation of ground level ozone. Emissions are mainly caused by fossil fuel combustion (NO_x and VOC), solvents (VOC) and agriculture (CH_4). There is a non-linear relation between the concentration of ozone in the air and its precursors NO_x, VOC, CO and CH_4. Abatement of NO_x emissions can lead to an increase or decrease in tropospheric ozone concentrations at ground level, depending on the NO_x/VOC concentration ratio (Barrett and Berge, 1996), but will always reduce ozone in the free troposphere.

Urban air pollution: NO_x, benzene, PAHs, SO_2, tropospheric ozone, particulate matter as well as other pollutants (e.g. CO, 1.3 butadien) all contribute to 'urban air pollution', which can cause damage and more specifically soiling to monuments and buildings; ozone and **particulate matter** (PM, but also called aerosols) in particular have shown to have adverse impacts on human health and are strongly related to the other air pollution problems (Lükewille *et al.*, 2001). Particulate matter is a complex conglomerate of water, particulates from natural origin (sea salt, wind-blown dust) and primary and secondary organic (EC, OC) and inorganic (SO_4, NO_3, NH_4) formed particulates. There is a non-linear relationship between the concentration of secondary particulate matter and its precursors. There are complex and poorly understood chemical linkages between ozone and secondary particulate matter formation in and around the urban atmosphere.

Eutrophication is the strong enrichment of ecosystems by nutrients (mainly nitrogen and phosphorus), which causes changes in ecosystems. NO_x and NH_3 contribute to eutrophication.

1.3.2. Global issues

Global issues considered in this report are stratospheric ozone depletion and climate change.

Stratospheric ozone depletion is caused by increased levels of chlorine and bromide compounds in the stratosphere. These compounds result mainly from the emission of chlorofluorocarbons (CFCs) used as the coolant in refrigerators and air conditioners, aerosol propellants and foaming and cleaning agents, as well as bromofluorocarbons (halons) used in fire extinguishers. Stratospheric ozone depletion can be harmful as it results in higher ultraviolet (UV-B) radiation at ground level. UV-B can initiate a number of chemical and biological processes, which can damage living organisms (UNEP, 1994). CFCs but also their substitutes (HFCs) are powerful greenhouse gases.

Anthropogenic induced climate change is caused by an increasing concentration of greenhouse gases and changes of aerosol content in the atmosphere. Some greenhouse gases and aerosols occur naturally in the atmosphere, although certain human activities add to the levels of most of these naturally occurring gases, while others result solely from human activities. Greenhouse gases and aerosols are formed in or emitted into the atmosphere as a result of several human activities including fossil fuel burning, agricultural activities and deforestation. Important greenhouse gases are carbon dioxide (CO_2), methane (CH_4), ozone (O_3), water vapour, nitrous oxide (N_2O) and several fluorinated compounds (such as CFCs, HCFCs, HFCs, PFCs and SF_6). Unlike air pollutants and aerosols, the main greenhouse gases are uniformly mixed in the atmosphere because of their relatively long atmospheric lifetime. Therefore, the environmental impact of greenhouse gases does not depend on the location of the emissions. Ozone, however, has a medium lifetime.

1.4. Categories of linkages

There are several interrelations between regional air pollution and climate change. White *et al.* (1989) provide an early overview of possible linkages.

Brink (2003) subdivides interrelations between air pollution and climate change into four categories: (i) emissions of one pollutant may contribute to regional air pollution as well as climate change; (ii) climate change and regional air pollution may have an effect on each other and on emissions; (iii) air pollutants and greenhouse gases may be emitted by the same source; and (iv) technical measures to reduce emissions of greenhouse gases may affect emissions of air pollutants and measures to reduce emissions of air pollutants may affect greenhouse gas emissions.

An example of interrelations in category (i) is the role of SO_2, which contributes to acidification and also plays a role in climate change, partly offsetting the greenhouse effect due to increased amounts of sulphate aerosols in the atmosphere. Examples of interrelations in category (ii) are the effect of acidification and nitrogen deposition on emissions of CH_4 and N_2O in some ecosystems and the effect of increased temperatures on nitrate leaching. Moreover, linkages between regional air pollution and climate change may exist because climate change may alter atmospheric transport patterns of air pollutants and the sensitivity of ecosystems for acidifying deposition. Category (iii) contains another important linkage between regional air pollution and climate change. Because emissions contributing to regional air pollution and climate change are to a large extent emitted by the same sources, policies focusing on these sources to reduce one of these problems may have an impact on the other. This is in particular the case with policies for climate change, which largely focus on reducing CO_2 emissions. CO_2 emissions are almost entirely produced by burning fossil fuels, which is also an important source of several air pollutants. CO_2 emissions can be limited by reducing the use of fossil fuels through energy efficiency improvements and a shift to renewable sources of energy. Climate policies leading to reduced fossil fuel use will have side benefits, because emissions of air pollutants such as SO_2, NO_x and VOC will also decrease. Interrelations in category (iv) occur if technical measures to reduce emissions of air pollutants have an effect on emissions of greenhouse gases and the other way around. Technical measures may have beneficial as well as harmful side effects. Examples are installing scrubbers in power plants to reduce SO_2 emissions causing an increase in CO_2 emissions through increased coal use, and three-way catalysts in cars reducing NO_x and VOC but at the same time causing an increase in N_2O emissions.

1.5. Structure of the report

We will use the subdivision as presented in the former section to structure the remainder of this report. First we will discuss the physical and chemical linkages in the atmosphere between different forms of air pollution and climate in Chapter 2 (category (i)). In Chapter 3 we will discuss linkages in impacts on humans and ecosystems (category (ii)) and in Chapter 4 we will discuss sources of emissions and linkages in control options (categories (iii) and (iv)). Chapter 5 discusses current policy practices and challenges. Chapter 6 provides an overview of recent European-scale projects that addressed linkages between several environmental issues in an integrated way.

Each of the Chapters 1 to 6 starts with the key messages of that chapter. At the end of each of the Chapters 1 to 5 we propose indicators to assess and express linkages between climate change and air pollution issues with respect to atmospheric interactions, impacts, control options and international policies respectively. The EEA may find the indicators useful to report on linkages between air pollution and climate change in a structured manner.

We conclude in Chapter 7 by proposing priority issues for further development of integrated assessment tools and summarising the proposed indicators.

The Annexes provide summaries of selected European studies that adopted an integrated approach towards climate change and air pollution, as well as summaries of workshops on the issue and references to relevant websites.

2. Atmospheric linkages between climate change and air pollution

Key messages

- Air pollutants such as ozone and particles contribute substantially to the radiative forcing of the atmosphere.
- Particularly relevant for the linkages between climate change and air pollution is tropospheric ozone. Climate change, on the one hand, influences ozone concentrations through dynamical and chemical changes in the atmosphere. On the other hand, increasing background ozone concentrations in Europe affect climate change because ozone is a potent greenhouse gas itself and indirectly influences the lifetime of other greenhouse gases such as methane.
- Particles have important health effects and are direct and indirect contributors to radiative forcing. The climatic effects of aerosols are dependent on their composition. Black carbon (soot) enhances warming, while other aerosol constituents (sulphates, nitrates, organic compounds) generally have a cooling effect. The net effect of reducing particulate matter (as required by the European national emission ceilings directive, mainly for health reasons) is probably leading to a further enhancement of the greenhouse effect. However, the issue of a net cooling/warming by aerosol critically depends on the highly uncertain effect of black carbon aerosol, which is at present strongly under debate.
- Methane is a greenhouse gas (GHG) and a precursor for tropospheric ozone; its lifetime is determined by the OH radical, a key trace gas in removing air pollutants and greenhouse gases from the troposphere.
- Important feedbacks and interrelations between the gases (e.g. NO_x–O_3–N_2O–CO_2 cycle) and their effects on each other exist. However, they are quite complex and are often poorly understood.
- Climate change induced stratospheric cooling is likely to delay the recovery of the stratospheric ozone layer by approximately 20 years. In turn stratospheric ozone determines tropospheric OH levels, important for air pollution, and the amount of detrimental UV radiation arriving at the earth's surface.
- More research is needed in order to understand the various atmospheric linkages and their distribution (e.g. ozone and particles) in the troposphere.

2.1. Atmospheric linkages: substances that affect both air pollution and climate change

2.1.1. Radiative forcing of air pollutants

Emissions of one pollutant may contribute to regional air pollution as well as climate change. Important in this respect is the contribution of air pollutants to radiative forcing (see Box 2.1).

Air pollutants contribute to radiative forcing in direct and indirect ways. We distinguish:

- air pollutants with direct radiative forcing like CO_2, O_3, CH_4, N_2O, NO_2, HFCs, PFCs and SF_6, and aerosols like sulphate aerosols and black and organic carbon and $PM_{2.5}$;

and

- air pollutants with indirect effects on radiative forcing: all gases that influence OH (NO_x, CO, VOC, H_2O, etc.), O_3 precursors (NO_x, VOC, CH_4, CO) and aerosol precursors (primary and secondary, including NH_3).

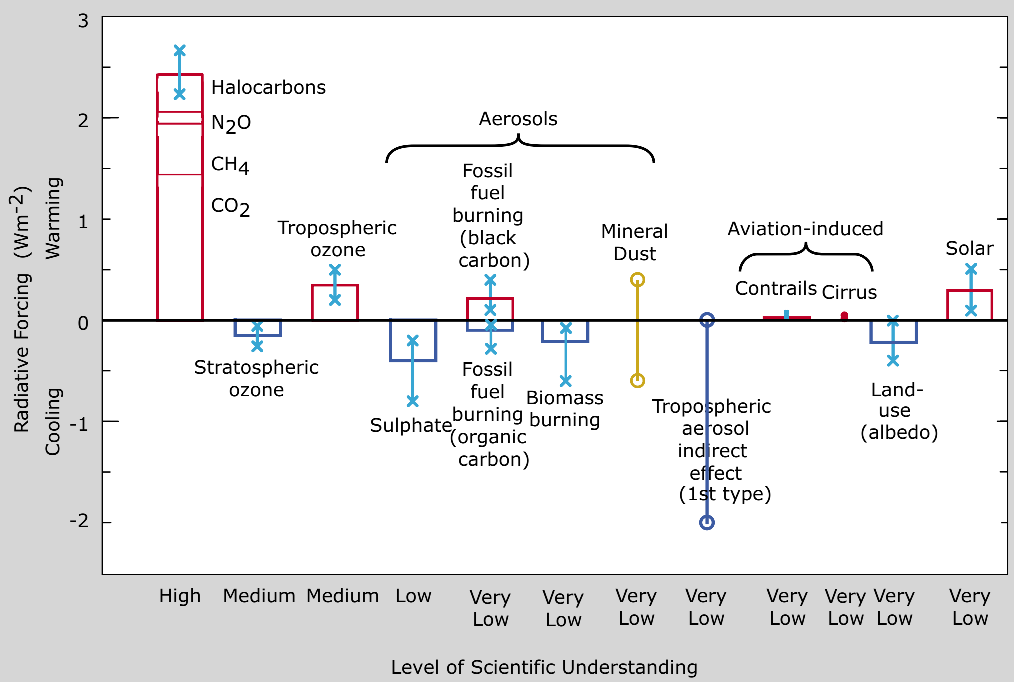
Many air pollutants can be seen as short-lived greenhouse gases and the control of radiative effects of air pollutants may therefore offer a faster response of the climate system than the control of major greenhouse gases, which are usually long-lived. However, the distribution of the short-lived gases varies highly in space and time and consequently it is difficult to quantify their global radiative forcing effects. Furthermore, the interrelations and feedbacks between the gases and their

Box 2.1. Radiative forcing

The earth absorbs solar energy from the sun, redistributes it through atmospheric and oceanic circulations and radiates it back to space at longer wavelengths. Any factor that alters the radiation received from the sun or lost to space, or that alters the redistribution of energy within the atmosphere and between the atmosphere, land and ocean, can affect climate. A change in the energy available to the global earth-atmosphere system due to external changes is called radiative forcing (Wm^{-2}) of the climate system. Radiative forcing of climate change constitutes an index of the relative global mean impacts on the surface-troposphere system due to different natural and anthropogenic causes.

Radiative forcing arises from changes in the atmospheric composition, alteration of surface reflectance by land use, and variation in the output of the sun. Except for solar variation, some form of human activity is linked to each. Positive radiative forcing tends to warm the earth's surface and lower atmosphere and negative radiative forcing tends to cool. Increases in the concentrations of greenhouse gases will reduce the efficiency with which the earth's surface radiates to space. Consequently more of the outgoing terrestrial radiation from the surface is absorbed by the atmosphere and re-emitted at higher altitudes and lower temperatures, which results in a positive radiative forcing that tends to warm the lower atmosphere and surface. The amount of radiative forcing depends on the size of the increase in concentration of each greenhouse gas, the radiative properties of the gases involved, and the concentrations of other greenhouse gases already present in the atmosphere.

Figure 2.1 The global mean radiative forcing of the climate system for the year 2000, relative to 1750



Note: The rectangular bars represent estimates of the contributions of these forcings, some of which yield warming, and some cooling.

Source: Ramaswamy *et al.*, 2001.

effects on each other are quite complex. For example, an increase in NO_x leads to a decreased lifetime of CH_4 and HFCs (via OH) and thus to reduced radiative forcing (see also Box 2.2).

Box 2.2 The OH radical (F. Dentener)

The main oxidant removing atmospheric trace gases from the troposphere is the hydroxyl (OH) radical (Levy, 1971). A net source of OH is the reaction of ultraviolet (UV) sunlight with ozone (O_3) (R1), and water vapour (H_2O) (R2):

$O_3 + hv \rightarrow O(^1D)$ R1

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

O_3 is produced by *in situ* photochemistry within the troposphere (formation of 'air pollution') and is also transported from the stratosphere (background ozone). UV radiation fluxes are strongly dependent on the solar zenith angle and the overhead O_3 column. Therefore OH levels are highest in the tropics where the stratospheric ozone layer is thinnest and the absolute humidity is highest.

The lifetime of OH is very short (1 second) and determined by a multitude of reactions and trace gas concentrations. The most important loss process of OH is the reaction with CO, CH_4 and hydrocarbons in general according to the following initial reactions:

$CO + OH \rightarrow CO_2 + HO_2$ R3a

$RH + OH \rightarrow RO_2$ R3b

$CH_4 + OH \rightarrow CH_3O_2$ R3c

Although CH_4 and CO constitute efficient OH sinks, these reactions do not necessarily strongly deplete OH because part of the radicals (e.g. HO_2) can be recycled, e.g. by the action of nitrogen oxides ($NO_x \equiv NO + NO_2$) if sufficiently available.

OH can now be measured *in situ* on the local scale, but there exist no *in situ* or remote sensing techniques that provide insight on the concentrations and trends of OH on regional, hemispheric or global scales. The only indirect method to determine large-scale OH utilises information on emissions and concentrations of the anthropogenic trace gas methyl-chloroform. However, especially the long-term and large-scale OH trends, derived using this method, are highly uncertain.

Therefore we have to rely on atmospheric models that include all abovementioned processes to estimated changes of the OH concentrations.

These models suggest that global OH decreased in the last century by − 9 to − 15 %. Further decreases by − 10 to − 20 % are expected to happen in the 21st century as indicated in the IPCC *Third assessment report* (Prather *et al.*, 2001)

However, the exact impact of changing emissions on OH, and therefore on the concentrations of a number of short- and long-lived trace gases, will depend on the magnitude and mix of the emissions of precursor gases, such as NO_x, CH_4, non-methane-hydro-carbons (NMHC), and CO. Generally, NO_x emissions will increase OH concentrations, and CH_4, NMHC and CO reduce large-scale OH. A recently emerging policy option is the possibility of reducing CH_4 emissions, which would lead to less ozone formation, and to higher OH concentrations (Fiore *et al.*, 2002).

An increase in NO_x also leads to an increase in O_3 which increases radiative forcing. At the same time a higher concentration of NO_x in the atmosphere may lead to increased N-deposition causing higher soil fertilisation which can lead to more CO_2 uptake by surface vegetation (depending on the level of N-deposition and the type of vegetation), which leads to reduced radiative forcing. Furthermore, increased N-deposition leads itself to increasing N_2O emissions (see also Chapter 3 for linkages in impacts).

The net effect of these processes on climate change is not clear. We elaborate in the next subsections on a limited selection of linkages: the role of aerosols, the linkage between tropospheric ozone pollution and climate change and vice versa, and the linkage between stratospheric ozone depletion and climate change.

2.1.2. Aerosols and climate change

Aerosols are (sub)micron particles suspended in the air, also referred to as particulate matter. Atmospheric aerosols and clouds play a substantial role in the radiative forcing of the earth's climate as they influence the radiation balance of the earth mostly through scattering and absorption processes. They have a residence time of few days, and are thus not evenly distributed in the atmosphere, with maximum concentrations close to their sources. There are still many uncertainties concerning the spatial distribution, the chemical composition of the tropospheric aerosols and especially the chemical coupling between PM and O_3. Furthermore, and perhaps most importantly, aerosols have an important impact on health (see Boxes 2.3 and 3.3).

Aerosols can affect the abundance of other greenhouse gases such as O_3, since their presence reduces the amount of UV-radiation that reaches the lower troposphere (Papayannis *et al.*, 1998, Dickerson *et al.*, 1997 and section 2.1.4), however this effect plays only a minor role in the overall radiative forcing of aerosols.

2.1.3. Tropospheric ozone pollution and climate change

Ground-level ozone is the major component of photochemical smog and elevated ozone concentrations. Tropospheric O_3 is a direct greenhouse gas and has an extremely variable chemical lifetime ranging from weeks to months in the dry upper troposphere, to hours or less in the shallow nocturnal atmospheric boundary layer (ABL). The average lifetime in the troposphere is of the order of weeks.

The limited number of surface measurements in Europe, which date back to the late 19th century, suggest that the concentration of O_3 has more than tripled in the 20th century. The lack of global information on pre-industrial tropospheric O_3 distributions is, however, a major uncertainty in the evaluation of the forcing of this key gas (Prather *et al.*, 2001).

Ozone background concentrations
Ozone levels in the troposphere typically vary from less than 10 ppb over remote tropical oceans up to about 100 ppb in the upper troposphere (Prather *et al.*, 2001), and often exceed 100 ppb downwind of polluted metropolitan regions. The reason for this variation is the rapid chemical turnover, which makes it impossible to determine the tropospheric burden from the available surface sites only.

Ozone levels in Europe and global influences
Ozone peak values have been decreasing significantly over the last 10 years, whereas, on the other hand, the lower percentiles in the ozone values have increased in polluted areas and there is evidence of a general increase in the tropospheric O_3 background. As ozone concentrations depend on the increasing emissions of ozone precursor gases, the observed ozone concentrations in Europe are also increasing, since emissions of these precursors are increasing. This increase in O_3 concentrations is not only due to an increase in local emissions, but also due to the long-range transport of precursor emissions (a regional/global scale phenomenon), giving rise to the concentrations observed far from their initial source (or formation) area (Midgley *et al.*, 2002).

Finally, another parameter (related to climate change) influencing the observed surface O_3 levels in urban areas is the presence of aerosols. Since radical reactions in the atmosphere are driven by sunlight, they are directly affected by temperature variations which change the rate of chemical reactions and by aerosols and clouds which attenuate the intensity of ultraviolet radiation (see Subsection 2.1.4). Moreover, O_3 also influences the presence of other GHGs, since, for example, through the chemical impact of O_3 on OH, the lifetime of CH_4 is modified and although CH_4 is much less abundant than CO_2 in the earth's

Box 2.3 Aerosols (F. Raes)

Aerosol particles in the atmosphere arise from natural sources such as wind-borne dust, sea-spray and emission of biogenic volatile organic compounds. They also arise from a range of anthropogenic activities, such as agriculture (e.g. tilling, waste burning), residential wood combustion and construction, road transport, but in particular the combustion of fossil fuels. Emitted directly as particles (primary aerosol) or formed in the atmosphere by (often photochemical) conversion of gaseous precursors (secondary aerosol), atmospheric particles range in size from a few nanometers (nm) to tens of micrometers (µm). A detailed description of the atmospheric processes leading to the formation of aerosols can be found in Raes *et al.*, 2000.

Today, the interest in aerosols is high mainly because of their effect on human health and their role in climate change. They also have a determining effect on visibility and contribute to the soiling of monuments. They can also have effects on ecosystems and crops, both by contributing to deposition of toxic material to soils and foliage and by interception of UV (Bergin *et al.*, 2001).

Aerosols and health
Epidemiological studies show that an increase in PM_{10} mass concentration by 10 µg m^{-3} results in an increase of 0.5–1.5 % in premature total mortality in case of short-term/episodic exposure, and in an increase up to 5 % in premature total mortality in case of long-term/lifelong exposure (Wilson and Spengler, 1996). As yet, there is no indication which physical or chemical PM characteristic is responsible for these effects. However, recent research seems to indicate that PM_{10} is associated with respiratory responses and $PM_{2.5}$ with cardiovascular diseases (Wyzga, 2002). Legislation in the EU and US is therefore expressed in terms of target values for PM_{10} and $PM_{2.5}$ (= the mass of particles with a diameter below 10 µm or 2.5 µm, respectively).

Aerosols and climate
Observations and model calculations show that the increase in the atmospheric aerosol burden is delaying the global warming expected from the increase in greenhouse gases. Whereas the increase in GHGs since pre-industrial times is producing a warming of 2.4 Wm^{-2}, the overall cooling effect of aerosols might be up to — 2.5 Wm^{-2} (Ramaswamy *et al.*, 2001; Penner *et al.*, 2001). The latter value is composed of contributions by, for example, sulphate and organic particles, which cool, and black carbon (BC), which heats. Modelling studies suggest that the abundance of BC (soot) relative to non-absorbing constituents has a strong influence on the magnitude of the cooling or warming effect (e.g. Hansen *et al.*, 1997; Penner *et al.*, 1998). Furthermore, an important parameter for the sign and magnitude of the effect is the state of mixing between BC and sulphate aerosols (Jacobson, 2001). Combustion processes are the dominant source for black carbon (e.g. Penner *et al.*, 1993) and organic carbon (OC) is the largest single component of biomass burning aerosols (see e.g. Andreae *et al.*, 1988). It should also be noted that the size of those particles mentioned largely corresponds with the $PM_{2.5}$ fraction considered in relation to the health problem. International and EU climate change policies aim at reducing the emissions of greenhouse gases by implementing the Kyoto Protocol. It is expected that negotiations of reductions beyond the Kyoto Protocol might consider also the role of aerosols (Hansen *et al.*, 2000).

Linkages
European air pollution policies such as the EC's national emission ceilings directive, and the implementation of the EU standards for PM, are expected to reduce aerosol burdens by 50 % or more. The need to reduce PM pollution in the developing world is even larger. Taking the IPCC at face value, it is expected therefore that PM policies will aggravate the global warming problem, and more stringent climate change policies (i.e. GHG emission reduction policies) are required. However, more detailed analyses will be required that consider the effect of specific PM reduction policies, e.g. those focusing on black carbon, and that consider the regional climate effects of PM, before definite statements can be made.

atmosphere, the total warming effect of CH_4 is substantial.

2.1.4. Stratospheric ozone and climate change

The stratospheric ozone layer effectively serves as a protective shield that reduces the harmful ultraviolet radiation (UV) reaching the earth's surface and modulates outgoing IR radiation from the earth. As a consequence, the depletion of stratospheric ozone observed over the last two decades, probably caused by the emission of man-made halocarbons (CFCs, halons),

Table 2.1 Interaction stratospheric ozone-climate change

Description	Process/ component	Chemical mid-latitude	Dynamical mid-latitude	Chemical polar	Dynamical polar	Montreal Protocol	Kyoto Protocol
Catalytic ozone destruction in the stratosphere: decreased depletion is anticipated due to lower emissions of CFCs, halons, CCl_4, CH_3CCl_3, HCFCs	CFCs, halons	x				X	
Chemical destruction of ozone by NO_x cycle; anticipated increase in N_2O emissions	N_2O	x					x
Formation of reservoir species HC1 decreases ozone destruction	CH_4	x					x
Temperature dependence of the Chapman cycle: anticipated decrease in temperature in the stratosphere	T (gas chem)	x					x
Additional polar ozone loss by cooling and a stronger vortex combined with spread-out of ozone-depleted air into mid-latitudes	Polar vortex		x	x	x		x
Increase in stratospheric H_2O as a result of changes in dynamics and methane oxidation, and consequent chemical reactions that affect ozone	H_2O increase	x	x				x
An increase of the stratospheric circulation intensity, leading to: • increase of tropopause height • accelerated removal of CFCs from the atmosphere • increase of transport subtropical air into mid-latitudes	Dynamics		x				?

Source: Kelfkens *et al.*, 2002.

has probably led to higher UV levels. Increased penetration of UV-B radiation leads among others (see Table 2.1) to more rapid photochemical destruction of CH_4, thereby reducing its radiative forcing (Houghton *et al.*, 2001).

Since the Montreal Protocol of 1987, a phase-out of ozone-depleting substances has been agreed upon. These countermeasures are expected to lead to a slow recovery of the ozone layer over the next century. It is expected that a slow recovery of the ozone layer will occur with a return to 'normal' (1980) levels around 2050 (WMO/UNEP, 2002; Slaper *et al.*, 1996). Excess skin cancer risk, caused by ozone depletion, are in those scenarios expected to rise until 2050–70.

Growing insight into the radiative balance of the atmosphere and its disturbance by the continuous increase in greenhouse gas emissions indicates cooling of the stratosphere and a change in dynamical processes. These changes can have effects on the ozone levels and furthermore they can interact with the chemical breakdown processes (Kelfkens *et al.*, 2002).

Kelfkens *et al.* (2002) concluded, under the uncertainties given by the risk assessment, that climate change induced stratospheric cooling is likely to delay the recovery of the stratospheric ozone layer by approximately 20 years and as a consequence results in a higher and more persistent increase in (effective) UV levels over Europe. In north-western Europe the increase in effective UV (with ozone climate interactions) is expected to peak at 9.4 % (relative to the 1980 level) around 2020 as compared to 8.7 % extra UV (in 2000), with no ozone-climate interaction assumed.

Kelfkens *et al.* (2002) concluded that research on depletion of stratospheric ozone and research on climate change follow separate tracks. But the interactions between climate change

Table 2.2 Illustration of the linkages between climate change and air pollution

	SO_2	NO_x	NH_3	VOC	CO	Primary PM+BC	CH_4	CO_2+ GHGs
Ecosystems								
• Acidification	√	√	√					
• Eutrophication		√	√					
• Ground level ozone		√		√	√		√	
Health impacts								
• Direct	√	√		√	√	√		
• Indirect by sec. aerosols and ozone	√	√	√	√	√		√	
Radiative forcing								
• Direct		√					√	√
• Via aerosols	√	√	√	√		√		
• Via OH		√		√	√		√	

and ozone layer, summarised above, are so complex and may induce such (potential) important effects that integration of these lines of research is recommended. Internationally, this asks for a closer cooperation of the panels active under the Montreal Protocol and the Intergovernmental Panel on Climate Change (IPCC).

2.2. Overview of important compounds

In the previous subsections a selection of linkages has been presented following a thematic approach. In this section we present an overview of the involved compounds and their contributions to the different environmental problems. Table 2.2 illustrates how the linkages between air pollution and climate change can be seen as a multi-pollutant/multi-effect problem extended towards radiative forcing.

2.3. Conclusions

The examples in the preceding paragraphs illustrate that air pollutants and greenhouse gases interact at various scale levels and that there is a clear link between air pollution and climate change. In particular, the fact that air pollutants can act as short-lived greenhouse gases and the complex contribution of aerosols to the overall greenhouse effect deserve special attention.

Overall, although there is significant scientific understanding of the chemical interactions between individual air pollutants, long-lived greenhouse gases and aerosols, the understanding of the complete relationship between the quantities emitted or formed and the concentrations eventually measured at different time scales is low. Also, more precise determination of the chemical composition of aerosols is necessary in order to assess the overall net warming or cooling effect, as this is the largest source of uncertainty among the radiative forcing, as described in the IPCC 2001 reports.

Moreover, tropospheric ozone background concentrations play an important role in the concentration of greenhouse gases and they also significantly affect urban scale air quality modelling. Hence, further studies aiming to determine ozone background concentrations in various locations should be conducted.

2.4. Proposed linkage indicators for the EEA

In order to assist the EEA to approach and report on linkages between air quality and climate change in a structured manner we propose here, as a first, very preliminary step, some potential indicators that could be relevant for describing the linkages. As noted, not all identified linkages can be assessed and described yet with the current state of knowledge and modelling framework available.

Below we propose 'state' linkage indicators to describe the linkages between climate change and air pollution.

- **Contribution of European air pollutants to global climate change over time in Europe —** This indicator can be developed on the short- to medium-time scale for most pollutants with the exception of black carbon. The proposed indicator can be expressed in different ways: in concentrations terms (ppb/ppm), in CO_2-equivalents (ppm-CO_2 equiv.) or in their contribution to the global radiative forcing (W/m^2).
- **Half-life time of the various air pollutants** — This indicator describes the development of the half-life time of the various air pollutants and thereby indirectly provides a measure of the effect that changes in atmospheric composition can have on the global warming potentials (GWPs). In the Kyoto Protocol, scaling factors are used to establish a common base for the effect of a unit of CO_2 reduction compared to other GHGs (GWP). This scaling factor is, among others, dependent on the half-life time of the air pollutant in the atmosphere. The half-life time is variable, depending on the development of the concentration of the OH radical in the troposphere. The development of this indicator is foreseen for the medium to the long term.
- **Climate change induced changes in weather patterns leading to changes in air pollution —** This indicator refers to the change of frequencies of stagnant high pressure systems leading to high pollution events. Meteorological data (e.g. on high press. occ., and precipitation) are available. The development of this indicator is foreseen for the medium to the long term. Quite a number of research groups in Europe are trying to link climate change induced changes in weather patterns to 'air pollution'.

3. Linkages of impacts

Key messages

- Climate change can enhance but also lower the impacts of regional air pollution such as ozone and particles, and vice versa.
- Climate change is likely to impact natural emissions of ozone precursor gases (NO_x, VOC) and of particles (mineral dust) and will therefore change the background concentrations of particles and ozone.
- Impacts of climate change and air pollution on humans and ecosystems interact in two ways. On the one hand, climate change can change the **exposure** of humans and ecosystems to impacts of air pollution, and the other way round. On the other hand, climate change can affect the **sensitivity** of humans and ecosystems to specific impacts of air pollution and vice versa.
- The **exposure** of ecosystems to air pollution can change as a result of phenological changes induced by climate change (e.g. changes in the length of the growing season) as well as by changed distribution of air pollutants through changed weather patterns. Their **sensitivity** may change as a result of, *inter alia*, climate-induced changes in soil processes, plant growth (both determining ecosystem vitality) and ecosystem composition.
- The **exposure** of humans to the ozone, PM and other pollutants is likely to be affected by climate-induced changes in their local and regional abundance. Insufficient information is available to assess changes in the **sensitivit***y* of humans to air pollutants because of climate change.
- In general, linkages regarding impacts are surrounded by a relative high uncertainty.
- Because of the long response times involved in impacts of climate change, interactions with regard to impacts are believed to be of lesser significance for the short to medium term than other types of linkages discussed in this report.

3.1. Introduction

Climate change and regional air pollution may have an effect on each other and on emissions.

In this chapter we summarise the interactions between climate change on the one hand and (i) regional air pollution and (ii) stratospheric ozone on the other hand regarding their impacts. The impacts of the three issues are often assessed separately. Many reasons exist for such a separate treatment (e.g. air pollution impact studies frequently focus on the term of one or two decades whereas studies of climate change often focus on the longer term, i.e. from decades to even centuries). However, there are also many interactions between the abovementioned issues, resulting in an amplification or mitigation of impacts of acid and nitrogen deposition and stratospheric ozone by climate change and vice versa. Because of this interdependency, an integrated assessment of the impacts of the issues is desirable.

The interactions between climate change, air pollution and stratospheric ozone consist of two parts, both resulting in changed vulnerability of ecosystems and human beings. The approach is also used in other studies like the 'Millennium assessment on biodiversity' in which the vulnerability of the ecosystem to environmental changes will be assessed. Firstly, changes in climatic conditions may alter the (level of) **exposure** to air pollution and air pollution may influence climatic conditions (e.g. through the cooling effect of sulphur aerosols). Likewise, climate change affects the breakdown of the stratospheric ozone layer and therefore the UV-B exposure. Secondly, one environmental problem may change the **sensitivity** of human and natural systems to other issues, negatively or positively. We describe the linkages for both the exposure and sensitivity, including some examples. Firstly, the linkages are described for the impacts on ecosystems and biodiversity, followed by an assessment of impacts on human health. We also add statements

Box 3.1 Examples of interactions between climate change and regional air pollution regarding the exposure to ecosystems (J. van Minnen)

- Changing weather patterns may alter atmospheric distribution of air pollutants. Such changes are caused by changing wind patterns and changes in precipitation amounts and intensities. Alcamo *et al.* (2002) have shown that changes in precipitation amounts might be limited (this conclusion was based on climate change projections of a single climate model). Further research is needed on this issue. The intensity of precipitation will determine the atmospheric concentration and deposition of acidifying compounds on soils and water and as such the exposure of plants (Seip and Menz, 2002).
- Climate change parameters that lead to a longer growing season (e.g. higher temperature) increase the exposure of plants to air pollutants like SO_2 and O_3, whereas parameters that shorten the growing season (e.g. water stress) reduce the exposure and damaging effects of air pollutants (Guardans, 2002; Mauzerall, 2002).
- Climate change affects ecosystem structure (e.g. growth stimulation under temperature increase or more frequent forest fires under precipitation decrease). Ecosystem structure is one of the determinants of surface roughness (Claussen, 1994), which affects the deposition pattern of air pollutants (Draaiers, 1993).
- Aerosols likely affect the CO_2 uptake of plants and thus plant growth, for example through its effect on the quantity of radiation that reaches plants (Mauzerall, 2002). The net effect is species specific.

about the uncertainties of the linkages, because the uncertainties are in general high.

3.2. Ecosystems and biodiversity

The impacts of air pollution and climate change on ecosystems and biodiversity have been issued in many studies in the last decades. The studies showed, for example, that climate change impacts are already visible (e.g. plant distribution, reviewed by Gitay *et al.*, 2001) or that nitrogen deposition had large impacts on ecosystem composition (e.g. Van Breemen *et al.*, 1998). The impacts on ecosystems are often treated separately for air pollution and climate change. However, recent studies show that climate change affects various processes in the vegetation (e.g. growth) and soil compartment (e.g. weathering) of ecosystems that are important in determining the exposure levels (Box 3.1) and sensitivity (Box 3.2) of ecosystems to air pollutants and vice versa. Thus the combined effect might differ from the sum of separate effects due to the interactions.

Some recent studies (such as those presented at the UNECE workshop on linkages and synergies; see Annex 7) concluded that climate change, air pollution and ozone all affect ecosystems and biodiversity. Secondly, they concluded that a number of linkages exist between these stress factors, but that the net effect is uncertain and can even go in different directions. Impacts of acid deposition can be amplified or mitigated by climate change and vice versa (Skelly, 1993). The changes can be expressed in changed critical loads (Posch, 2002) or critical climate change ([1]) (Van Minnen et al., 2002). Thirdly, various compounds are involved in the linkages between climate change and air pollution. Ozone and nitrogen are two important ones (Box 3.2). Fourthly, the studies concluded that the linkages vary over spatial and temporal scales. On a local scale, for example, climate change effects on the surface roughness and therefore deposition patterns of air pollutants might be important, but on a regional scale these effects will be less relevant for the total deposition. Finally, because of the complex interactions,

([1]) Critical climate has been defined as a 'quantitative magnitude of climate change above which unacceptable long-term effects on ecosystems may occur, according to current knowledge' (Van Minnen *et al.*, 2002). The method in the current stage only defined thresholds for changes in monthly mean temperature and precipitation.

Box 3.2 Examples of the interactions between climate change and regional air pollution regarding the sensitivity of ecosystems (J. van Minnen)

Soils

- Climate change most likely alters many soil processes, having consequences for the entire ecosystem. For example, climate change (especially temperature) affects the weathering rate of soils and thus the cation availability. Cations are important drivers of the buffer capacity of soils and thus the sensitivity of plants to air pollution (Posch, 2002). Posch showed for a number of climate change scenarios that climate change increases the weathering rate in many regions of Europe, resulting in higher critical loads (i.e. lower sensitivity of ecosystems to air pollutants). In some other areas, however, ecosystems might become more sensitive to air pollution with climate change, especially regions projected to become drier.
- Likewise, climate warming may increase the mineralisation process in soils. This leads to more nitrogen in the soil. The nitrogen availability also increases by deposition (through air pollution). On the one hand, the increased nitrogen availability results in more nitrogen available for plants. This, in turn, increases plant growth and thus the C sink (especially if nitrogen is the limiting compound; Bazzaz and Sombroek, 1996), and enhances the response of an ecosystem to increased CO_2 levels in the atmosphere and changes in temperature. On the other hand, an overload of nitrogen leads to eutrophication and changed ecosystem composition (Alkemade *et al.*, 1998; Van Oene and Berendse, 2002), decreased vitality of ecosystems, and increased emissions (N_2O) and leaching of nitrogen (Grennfelt *et al.*, 1994; Van Breemen *et al.* 1998; Bouwman and van Vuuren, 1999) The changes in ecosystem composition and vitality may increase the sensitivity of an ecosystem to other stress factors.

Direct effects on plants

- Ozone affects the stomatal activity of leaves and as such increases the sensitivity of plants to reduced moisture availability (e.g. Mortensen *et al.*, 1995; Emberson *et al.*, 2000).
- Climate change parameters that trigger stomata opening (e.g. increasing temperature, humidity) increase the sensitivity of plants to air pollutants like SO_2 and O_3. Parameters that lead to stomata closure (e.g. water stress, increased CO_2) help to protect the plant from damaging effects of air pollutants. The net effect varies for different ecosystem types (natural and managed), type of interaction, the concentration of the pollutants and regions (Bazzaz and Sombroek, 1996; Mauzerall, 2002).
- Ozone decreases the winter hardiness of many agricultural and natural species. Thus, increased ozone levels may increase the risk of frost damage (reviewed by Bazzaz and Sombroek, 1996).

Ecosystem composition

- Temperature and precipitation are factors that determine ecosystem composition directly (details, for example, in Leemans *et al.*, 1996; Leemans and Hootsman, 1998). As such climate change may result in changes in ecosystem composition. Such changes have been observed under historic climate change (e.g. Prentice *et al.*, 1998) and are also projected for the future (e.g. White *et al.*, 1998; Sitch *et al.*, 2003). Since critical loads of air pollution are species specific, the critical loads in a region may change if ecosystem composition changes, meaning that the sensitivity to air pollution changes.
- Also air pollution (especially nitrogen) affects ecosystem composition (e.g. Alkemade *et al.*, 1998; Van Oene and Berendse, 2002). This may change the sensitivity of an ecosystem to climate change (e.g. the response to increasing CO_2 levels in the atmosphere).

new environmental impact models should be developed that are capable of assessing changes in multiple stress factors on different scales.

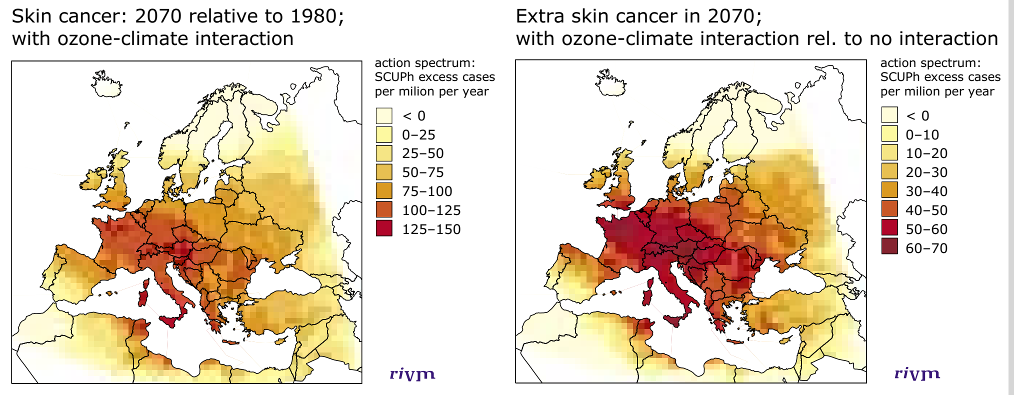
3.3. Human health

Numerous publications exist regarding the impacts of air pollution (e.g. through particles and ozone) and climate change (e.g. through heat-related mortality and vector-borne diseases) on human health. In this report we will not describe the separate relationships, but focus on the interactions between air pollutants and climate change and the consequences for human health. Similar to ecosystems, the linkage between climate and air pollution can be categorised in linkages with respect to the exposure and sensitivity of humans to one of the issues. Regarding the former, various linkages are described in Box 3.3.

Box 3.3 Examples of interactions between climate change and regional air pollution regarding the exposure of humans (J. van Minnen and H. C. Eerens)

- Climate change may affect distribution patterns and atmospheric mixture of pollutants. This may lead to changes in the frequency and extent of episodes (e.g. ozone and PM_{10}) and thus damages to human health.
- Ozone exposure changes under climate change. The changes are initiated in two ways. Firstly, climate change may result in increased emissions of pollutants. Secondly, temperature is one of the drivers of ozone exposure. Increased temperatures, especially in the summer, will result in a higher background concentration and in more and longer ozone episodes. Anderson, Derwent and Stedman (2001) show that elevated O_3 episodes in the UK especially occur when the daily temperature exceeds 25 °C. Such conditions will occur more frequently under climate change. This can have severe consequences for human health both in the short and long term (Van Bree, personal communication).
- Increased (annual) temperatures result in less extreme winters, resulting in less exposure to fine particulates. The exposure to particulates may also be reduced by various greenhouse gas mitigation policies. Reduced exposure to these particulates can increase life expectancy by two to three years (Kovats *et al.*, 1999; Mechler *et al.* 2002). Vice versa, policies to reduce particulate emissions (e.g. because of health reasons) might contribute to climate change control, depending on the type of particles that are reduced (see section 2.1.2).
- Particulates are both drivers of climate change and air pollution. Their spread and concentration depend on climate conditions. The concentration in the lower atmosphere can, for example, largely increase under cold weather conditions with less wind. In Europe such cold periods might occur less frequently under climate change (Kovats *et al.*, 1999).
- In Subsection 2.1.4 we discussed the effect of climate change on the recovery process of the stratospheric ozone layer, including some of the uncertainties. Climate change may slow down the recovery, causing more UV-mediated skin cancer (Figure 2.4). Kelfens *et al.* (2001) quantified the excess skin cancer risk in 2070 for the mid-latitudes in Europe, considering some of the uncertainties. They showed that between 50 and 150 extra cases per million inhabitants per year may occur (compared to the situation of no delayed recovery of the ozone layer).

Figure 2.4 Increase in skin cancer incidence in 2070



Note: The change in risk is expressed as the number of extra cases per million inhabitants per year (comparing projected number of cases with ozone–climate interaction and without ozone–climate interaction). Computations are based on the UV sensitivity of the Dutch population.

Source: Kelfkens *et al.*, 2001.

With respect to exposure, particles are critical for the linkages between air and climate change because the net effect of reduction on climate change is unclear whereas the net effect on human health is positive (see Box 3.4 for details). We defined one indicator for this linkage to quantify the climate change effect on the frequency of ozone and PM episodes.

Regarding the sensitivity of humans to air pollution and climate change, only a limited amount of information is available regarding the linkage. One example of a linkage is that humans may become less prone to respiratory infections (e.g. influenza) under increasing temperatures, resulting, in turn, in a lower sensitivity to air

Box 3.4 Health risks of fine particulates

Introduction
Particles such as sulphate have a negative radiative force (cooling) and compensate some of the positive radiative forcing of GHGs (see Box 2.3) From an air pollution point of view, further reductions of certain particles are important.

Expected health effects
The 'Global burden of disease' project has recently expanded its analysis of the impact of common risk factors on health to include environmental factors. It has been estimated that, worldwide, close to 1 000 000 premature deaths occur due to long-term exposure to high PM concentrations (Ezzati *et al.*, 2002).

Such effects are to be seen as a reduction of life expectancy by a few years, and increased infant mortality in the more highly exposed areas (Brunekreef, 1997; Bobak and Leon, 1999), increased bronchitis rates, reduced lung function and perhaps other chronic effects. For almost all types of health effects, data are available not only from studies conducted in the US and Canada (Dockery *et al.*, 1996; Raizenne *et al.*, 1996), but also from Europe (Braun-Fahrlander *et al.*, 1997; Nyberg *et al.*, 2000), which adds strength to the conclusions.

Vulnerable groups
The very young and the very old, as well as persons with lower socioeconomic status, are apparently especially affected by PM air pollution (Gwynn and Thurston, 2001; Krewski *et al.*, 2000; Pope *et al.*, 2002). In the time-series studies, it has been well established that elderly subjects (and, possibly, very young children) are more at risk than others (Schwartz, 1994). Subjects with pre-existing cardiovascular and respiratory disease are also at higher risk (Dockery, 2001; Goldberg *et al.*, 2001). This is remarkably similar to the experiences of the populations exposed to the London 1952 smog episode. Children with asthma and bronchial hyper-responsiveness have also been shown to be more susceptible to ambient PM (Boezen *et al.*, 1999; Pope and Dockery, 1992) although effects have been observed in non-symptomatic children as well.

Main sources contributing to the health effects of particulates
The short-term studies suggest that a number of source types are associated with mortality, including motor vehicle emissions, coal combustion, oil burning and vegetative burning. Some studies have also implicated traffic as one important source of PM related to morbidity and mortality in time-series studies (Hoek *et al.*, 2002; Janssen *et al.*, 2002; Roemer and van Wijnen, 2001a; Roemer and van Wijnen, 2001b).

Source: Brunekreef and Dybing, 2003.

pollutants and particulates (Kovats *et al.*, 1999). The relationship is, however, still uncertain. Therefore this aspect and other aspects need to be further researched. In contrast, climate change may result in increased temperatures in summer, potentially causing a higher sensitivity to ozone.

3.4. Proposed linkage indicators for the EEA

In order to assist the EEA to approach and report on linkages between air quality and climate change in a structured manner we propose here, as a first, very preliminary step, some potential indicators that could be relevant for describing the linkages. As noted, not all identified linkages can be assessed and described yet with the current state of knowledge and modelling framework available.

We identified various indicators to illustrate the linkages between air pollution and climate change regarding the impacts and to assess the effectiveness of different policies (see Table 3.1). A first criterion to define the indicators was, obviously, the assessment of linkages. As such, separate indicators for both issues (as they are currently developed for climate change state and impacts) (Erhard, Voigt and Van Minnen, 2002) are excluded. Secondly, the indicators should be easy to understand and relevant to both scientists and stakeholders. Therefore a number of policy effectiveness indicators (e.g. the

Table 3.1 Impact and response indicators for the relationship between climate change and air pollution

Indicator	Unit	DPSIR	Development time [1]	Type [2]
Climate change effect on percentage area exceedance of critical loads (total acidity)	% change	I	S	Mo
Climate change effect on percentage area exceedance critical loads (total nitrogen)	% change	I	S	Mo
Climate induced change of emissions	% change	I	S	Me, Mo
Climate change effect (esp. temperature) on frequency of episodes of air pollutants	% change	I	M	Mo
Nitrogen effect on climate change induced changes in ecosystem composition	Additional % change	I	M	Mo

DPSIR = 'Driving forces, pressure, state, impacts, response'; note that the type of indicator can be different from a climate change or air pollution perspective.

(1) Development time means the time period that an indicator becomes applicable for assessments. S = short (0–2 years), M = medium (3–5 years), L = long (6–10 years).
(2) Indicator type illustrates the main source of information. Me = measurements (past trends), Mo = modelling (scenarios).

CC effect on the effectiveness of air pollution policies) have been selected. A final criterion was the scientific soundness and related uncertainty. As mentioned before, linkages of climate change and air pollution impacts are in general surrounded by a relative high uncertainty. Some exceptions exist, however, such as the climate change effect on critical loads. Therefore the climate change effect on critical loads (both acidity and nitrogen) have been defined as indicators that are applicable in the short term, whereas the effects of air pollution on climate change impacts are less clear. An example of the latter type of indicator is the 'nitrogen effect on climate change induced changes in ecosystem composition' that has been defined as a medium-term indicator.

4. Linkages in emissions and control options

Key messages

- From a policy perspective, the most important linkages between climate change and air pollution exist at the level of emission sources. Air pollutants and greenhouse gases are often emitted by the same sources and hence changes in the activity levels of these sources affect both types of emissions.
- Technical emission control measures aiming at the reduction of one type of emission from a particular source may reduce or increase the emissions of other substances. In the energy sector, efficiency improvements and increased usage of natural gas can address both problems (synergies), while desulphurisation of flue gases reduces sulphur emissions but can — to a limited extent — increase carbon dioxide emissions (trade-offs). In agriculture, some specific measures to abate ammonia emissions could enhance nitrous oxide and/or methane emissions, while other types of measures would reduce these.
- Energy scenarios that ignore the linkage between the emissions of local and regional air pollutants and greenhouse gases ignore the constraints imposed by concerns about local and regional air quality on the development of the energy system and thus tend to overestimate the potential growth of greenhouse gas emissions. Similarly, an integrated assessment across economic sectors is important to identify possible situations in which emission reductions in one sector or region of one type of pollutant would lead to increasing emissions in another sector or region.
- Implementing climate policies, e.g. in order to achieve the Kyoto Protocol targets, can significantly reduce the costs of meeting air quality targets. Conversely, meeting stringent air quality targets is likely to eventually require measures beyond end-of-pipe technological solutions, and require broader structural changes (e.g. in the energy mix), consistent with climate goals.

4.1. Linkages in emissions and control options

Many measures to abate air pollution also benefit the climate through reduction of GHG emissions, and vice versa. For achieving overall cost-effectiveness, it is necessary to understand these synergies in emission controls and to address local, regional and global objectives simultaneously rather than separately. As marginal costs of further air pollution abatement measures tend to increase rapidly once a certain reduction level has been achieved, any potential for cost savings for strategies to reach air quality objectives must be explored. Synergies may free resources that allow reaching more ambitious targets. Many of the driving forces underlying air pollution and climate change are identical: economic growth, consumption and production processes, and demography. A sustainable development strategy must address these issues in an integrated manner.

Emissions of air pollutants and greenhouse gases may be interlinked in various ways:

- Air pollutants and greenhouse gases are simultaneously emitted from the same sources. Any measure modifying the activity level of a source (e.g. energy conservation, fuel substitution, change in production level, etc.) thus influences emissions of air pollutants and greenhouse gases simultaneously.
- Certain technical emission control measures have effects on more than one pollutant. Thus, measures aimed at the reduction of one pollutant may lead to reductions or increases of other pollutants.

A number of studies have addressed the synergies and trade-offs emerging from these linkages.

Energy emission models have been used to demonstrate that the structural changes of energy strategies that are implemented to control CO_2 emissions (e.g. less coal use) result in many cases also in lower emissions of air pollutants (Barker and Rosendahl, 2000; RIVM *et al.*, 2001, Rentz *et al.*, 1994; Syri *et al.*, 2001).

It has also been shown that global energy scenarios that ignore the linkage between the emissions of local and regional air pollutants and greenhouse gases overlook the constraints imposed by concerns about local and regional air quality on the development of the energy system and thus tend to overestimate the potential growth of greenhouse gas emissions (Nakicenovic *et al.*, 1995; Amann *et al.*, 1995).

If air quality is safeguarded by appropriate provisions (such as national emission ceilings), emissions of air pollutants and emissions of greenhouse gases can, up to a certain extent, be decoupled through the application of emission control technologies. However, it has been demonstrated that in such a case energy strategies that result in lower GHG emissions enable the compliance with emission ceilings at significantly lower costs due to the lower volume and different structure of energy consumption.

For Europe, Syri *et al.* (2001) and the EEA (2004) have estimated that the costs of controlling regional air pollution, including the costs of implementation of the emission ceilings of the national emission ceilings directive and of the Gothenburg Protocol, could be reduced by up to 10 %. These cost savings compensate 20 to even more than 50 % of the additional costs incurred by the constraint on carbon emissions. Similar results were obtained by Alcamo *et al.* (2002).

To be efficient, such strategies must be considered in their full context. A limited focus (e.g. on single countries) might invoke even counterproductive effects in an international context.

For instance, Klaassen *et al.* (2002) have pointed out that a regional strategy to enhance natural gas infrastructure, while reducing global CO_2 emissions, may increase SO_2 emissions in other regions due to the possible risk of switching to coal in gas-exporting countries.

It is also important that such an analysis include all economic sectors. The increased use of biomass in the domestic sector that occurred in recent years in some EU countries has contributed to the reduction of CO_2 emissions but has increased emissions of PM, CO, VOC and PAH emissions from this sector (compare, for example, IIASA, 2002). In Asia, a replacement of coal by renewables in the electricity sector may result in higher use of coal in some other sectors, where less technical potential for emission controls exists, so that, as a consequence, SO_2 and PM emissions might increase (Klaassen *et al.*, 2002).

A recent EEA study (EEA, 2004) points out that economic instruments, such as GHG emissions trading systems, can have significant effects on the distribution and levels of air pollution emissions. While carbon trading within Europe can reduce the overall costs of emission reductions for given carbon targets, it tends to shift the significant co-benefits of abatement measures from western Europe to other regions. Unconstrained trading of GHG may not be cost-effective, if air quality objectives are taken into account. In some countries, GHG trading may not make sense, as the structural measures for CO_2 abatement may be necessary to achieve the emission reductions (e.g. for NO_x) that are required to comply with the national emission ceilings. The other linkage between emissions of air pollutants and greenhouse gases is related to the effect of technical emission control measures on multiple pollutants.

There are a number of emission control technologies that reduce both air pollutants and greenhouse gases. For instance, some of the measures in the agricultural sector that reduce NH_3 emissions (e.g. dietary changes, improved storage of manure) also lead to lower N_2O emissions (Brink *et al.*, 2001a). Under certain conditions, new engine technologies that improve fuel efficiency and thus reduce CO_2 emissions also have, at the same time, lower NO_x emissions. Selective catalytic reduction (SCR) on gas boilers reduces not only NO_x, but also N_2O, CO and CH_4 (IPCC, 1997). The three-way catalysts on cars reduce NO_x, CO and CH_4. Regular inspection and maintenance programmes on oil and gas production and distribution facilities will reduce losses of CH_4, but also of other VOCs.

There are, however, several examples where, at least in principle, emission control technologies aimed at a certain pollutant could increase emissions of other pollutants. This is the case for all emission control measures that increase energy consumption and thus the related emissions of greenhouse gases. Desulphurisation techniques involving $CaCO_3$ increase CO_2 emissions (IPCC, 1997), and catalysts that are used to reduce NO_x, VOC and CO emissions from vehicles tend to cause higher N_2O and NH_3 emissions (e.g. Becker *et al.*, 1999; Baum *et al.*, 2000). Also the substitution of gasoline engines with more fuel-efficient diesel engines might lead to higher PM/black carbon emissions (EC, 1998). A similar effect holds for the new direct injection gasoline (GDI) engines (Kwon *et al.*, 1999; Lappi *et al.*, 2001). Options to reduce losses of NH_3 from the application of manure (e.g. deep injection) may result in an increase of emissions of N_2O from soils (Brink *et al.*, 2001a).

While some of these effects are well documented, their quantitative relevance in an overall emission control strategy needs to be examined. Not many studies are available that have addressed such issues. Brink *et al.* (2001b) have analysed for the agricultural sector the spillover effects of NH_3 controls on CH_4 and N_2O emissions, and vice versa, and found that the impact of cost-effective NH_3 abatement strategies on N_2O and CH_4 emissions differs between countries, depending on the NH_3 control options applied. Most importantly, Brink (2003)

Box 4.1 Integrated studies (C. Brink)

For some countries, integrated studies have been carried out addressing the joint abatement of CO_2 emissions and air pollutants. The two studies below monetise the effects of CO_2 abatement.

Interactions in reducing energy-related emissions in Belgium
Proost and Van Regemorter (2001) perform an integrated optimisation analysis for reducing energy-related emissions of air pollutants and greenhouse gases. They adapted the Markal model for Belgium to include atmospheric transport and location specific damages from pollution, including damage across the border. They consider monetary values of impacts of Belgian emissions on public health, terrestrial ecosystems and materials. Like most of the literature on ancillary benefits of CO_2 abatement, interactions between greenhouse gas reduction policies and air pollution occur because energy efficiency improvements reducing CO_2 emissions simultaneously reduce emissions of SO_2, NO_x, VOC and PM. In addition, they include specific abatement technologies for air pollutants.

Benefits of energy saving in Hungary
The potential importance of benefits related to public health resulting from CO_2 mitigation policies is indicated in an assessment of the cost and benefit of energy saving in Hungary, originally designed to reduce CO_2 emissions (Aunan *et al.*, 1998; Aaheim *et al.*, 1999). Aunan *et al.* (1998) give an extensive overview of the various effects of energy saving in Hungary, namely reduced damage to public health, building materials and agricultural crops obtained from reducing emissions of air pollutants, as well as reductions in greenhouse gas emissions. The benefits (i.e. avoided damages) are monetised in order to be able to add up various effects of reduced energy consumption. They conclude that the dominant benefit of the energy-saving programme relates to public health through reduced concentrations of air pollutants. Reduced damage to materials also gives significant benefits. Compared to the reduction in the local and regional effects, the benefits from reducing GHGs are likely to be minor (Aaheim *et al.*, 1999).

has shown that it is possible to cut ammonia emissions significantly and at the same time reduce nitrous oxide and methane emissions.

Thus, in order to maximise the synergies and to avoid negative spillover effects from emission control strategies to other pollutants, it is necessary to carefully design the basket of measures and the timing of their application. Example studies are presented in Box 4.1.

This temporal aspect is important because of the different lifetimes of air pollutants and greenhouse gases in the atmosphere, the different time scales of their impacts and the need to avoid 'locking in' into short-term strategies that disable the long-term structural changes that are necessary for managing sustainable climate futures (Gritsevskyi and Nakicenovic, 2000).

Integrated assessment of linkages between climate relevant gases and air pollutants in Europe requires building a new model that will capture interactions among pollutants and allow systematic exploration of co-benefits at the continental as well as at the national level (Amann *et al.*, 2003). This model needs to be linked with tools used for designing longer-term energy and climate policies. When building such links it is necessary to harmonise the methodologies and the assumptions used by different modelling tools. Depending on the purpose of the analysis, models applied in the climate policy debate use different cost concepts (welfare loss due to imposition carbon constraint, or the increase in the energy system cost). They also use different interest rates. In many studies oriented towards identification of the reaction of energy consumers to higher energy prices induced by the carbon constraint, the market interest rate is used. Since the expenditures on air pollution control are usually treated as infrastructure investments, a much lower social discount rate is used. Some energy system models include the expenditures on air pollution control, some do not. Thus, in order to avoid double counting, it is necessary to check the scope of costs included in the two types of models and also to unify other assumptions. More remarks on problems with linking air pollution and climate change models are to be found in EEA (2004).

4.2. Conclusions

Air pollutants and greenhouse gases are often emitted by the same sources, and changes in the activity of these sources affect both types of sources. Technical control measures to reduce a pollutant may reduce or increase the emissions of other substances.

From a policy perspective, the most important linkage between climate change and air pollution exists at the emission sources.

Integrated assessments across economic sectors, taking into account all relevant pollutants, are important to identify possible options to simultaneously reach air pollution and climate change goals in the most cost-effective way, and to avoid one-issue solutions with unknown side effects.

Implementing climate policies, for example in order to achieve the Kyoto Protocol targets, can significantly reduce the costs of meeting air quality targets. Conversely, meeting stringent air quality targets is likely to eventually require measures beyond end-of-pipe technological solutions, and require broader structural changes (e.g. in the energy mix), consistent with climate change goals.

4.3. Proposed linkage indicators for the EEA

In order to assist the EEA to approach and report on linkages between air quality and climate change in a structured manner we propose here, as a first, very preliminary step, some potential indicators that could be relevant for describing the linkages. As noted, not all identified linkages

Table 4.1 Driving forces and pressure indicators for climate change and air pollution

Indicator	Unit	DPSIR	Development time (1)	Type (2)
Structural changes affecting both GHG and AP emissions (sectoral economic changes)	EUR, %	D	S	Me
Technological changes affecting both GHG and AP emissions, e.g. development specific technologies	e.g. % in fuel mix	D	S	Me
Emissions of air pollutants and GHGs presented together	Tonnes/ year	P	S	Mo/Me

DPSIR = 'Driving forces, pressure, state, impacts, response'; note that the type of indicator can be different from a climate change or air pollution perspective.

(1) Development time means the time period that an indicator becomes applicable for assessments. S = short (0–2 years), M = medium (3–5 years), L = long (6–10 years).
(2) Indicator type illustrates the main source of information. Me = measurements (past trends), Mo = modelling (scenarios).

can be assessed and described yet with the current state of knowledge and modelling framework available.

In Table 4.1 two driving force indicators and one pressure indicator are proposed to describe the linkages for climate change and air pollution.

- The first indicator describes the change in the mix of economic sectoral output levels that by definition affect both GHG and air pollutant emissions.
- The second indicator concentrates on technological changes affecting both GHG and air pollution. In this indicator the contribution/ penetration of so-called zero-emission technologies such as hydrogen and solar power in a certain sector can be quantified.
- The third proposed indicator combines the traditional emission indicator from GHG and air pollutants in one reporting framework, where up to now they have been presented separately. Non-CO_2 emissions can hereby be expressed in CO_2-equivalent emissions.

5. Current policy practices and opportunities

Key messages

- Opportunities for synergies and avoiding trade-offs have been integrated into international air quality policies or policy negotiations in Europe, such as the 'Clean air for Europe' programme (CAFE) where the links between air pollution and climate change are an integral part of the analysis which will lead to the adoption of the Thematic Strategy on Air Pollution in mid 2005. Neither the United Nations Economic Commission for Europe Convention on Long-Range Transboundary Air Pollution (UNECE CLRTAP), nor the current climate negotiations (United Nations Framework Convention on Climate Change — UNFCCC) address these issues on policy level. At the technical assessment level, however, the opportunities are increasingly noted (Intergovernmental Panel on Climate Change — IPCC; UNECE Task Force on Integrated Assessment Modelling — TFIAM).
- Linkages can be taken into account when designing different types of policies such as economic instruments, regulatory policies, voluntary agreements, and awareness and education strategies. Policies targeting the activities that release the air pollutants and greenhouse gases (e.g. combustion of fossil fuels, intensive agriculture) rather than the emissions of one specific substance (like carbon dioxide or sulphur dioxide emissions from energy use, or ammonia emissions from agriculture) have a larger potential for capturing possible synergies.
- Climate changes policies, if developed independently from air pollution policy, will either constrain or reinforce air pollution policies, dependent on the choice and design of the policy instruments, and the other way around. From an economic perspective, policies that may not be regarded as cost-effective from a climate change or an air pollution perspective alone may be found to be cost-effective if both aspects are being considered.
- If climate change considerations were taken into account when designing policies and measures to abate local and regional air pollution (and vice versa), the cost-benefit equation and thus the relative priorities of policy options could change considerably; there is as yet no agreed operational framework to evaluate the importance of climate change versus air pollution.

5.1. Introduction and history

In Chapter 4, the response options that are available to address both climate change and air pollution were discussed, focusing on technological options. What are the policies and measures that can be used to implement these options, and how do they play out in the two areas of air pollution and climate change? In the following, we will discuss current policy practices and opportunities for the future.

The increasing awareness of the linkages between different environmental issues can be illustrated by the developments in the history of CRLTAP. Since its establishment in 1979, a considerable amount of protocols regarding air pollution have been adopted. The first protocols focused on one single substance and on one main environmental effect. The first sulphur protocol in 1985 aimed at reducing SO_2 in order to combat 'acidification'. The protocol on nitrogen oxides (NO_x) (1988) focused on the eutrophication issue and the protocol on volatile organic compounds (VOCs) (1991) on the mitigation of tropospheric ozone. However, in the 1991 VOC protocol there was already a call to include nitrogen oxides in renegotiations of the protocol which had to start no later than six months after entry into force of the protocol. Furthermore, multi-pollutant and multi-effect approaches were the subject of discussion in the CLRTAP Working Group on Strategies (WGS) from 1992 on (Wettestad, 2002). There was an increasing insight that important efficiency gains could be captured by simultaneously controlling acidification and eutrophication risks and ground-level ozone concentrations. Finally, in 1999 the Gothenburg Protocol was adopted. This protocol focuses on the four substances nitrogen oxides, volatile organic compounds, sulphur dioxide and ammonia and on the three environmental issues acidification, tropospheric ozone formation and eutrophication.

Also within policies in the European Union, a multi-pollutant, multi-effect approach is taken, as can be seen from the developments of the acidification and ozone strategy towards the national emission ceilings directive (2001) and the new 'Clean air for Europe' (CAFE) programme which commenced in 2001. With regard to the linkage to climate change, the EMEP Steering Body resulting under CLRTAP '…recognised at its 26th session in September 2002 the important links between regional air pollution and climate change' (UNECE, 2002). It welcomed the work initiated to explore such links and requested the Task Force on Integrated Assessment Modelling to aim at addressing all aspects of these links in its future work.

Despite these developments, international policy-making on climate change or stratospheric ozone still takes place independently from — and in other policy arenas than — air pollution. Negotiations on reducing greenhouse gas emissions take place within the 1997 UN Framework Convention on Climate Change (UN FCCC) and substances that deplete the ozone layer are dealt with in the 1987 Montreal Protocol. The policy arena for climate change and ozone depletion is global, as opposed to the European level negotiation and national implementation of regional air pollution policy and local implementation of urban air pollution policies. In this section, we discuss current policy practices and future policy opportunities capturing co-benefits and avoiding trade-offs.

5.2. Air quality policies and climate change

In general, the opportunities offered for synergies between air quality policies and climate change responses have been integrated into international air quality policies or policy negotiations in Europe, such as CAFE where the links between air pollution and climate change are an integral part of the analysis which will lead to the adoption of the Thematic Strategy on Air Pollution in mid 2005. On the other hand, many of the policies that are currently being implemented or considered in Europe do have the potential to capture the co-benefits. For example, the IPPC directive addresses multiple pollutants, and sources of GHGs (EC, 1996). Synergies between the IPPC and the draft emissions trading directive have been identified (EC, 2002). Energy efficiency standards in different sectors, such as for those power plants and automobiles, that have been developed primarily for reasons other than climate change, such as air quality, also address climate change. Alcamo *et al.* (2002) show that, while regional air pollution and climate change may be fairly weakly coupled in the area of environmental impacts, they are strongly coupled in the area of environmental policy.

More explicitly, the opportunities for co-benefits have been identified by scientific research (see Chapters 2 to 4) and are being picked up by technical assessment bodies, such as the UNECE Task Force on Integrated Assessment Modelling (TFIAM) under LRTAP. In the context of UNECE, integrating climate change considerations into regional air pollution policies appears to be a logical next step following the development and implementation of a multi-pollutant, multi-effect approach. Recent integration of the issues through analyses with integrated assessment tools, such as RAINS and IMAGE, is starting to explore the potential synergies and trade-offs in more detail.

5.3. Climate change policies and air pollution

Similar to the situation with respect to air quality policies, international climate change policy development to date did not explicitly take into account the potential for synergies. For example, in the negotiations of the United Nations

Framework Convention on Climate Change (UNFCCC), the opportunities are not being considered other than that general references are made to the need to integrate climate change response strategies with sustainable development objectives. Nevertheless, many of the policy measures being considered to control GHG emissions clearly have benefits for air pollutants. Examples are carbon or energy taxes, research, development and demonstration (RDD) of environmentally sound technologies, and voluntary programmes to reduce energy use and associated GHG emissions, which would also reduce air pollutants. The implications of GHG emissions trading programmes for other pollutants are more complex, since for local and regional air pollution the location of the emissions, which changes under a trading regime, is important (Pearce, 2000). The EEA (2004) shows that GHG emissions trading in Europe can have positive effects on regional air pollution.

Also in the area of climate change, scientific research and technical assessments are starting to identify the potential synergies. For example, the *Third assessment report* of the Intergovernmental Panel on Climate Change (Metz *et al.*, 2001) extensively discusses the concept of co-benefits as one of the promising linkages between climate change response and wider sustainable development strategies. According to model calculations reported by Van Harmelen *et al.* (2002), the indirect effects of climate policies in Europe targeting the stabilisation of greenhouse gas concentrations in the atmosphere were found to cut the costs of abating SO_2 emissions by 50–70 % and for NO_x by about 50 %. For the shorter-term implementation of the Kyoto Protocol, costs savings of 10 % of the costs of controlling acidification and ground-level ozone were found (without emissions trading) by Syri *et al.* (2001). Outside Europe, the potential synergies between greenhouse gas mitigation options and abatement of local air pollution have received more attention than in Europe. This is especially true in developing countries (for Chile, Brazil, Mexico, see Cifuentes *et al.*, 2001) and in the United States, where NGOs such as the World Resources Institute (McKenzie, 1996) and Resources for the Future (Burtraw and Toman, 1997) have actively promoted an integrated approach, primarily on the basis of the advantages for human health. In the USA, harmonised options for joint abatement of air pollutants and GHGs are being promoted at the State level (STAPPA/ALAPCO, 2000). Also at the local level the linkages are being considered. Several countries have mentioned the linkages in their national communications to the UNFCCC (Japan, United Kingdom, Czech Republic, Baltic States, others; see www.unfccc.int). Several studies suggest that the 'ancillary' benefits of greenhouse gas abatement — usually primarily air quality related — may be of the same order of magnitude as the abatement costs (Metz *et al.*, 2001) and therefore shouldn't be ignored in policy development.

It is important to note that policy beyond climate change and air pollution may have an effect on emissions, which is at least as significant as these policies themselves. The general development pathway (the 'baseline') that societies may choose determines how effective environmental policies can be. For example, the strategic goal of the European Union from the 2000 Lisbon meeting 'to become the most competitive and dynamic knowledge-based economy in the world capable of sustainable economic growth with more and better jobs and greater social cohesion' may lead to a structural change in the economic structure of European countries which can have lower environmental pressures as a co-benefit.

We also note that in addition to policies targeting emissions of greenhouse gases and air pollutants, there may be options in the area of adaptation to climatic changes and high levels of air pollution, for example a shift to new crops which may be less vulnerable to the impacts of both climatic changes and air pollution. In this section, however, we only address specific environmental and energy policies targeting emissions of GHGs and air pollutants.

5.3. Policies and instruments

The various types of policies, measures and instruments can be categorised as follows: economic instruments, regulatory instruments, voluntary agreements, and information and education programmes. Some of their characteristics are discussed below, with respect to the linkages between air pollution and climate change, with some emphasis on the differences between the European Union, the central European accession countries, and eastern European countries.

Economic instruments

- **Taxes and subsidies.** The design of tax systems which can be considered to control GHG emissions can have a direct effect on emissions of air pollutants. For example, an energy tax would induce more efficient energy use and energy savings in general, with generally positive effects on both air pollutants and GHG emissions. A carbon tax would place the heaviest burden on the fuels with the highest specific GHG emissions, from coal to oil to gas. In general, this priority in terms of their contribution to climate change is similar to their relative contributions to air pollution. Implementation design of a tax system primarily targeted at GHG emission reductions does affect the ancillary benefits. For example, raising an energy or carbon tax at the producers' end of the system has implications for air pollutant emissions that are different from a situation where the tax is raised at the users' end. Also the use of the tax revenue can affect emissions of both GHGs and air pollutants (e.g. recycling through reduced labour taxes can decrease the benefits while targeted usage for stimulating renewable energy would increase the benefits). Subsidies for energy efficiency or low-emission technologies can also have significant co-benefits for both air quality and climate change.
- **Emissions trading and emissions ceilings.** Again, the impact of greenhouse gas or air pollutant emissions trading systems from one problem on the other is dependent on the design of the policy. It has been shown that the rules for GHG emissions trading can have an important impact on the regional distribution of air pollutants, possibly affecting the ability of countries to meet air quality standards: it may be less or more costly to meet such targets, depending on specific circumstances ([2]). GHG emissions control could be targeted at those areas where the ancillary benefits for regional and urban air pollution are the greatest. Trading systems tend to ignore such effects (like the recently adopted EU CO_2 emissions trading directive).

Regulatory instruments

- **Standards.** The design of the regulatory instrument determines if there are synergies or trade-offs between air pollution and climate policy. The well-known example of a trade-off is a requirement for desulphurisation of stack gases, which would increase energy consumption and associated greenhouse gases. Energy efficiency standards generally have positive implications for both air pollution and climate change. Standards can also be technology based, such as BAT ('best available technology') or BATNEEC ('BAT not entailing excessive costs'). This approach, e.g. incorporated in the EU's integrated pollution prevention control directive (IPPC), implicitly integrates different environmental issues. Finally, standards can be set

([2]) In areas where air quality standards are met and critical loads not exceeded with or without trading, there are no cost implications.

on the basis of emissions, but if this happens on the basis of individual substances, trade-offs are possible.

- **System targets.** Target setting, such as for a particular percentage of renewables in the European fuel mix, can have significant co-benefits.

Voluntary agreements
Voluntary agreements between governments, or the European Union, and private sector groups are becoming increasingly popular. In principle, such agreements can take potential synergies and trade-offs easily into account. An example is the voluntary commitment to reduce the CO_2 emissions from new vehicles by European (ACEA), Japanese (JAMA) and Korean (KAMA) car manufacturers (ACEA, 1999). This commitment simultaneously limits emissions of other fuel consumption related emissions.

Public information and education
Thus far, information and education campaigns have been more popular in the area of climate change than in the area of air pollution, since in the latter area thus far most solutions were of a technological nature, focusing on production processes rather than consumption. However, in order to come to an effective abatement of the remaining air pollution problems in Europe, structural socioeconomic and behavioural changes may be needed, and information and education campaigns can then play a role in supporting the control of both greenhouse gas emissions and air pollutants An example is the EU energy-labelling strategy.

In practice, there can be no preference for any of the above types of policies, from the perspective of capturing co-benefits, since these are dependent on the specific design of the policy. In general, a portfolio of these options will have to be developed. More importantly, the portfolio of options for either climate change response or air quality policies and the ranking of options will change if the other problem is added to the list of criteria.

5.4. Conclusions

From the above it becomes clear that some policies address climate change and air pollution simultaneously by design (e.g. policies aiming at influencing the activity volume of common sources of GHG and air pollutants). Other policies target only one type of emission, with or without side effects (e.g. promoting particular end-of-pipe technologies addressing specific emissions).

5.5. Proposed linkage indicators for the EEA

In order to assist the EEA to approach and report on linkages between air quality and climate change in a structured manner we propose here, as a first, very preliminary step, some potential indicators that could be relevant for describing the linkages. As noted, not all identified linkages can be assessed and described yet with the current state of knowledge and modelling framework available.

It would be interesting to highlight the co-benefits of particular policies in the EEA's future reporting. A few initial ideas of how this could be done are summarised in Table 5.1.

- The first indicator describes the number of policies adopted, which explicitly or implicitly address both types of pollution simultaneously (by Member State), possibly grouped according to the categories used above. This indicator can be implemented on the basis of the Member State submissions in the context of the national emission ceilings (NEC) and the GHG monitoring mechanism (MM). Until now, the Member States' reporting on policies and measures (existing/adopted or planned/additional) under the GHG MM is more advanced than under the NEC. Revised guidelines may be needed to have countries include appropriate information.

Table 5.1 Policy response indicators for the relationship between climate change and air pollution

Indicator	Unit	DPSIR	Development time (1)	Type (2)
Policies adopted addressing climate change and air pollution simultaneously	Number	R	S	Me
Effects of climate change measures on air pollutant emissions	% reduction	R	S	Mo
Effects of climate change measures on costs of air quality policy	% change	R	S	Mo
Effects of climate change policies on urban air pollution and health	DALYs	R	M/L	Mo

DPSIR = 'Driving forces, pressure, state, impacts, response'; note that the type of indicator can be different from a climate change or air pollution perspective.

(1) Development time means the time period that an indicator becomes applicable for assessments. S = short (0–2 years), M = medium (3–5 years), L = long (6–10 years).
(2) Indicator type illustrates the main source of information. Me = measurements (past trends), Mo = modelling (scenarios).

- The second indicator describes the effects of climate change measures on emissions of air pollutants, to be derived from integrated model-based analyses. This indicator can be implemented in the short term, on the basis of existing information. In the longer term, information about these effects may be included in the Member State submissions in the context of the GHG MM. The reverse — GHG emission reductions as a result of air pollution policies — appears to be less significant, due to the fact that air quality purposes often address specific air pollutants that can be controlled through technological options which do not influence GHG emissions to a great extent.
- The third indicator describes the effects of climate change measures on costs of air quality policies, to be derived from integrated model-based analyses on the European scale, as was done in the context of the AIR-CLIM project and for the Kiev report (see Annex 5). This indicator can also be implemented in the short term, on the basis of existing information. Cost reductions can be expressed in percentage costs saved. As in the previous indicator, the reverse — cost savings of air pollution policies for climate change policies — appears to be less significant.
- The fourth indicator describes the effects of climate change policies on urban air pollution and health. This indicator could be derived from model-based analyses. Uncertainties are large, and further development of assessment methodologies would be needed, and are foreseen in the European Topic Centre on Air and Climate Change (ETC-ACC) work programme. This indicator may be seen as an option for the somewhat longer term.

6. History of integrated assessment of air pollution and climate change

Key messages

- The complex atmospheric interactions between air pollution and climate change are presently not understood sufficiently well to allow their quantitative incorporation in integrated assessment modelling. Instead, these interactions should be taken into account in integrated assessment of the two issues in a qualitative fashion. The same counts for interactions between air pollution and climate change in impacts.
- Sufficient knowledge appears to be available to include many of the linkages, at the level of emission sources and control strategies, quantitatively in integrated assessment and integrated assessment modelling in the near future.
- It is important to take into account the linkages between climate change and air pollution both in cost-effectiveness analysis (how to reach adopted environmental quality goals in the cheapest manner) and cost-benefit analysis (what is the economically optimal level of abatement?).
- Choice and design of policies and measures to address climate change can affect the spatial and temporal distribution of emissions and hence their effectiveness in terms of air pollution. This needs to be taken into account in integrated assessment studies.
- The experience acquired with a framework of models in previous European integrated assessment studies provides a good basis for future activities, which include both air pollution and climate change. While components of this framework focusing on the two issues can be further improved to include linkages, a 'soft link' between the compounds appears to be appropriate because of the disparate characteristics of the problems in terms of time, space and complexity.

6.1. History of integrated assessment of air pollution and climate change in Europe

In the previous chapters, an overview was given of the knowledge in the areas of atmospheric linkages, linked impacts, common sources, and technical options, respectively. Here, we focus on studies that have taken an integrated perspective, covering several of these issues at the same time. Such studies are few, often performed by the same institutions, and are concentrated in the developed countries. Annexes 1 to 7 give summaries of the main aspects of these projects.

In Europe, in 1997, the 'European environmental priorities' project (EEP) (RIVM, 2001) focused on 12 prominent environmental problems, including climate change and air pollution, analysing possible priorities in the context of the EU's fifth environmental action programme (EAP5). The scenario-based project looked at established and possible future environmental goals and evaluated the effectiveness and costs of current and possible future responses (technical options and policies, and measures to implement those). The emphasis in the project was on individual problems and their relative importance. Linkages between the different issues were not comprehensively analysed, but the project suggested that synergies between policy options would be possible. For climate change and air pollution, the project suggested that there might be room for further optimisation of the policy packages, if 'spillover' effects (lower emissions of air pollutants because of energy efficiency measures driven by GHG policies) were taken into account. Thus the efficiency of the additional policies would be improved. An economic analysis of an 'accelerated policy' scenario showed that the macroeconomic costs of the direct costs associated with problems other than climate change policies are likely to be relatively small.

The project contributed to the report *Environment in the European Union at the turn of the century* (EEA, 1999) of the

EEA. Reactions to this report, amongst others from stakeholders, suggested that the capabilities of the EEA to perform integrated scenario analysis could be strengthened, *inter alia,* by more thoroughly addressing uncertainties. In order to address this issue and to start the preparatory process for the next *European state of the environment* report in 2005, the so-called 'ShAIR' project was initiated (EEA, 2001). This project developed an updated projection of air pollutants and GHG emissions on the basis of the earlier 'Shared analysis energy' project, testing and evaluating the available integrated assessment framework. Four European research institutions involved in the EEP project discussed above also participated in the ShAIR project (RIVM, NTUA, IIASA, TNO), and thus the experience from the earlier project as well as the same analytical tools could be used. The ShAIR project identified a clear link between the effects of policy and measures for long-range air pollution, urban air pollution and greenhouse gas emissions, notably because the main emission sources are the same: the energy, industry and transport sectors. Energy efficiency, regulations influencing the fuel mix, and low- and zero-emission vehicles were identified as options to address various issues at the same time. But also in physical and chemical terms, the issues were noted to be coupled, e.g. through hemispheric background concentrations of ozone, influenced by methane. The project also noted that for a better and more fully integrated assessment, gaps in knowledge would have to be filled, notably in the area of adequate data at national and regional level, especially on emissions, and models for integration and development of projections.

While the above studies focused on policy support (primarily for the European Commission's Environment Directorate-General), in parallel the AIR-CLIM project funded by the Commission's Directorate-General for Research focused much more explicitly on developing the scientific methodology to perform integrated assessments of air pollution and climate change (Alcamo *et al.*, 2002). More specifically, the AIR-CLIM project further explored the soft link between the IMAGE climate model and the RAINS model (acidification mainly). AIR-CLIM developed consistent scenarios of regional air pollution and climate change in Europe, analysed links between climatic changes and critical levels of acidification and evaluated long-term reductions of the costs of controlling air pollution in Europe due to climate policy. A key finding of AIR-CLIM is that costs of air pollution abatement are reduced considerably as a side effect of climate policies.

In a study in support of the report *Europe's environment, the third assessment* of the European Environment Agency (EEA, 2004), the same suite of models as used in the projects discussed above (IMAGE, RAINS) was used to analyse the implications of GHG emissions trading on air quality in Europe.

In the Netherlands, in 2002 the project 'Approaches to analyse interactions of climate change, acidification and ozone' ('National research programme' — NRP; van Ierland *et al.*, 2002) focused on the interactions of climate change, acidification, eutrophication, tropospheric ozone and some other air pollutants, and on the approaches for an integrated analysis for these problems. Furthermore, apart from the examination of the existing approaches, the study also suggested new methods for scenario and optimisation analysis, with a focus on the European situation. While none of the institutions involved in the abovementioned European projects was involved in the NRP project, it used some of the databases and models that were used in these studies (e.g. the IMAGE and RAINS models). A new economic method to model interactions between reduction strategies was developed (a comparative static optimisation model). More specifically, interactions between ammonia abatement strategies and controls of N_2O and CO_2 in agriculture were analysed, as well as interactions between ozone and acidification. The NRP project confirms much of the knowledge gaps identified by the ShAIR project, notably the need for a flexible database of emissions with some sectoral, spatial and temporal resolution, and the importance of taking into account the different temporal scales of global and regional issues. The project recommends further developing soft links between various available models. For an integrated analysis of climate change and air pollution, the project also recognises the importance of having endogenous optimisation of the energy sector in the models used rather than analyse only end-of-pipe solutions to air pollution control with exogenous assumptions for energy supply.

6.2. Ancillary and co-benefits

The abovementioned projects at the European level generally share an approach in which medium to long-term socioeconomic scenarios are developed, a range of environmental consequences is determined and compared with environmental goals, followed by an analysis of (additional) measures that would be needed to meet these goals, and their costs. The core research teams in most of these projects are the same. Several linkages at the level of atmospheric processes and impacts were taken into account. A completely different approach to address linkages between climate change and air pollution dominated a workshop initiated by the IPCC in collaboration with the Resources for the Future Institute and the World Resources Institute (OECD, 2000). The results of this workshop played an important role in the IPCC's *Third assessment report* (Metz *et al.*, 2001). Most of the studies discussed in this workshop and by the IPCC are from the USA and other non-European countries. Here, the emphasis was on quantifying the 'ancillary' benefits of greenhouse gas mitigation policies, preferably in monetary terms, using economic models and indicators. A wide range of ancillary benefits was explored, but the monetary valuation of these benefits was clearly dominated by reduced health impacts, usually related to reduced air pollution. Different from the European studies discussed above, the studies quoted in the IPCC and OECD reports usually have the character of case studies in particular cities or regions, some of them being top-down macroeconomic modelling studies on country level. The results of the workshop and their policy relevance was evaluated by the OECD (Davis *et al.*, 2002). It was concluded that ancillary benefits and costs may be very important to the assessment of policy options, influencing decisions about both the level and the type of mitigation policy action, suggesting that these benefits and costs should routinely be considered in climate policy decision-making processes.

6.3. Implications for integrated assessment: discussion

A fully integrated assessment of the linkages between air pollution and climate change has not been performed yet. Even if the studies discussed above capture elements of the various types of linkages, many — if not most — of the linkages summarised in Sections 2.1–2.5 are not yet taken into account. All European studies show the importance of the links, which seem to be most relevant in the area of policy options and somewhat less so in the area of impacts. The economic studies of ancillary benefits of GHG mitigation suggest that the avoided damages in terms of public health can compensate a sometimes significant part of the costs of the measures, sometimes all. It is important to note that the different studies address different questions and as a consequence have different objectives, use different tools and provide different answers. The European studies discussed above take environmental goals (reduction of GHG emissions, meeting air quality objectives) as a starting point, and analyse policy options that would address multiple objectives, and (sometimes) their costs. In the USA and other countries, where there are as yet no GHG emission reduction objectives, and often a less systematic framework to meet air quality goals, the starting point is formed by the costs of climate policy. The emphasis here is on quantifying the ancillary benefits of climate policy, to address an 'earlier' question: is it worthwhile to control GHG emissions? The difference can also be considered as a cost-effectiveness versus cost-benefit analysis. For longer-term policy development, e.g. a second commitment period of the Kyoto Protocol (or another post-Kyoto regime), both approaches seem valid, combining attention for the avoidance of multiple environmental and other effects of economic activities with an assessment of the costs of policy measures.

From a policy perspective, it may be recommended that for integrated assessment most attention is spent on policy linkages, and the development of tools for quantitatively evaluating the potential synergies and trade-offs between them. At the same time, since particular policies may have undesirable, possibly counterproductive results because of uncertain effects on atmospheric and climatic processes, integrated assessment should not be limited to cost analysis, but should also take into account these risks, at least in a qualitative fashion. In addition, rather than focusing solely on cost-effectiveness or cost-optimisation, integrated assessment of policy options should also evaluate their potential consequences for equity.

As argued above, especially when traditional end-of-pipe solutions to reach air quality targets may be insufficient, an integrated assessment of greenhouse gas and air pollutant emission reduction options — including changes in production and consumption patterns — is becoming relevant. This is becoming increasingly clear especially in countries that have difficulties meeting air quality objectives with traditional approaches, e.g. for NO_x. Such an integrated analysis is not yet possible in the RAINS model. Therefore, for example in the EEA study referred to above (EEA, 2004), the ancillary benefits of greenhouse gas emission mitigation for air pollutants were included, but not the potential ancillary benefits of a full suite of air pollution abatement options on greenhouse gas emissions. An effort is currently under way to include greenhouse gas emissions and abatement cost curves in the model. In this way, interactions between pollutants and co-benefits between air pollution abatement and climate change mitigation can be more fully captured (Amann *et al.*, 2003). The European Union has ratified the Kyoto Protocol, and in the context of its sustainable development strategy has pledged a further reduction of regional CO_2 emissions by 1 % per year after the first commitment period, until 2020. In various European countries (Germany, Netherlands, France, United Kingdom, Switzerland) longer-term reductions of greenhouse gases of 40–60 % of 1990 emissions have been proposed, based on scenario analysis which suggest such goals to be credible and technologically feasible. Meeting such objectives has very significant implications for air pollutant emissions. Integrated assessment therefore has to go beyond a limited analysis of the cost-effectiveness of air pollution abatement strategies to fully incorporate structural changes (Landrieu, 2002).

Again focusing on the policy linkages, it is important to note that the importance of using economic instruments to achieve environmental goals is increasing. In December 2002, the European Union adopted a proposal to introduce a CO_2 emissions trading system, which intends to help achieve the Kyoto targets starting by 2005. As the EEA (2004) illustrated, introducing such an instrument has very significant implications for the regional distribution of air pollutants, and thus on the strategies of countries to meet the UNECE Gothenburg Protocol, and the EU NEC directive. The characteristics of air pollution and climate change are different in various ways. First, the primary drivers behind air pollution and climate change mitigation policies are different: public health and environmental protection, respectively. Secondly, the time scales and spatial scales are different. The inertia of the climate problem and the long time scales needed for structural economic and behavioural changes are different from the much shorter time scales that were characteristic of air pollution abatement until recently (3). Climate change necessitates a global response; air pollution can generally be addressed locally or regionally. Thirdly, the policy approaches are different: a technological approach with absolute standards for air quality and a more structural approach including economic instruments for climate change. These new developments necessarily have implications for the further development of integrated assessment methods. Rather than a 'hard', full integration of modelling tools in the respective areas, a more loosely coupled framework of various tools may be developed and applied, bridging spatial and temporal scales, and allowing for combining the analysis of broad global developments with the policy options at the sectoral level. The modelling tools in both areas (e.g. RAINS for regional air quality and IMAGE for climate change) could be further developed to enhance the consistency between modelling runs and facilitate data exchange between the systems. Sectoral models (energy, transport) should be incorporated into the framework (Vainio, 2002).

As also noted at the TFIAM/ETC-ACC workshop, the objective of the work on linkages and synergies between regional air pollution and climate change should be to provide policy-makers with the information necessary to make choices. These choices need to be made with the objective of (1) reducing pollutants maximising the positive linkages and minimising the negative ones; and (2) taking those measures that are most cost-effective and sustainable in view of the objectives in both policy areas.

(3) The bridging between temporal scales is a difficult issue to treat in an integrated techno-economic assessment. The integration of the long-term time frame of climate change and the shorter time frame of air pollution may require balancing long-term benefits with short-term benefits. The outputs of the integrated modelling framework such as the IMAGE/RAINS soft-linked package could highly depend on the respective depreciation schemes adopted in each model. Equity, specifically intergenerational equity considerations, could be a way to overcome the problem.

7. Discussion and future EEA work

Key messages

- There are many institutional, scientific and political barriers to integration of climate change and air pollution in policy development. However, compelling arguments in support of integration suggest that these barriers should and can be overcome. These arguments include the increased cost-effectiveness of policies, reduced public health and ecosystem risks and the early identification of potential perverse effects of single-issue policies.
- An improving knowledge base can help the policy integration process. Further research needs to include the improved understanding of chemical and physical interactions of air pollutants and greenhouse gases in the atmosphere (e.g. ozone, PM/aerosols); the development of comprehensive integrated assessment frameworks based on a loose coupling of individual tools; case studies demonstrating the reality of co-benefits; and analyses of policies and measures that integrate air pollution and climate change concerns.
- The EEA can help furthering the issue of integrating air pollution and climate change in its reporting system. This includes the coverage of the linkages in the 2005 *State of the environment and outlook report*, but also inclusion of the linkages in reports and fact sheets on air pollution and climate change, respectively.
- One example of the inclusion of linkages between air pollution and climate change in the EEA reporting system is to explore the introduction of a focused set of additional indicators on the linkages for the components of the DPSIR chain.

In the preceding chapters, we have provided an overview of the atmospheric linkages between air pollution and climate change, as well as linkages in impacts, and emissions and control options. We have also discussed current policy practices and opportunities and given examples of integrated assessment projects addressing linkages. In this final chapter, we pull the information together by identifying existing barriers to integration, and by synthesising arguments in favour of integration of the two issues. We then provide suggestions for further work to fill research gaps. Finally, we discuss how the knowledge on linkages between air pollution and climate change may be used in EEA reporting, notably the 2005 *State of the environment and outlook report*. We present as a first, very preliminary step some potential indicators as proposed in the preceding chapters which may help the EEA to report on linkages in a structured manner.

7.1. Barriers to integration

Despite the increasing awareness of the importance and benefits of taking linkages into account, several factors contribute to the fact that potential synergies are as yet not harvested in international policy negotiations and national policy developments, and trade-offs ignored.

- The linkages are very complex, the knowledge base is still incomplete.
- Air pollution and climate change effects have different time scales (and time preferences and target periods).
- Scientific air pollution and climate change communities show too little overlap.
- If climate change considerations were taken into account when designing policies and measures to abate local and regional air pollution (and vice versa), the cost-benefit equation and thus the relative priorities of policy options could change considerably. There is as yet no agreed operational framework to evaluate the importance of climate change versus air pollution.

- The political negotiating networks, legal frameworks and format and timing of reporting requirements (4) are separated; the number of people with knowledge of both areas is very small and appropriate joint institutional arrangements are largely absent.
- There is a latent and sometimes open concern in policy-making communities that including climate change in the air pollution policy development — and vice versa — may lead to a loss of control over the problem.
- Detailed policy frameworks have been developed over many years in ways that are not easily changeable to include other issues which may complicate further negotiations.
- It is not evident at which level integration should take place: integration of air pollution and climate change should be addressed by the international conventions, but national and local governments should also take synergies and trade-offs into account when designing policies in both areas.

7.2. Arguments in favour of integration of climate change and air pollution policies

If there are so many barriers, why and how should the integration be pursued? The following arguments are in favour of increased integration of policies in the areas of air pollution and climate change.

- Initial abatement of air pollution was possible largely through technological options such as add-on technologies or industrial process changes. It becomes increasingly clear that abatement of the remaining air pollution would need fuel shifts or structural socioeconomic and/or behavioural changes, similar to most of the options for the control of GHG emissions. Integration would facilitate the implementation of these options.
- Climate changes policies, if developed independently from air pollution policy, will either constrain or reinforce air pollution policies, dependent on the choice and design of the policy instruments, and the other way around. Integration will help identifying synergies, and avoiding unexpected perverse effects.
- From an economic perspective, policies which may not be regarded as cost-effective from a climate change or an air pollution perspective alone, may be found to be cost-effective if both are being considered. Integration thus improves the cost-effectiveness of policies.
- Air pollution and climate change have a significant overlap in terms of sources of emissions, and their respective impacts through atmospheric chemistry, weather conditions and vulnerability of natural and human systems are linked. Although not always spelled out in detail in policy documents, there is general agreement that abatement of one environmental problem should not worsen another environmental problem.

Including the above issues both in international development (UNFCCC, UNECE CLRTAP, EU directives) and in national and local policy development and implementation would help to capture co-benefits and avoid trade-offs.

7.3. Research gaps

From the above it becomes clear that there are very interesting opportunities to capture the co-benefits of climate change and air pollution policies and avoid the dis-benefits or trade-offs, but that it is not easy to implement them. The potential in terms of reduced abatement costs and improved

(4) An exemption is formed by the emissions inventory methods, which are converging between the UNFCCC, UNECE and the EU (e.g. national emission ceilings directive).

human and ecosystem health is great. Improving the knowledge base can help supporting a process of increasing integration in policy development. Areas where additional research in support of European policy development would be needed include:

- further research in understanding the chemical and physical interactions of air pollutants and greenhouse gases in the atmosphere, with particular emphasis on:
  - — the long-range transboundary transport of ozone precursor gases (NO_x, VOC, CO), and the net effect of their emissions on climate change;
  - — a more precise determination of the chemical composition of aerosols/particulate matter, in order to assess the net warming or cooling effect and the specific health impacts;
- better defining co-benefits (calculation and allocation of costs and benefits);
- developing appropriate assessment frameworks, taking into account monetary and physical aspects of co-benefits;
- improve integrated modelling, e.g. by adding climate change elements to air pollution models (e.g. RAINS) and air pollutants to climate models (e.g. IMAGE) and developing a soft link between the two;
- investigate linkages between air pollution and climate change and other environmental issues (waste, water, ecosystem resilience), and with socioeconomic issues (congestion, safety, distributional effects of policies, employment);
- implementing case studies which demonstrate the reality of co-benefits;
- elaborating a transparent methodology to analyse and describe the relative importance of the various uncertainties in order to improve the quality of integrated environmental assessments;
- analysing policies and measures that integrate air pollution and climate change concerns.

7.4. Addressing linkages between air pollution and climate change in EEA reporting

The EEA can increase the awareness of the importance of the linkages between air pollution and climate change by addressing them in its reporting. The linkages can be addressed in the EEA's reporting system in various ways. Maybe the most important short-term opportunity is formed by the 2005 *State of the environment and outlook report*. Eventually, some of the proposed indicators could lead to inclusion in the EEA core set of indicators and the development of associated description and fact sheets. Other indicators could be developed and used in specific reports independent of the core set. Other possibilities include the inclusion of a summary of associated greenhouse gas emissions in the reporting of air pollutant emissions and air quality — and air pollutants in GHG reporting. For reporting of EU GHG emissions in the context of the GHG monitoring mechanism, and air pollutants in the context of the national emission ceilings directive and the UNECE Convention on Long-Range Transboundary Air Pollution, inclusion of 'the other' substances would directly highlight the linkages, but would first require a discussion with the Member States about the usefulness and feasibility. Also, the linkages could be highlighted in EEA reports about environmental issues at the sectoral level, such as energy, transport and agriculture.

Indicators
With regard to the development of indicators, it will be important to identify what the relevant linkages are that the EEA would like to present and describe in the SoEOR2005 and other reports. Based on this review and earlier work by the ETC-ACC, as a first, very preliminary step some potential indicators that can be relevant for describing the linkages are presented in Table 7.1.

As noted, not all identified linkages can be assessed and described yet with

Table 7.1 Examples of possible indicators for linkages between air pollution and climate change

Indicator	Unit	DPSIR	Development time [1]	Type [2]
Structural changes affecting both GHG and AP emissions (sectoral economic changes)	EUR, %	D	S	Me
Technological changes affecting both GHG and AP emissions, e.g. development-specific technologies	e.g. % in fuel mix	D	S	Me
Emissions of air pollutants and GHGs presented together	Tonnes/ year	P	S	Mo/Me
Concentrations of air pollutants which also affect climate change (sulphate, ozone and black/organic carbon) eventually expressed in CO_2-equivalent concentration units or in their contribution to the total radiative forcing of GHG and air pollutants in the European atmosphere over time.	ppb/CO_2-equival./W/m^2	S	S (SO_2) M (O_3) L (BC)	Mo/Me
(Index) Half-life time changes of air pollutants such as CH_4, NO_x, CO	Year/index	S	S/M	Mo
Climate change effect on percentage area exceedance of critical loads (total acidity)	% change	I	S	Mo
Climate change effect on percentage area exceedance critical loads (total nitrogen)	% change	I	S	Mo
Climate change effect (esp. temperature) on frequency of episodes of air pollutants	% change	I	M	Mo
Nitrogen effect on the climate change induced changes in ecosystem composition	Additional % change	I	M	Mo
Policies adopted addressing climate change and air pollution simultaneously	number	R	S	Me
Effects of climate change measures on air pollutant emissions	% reduction	R	S	Mo
Effects of climate change measures on costs of air quality policy	% change	R	S	Mo
Effects of climate change policies on urban air pollution and health	DALYs	R	M/L	Mo

DPSIR = 'Driving forces, pressure, state, impacts, response'; note that the type of indicator can be different from a climate change or air pollution perspective.

[1] Development time means the time period that an indicator becomes applicable for assessments. S = short (0–2 years), M = medium (3–5 years), L = long (6–10 years).

[2] Indicator type illustrates the main source of information. Me = measurements (past trends), Mo = modelling (scenarios).

the current state of knowledge and modelling framework available. Some of the indicators reflect current and past trends and can be derived from monitoring and statistical information. Other indicators, especially the forward-looking ones, require a modelling approach. At IIASA, currently work is under way to develop the RAINS model further to include also emissions of GHGs and technology options to reduce air pollutants and GHG simultaneously. In addition to the existing cost curve of air pollutants, IIASA will develop cost curves for the six GHGs (CO_2, CH_4, N_2O, PFC, HFC, SF_6) included in the Kyoto Protocol and implement an integrated cost approach over all pollutants. The time horizon for this new technology database, on a country-by-country basis for the EMEP region, will be 2030. In parallel, IIASA is developing a methodology to assess structural change with RAINS. This kind of tool can be used to quantify several of the forward-looking indicators suggested above.

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Introduction to the Annexes

Chapter 6 presented a short history of integrated assessment studies capturing elements of the various types of interactions between air pollution and climate change. In Annexes 1 to 5, these recent European projects are presented in more detail.

The following projects were selected:

- 1997–2001: European environmental priorities project: linkages noted between air pollution and climate change (Annex 1)
- 1998–99: ShAIR project in support of EEA 'Environment in the EU': opportunities for multiple-issue response options identified (Annex 2)
- 1998–2002: AIR-CLIM: costs of air quality policies greatly reduced under climate policy scenario; first project including impact analysis (Annex 3)
- 2000–02: Netherlands national research programme: modelling interaction between response strategies in agriculture (Annex 4)
- 2001–03: Study in support of the EEA report *Europe's environment, the third assessment* including analysis of effects on spatial distribution by GHG emissions trading and AE/GHG abatement costs (Annex 5)

In Annex 6 a summary is given of the proceedings of a recent OECD workshop with different contributions describing the ancillary benefits and costs of greenhouse gas mitigation.

Moreover, in Annex 7, the draft conclusions of the Task Force on Integrated Assessment Modelling (TFIAM) Workshop on Linkages and Synergies of regional and global emission control are given as presented by the TFIAM Secretary, Henning Wüester.

Annex 8 presents a selected overview of earlier-held workshops in this field.

Finally, Annex 9 lists a selected number of Internet sites giving information about linkages between climate change and air quality.

Annex 1: European environmental priorities: an integrated economic and environmental assessment (EEP project)

Study name:	European environmental priorities: an integrated economic and environmental assessment
Year of development:	1997–2001
Institute:	RIVM (leading institute), IIASA, EFTEC and ICCS-NTUA
Spatial coverage:	Europe (mainly EU-15, while accession countries are partly assessed)
Spatial specificity:	Europe as a whole
Time horizon:	1990–2010
Focus (thematic coverage):	Different environmental themes

Background information
The European environmental priorities study has been carried out in order to guide the future priority setting of European environmental policies. The Commission funded this study because, after the review of the European Union's (EU) fifth environmental action programme (fifth EAP), it had concluded that it was important to focus on key priorities and translate further the programme's strategy into a set of pragmatic and operational tools.

Scope and objectives
The study is an economic and environmental analysis of priorities for a European environmental policy plan. It focuses on 12 identified prominent European environmental issues such as climate change, chemical risks and biodiversity. It incorporates information on targets, scenario results, and policy options and measures, including cost and benefits. It aims to determine:

1. Whether the current environmental policies are adequate
2. What technology can contribute to solving the policy gaps as identified
3. Whether the new targets chosen for this study are achievable, and
4. If so, whether these targets are economically reasonable, and finally
5. What policy responses and instruments can be recommended.

Methodology used
The analysis is based on an examination of the cost of avoided damage, environmental expenditures, risk assessment, public opinion, social incidence and sustainability. The integrated assessment methodology has combined economic models, energy use models, emission data sets and models, environmental effect models, economic benefit models, and databases on the costs and efficiency of policy measures. This enables the scenario evaluation of Europe's environment and the identification of policy priorities.

Scenario development
To answer the research questions, three environmental policy scenarios have been evaluated:

- 'baseline' (BL), which consists of policies in place or in the pipeline (PIPP);
- 'technology driven' (TD), which abates proximate cause, by requiring

that all available 'proven' technology are to be implemented;
- 'accelerated policy' (AP) is related to new targets (set by the Environment DG) and mixes technology implementation with structural measures, where TD tends to fail the cost-benefit test.

Indicators
- Greenhouse gas emissions
- Air pollutant emissions (SO_2, NO_x, VOC and PM_{10})
- Ecosystems with deposition exceeding critical loads for acidification (percentage of ecosystem area)
- Ecosystems with deposition exceeding critical loads for eutrophication (percentage of ecosystem area)
- Population exposure to ozone
- Vegetation exposure to ozone
- PM_{10} exposure above target level
- Heavy metals, dioxins and PAHs emissions
- Pressure on nature
- Benefits welfare costs
- Benefit/cost ratio

Main findings with regard to linkages
- Full application of available technological solutions ('end-of-pipe'), without regard to costs, might show considerable improvements for some environmental problems. Technological means can solve problems, like acidification and tropospheric ozone.
- However, estimates suggest that yearly environmental expenditures may rise to about EUR 50 billion over the expected costs under baseline conditions. Acidification and tropospheric ozone abatement policies will take a lot of the direct costs. Welfare costs are significantly lower: about EUR 30 billion in 2010. With the implementation of all available technical abatement measures, the environmental expenditures as a percentage of gross domestic product (GDP) will only be 1 % larger than in the baseline scenario.
- Implementing additional policies based on least-cost solutions and considering specific policy targets for climate change, acidification, tropospheric ozone, waste management and human health and air quality (especially, particulate matter) might show considerable improvements to the environment, but to a lesser extent than applying all available 'end-of-pipe' technologies. Ecosystems and human health will benefit from this improvement. Almost all the targets set for this study are achievable.
- Some policies have positive effects on other environmental problems without being purposely developed for solving them. Climate change policies have a significant impact on acidification, tropospheric ozone, chemicals, primary particulate matter and air quality. Air quality and tropospheric ozone will also benefit from additional acidification policies. Climate change-related policies make policies required to reach acidification and ozone targets cheaper (by EUR 6 billion per year). Allowing flexible Kyoto mechanisms will lead to fewer cost savings for these problems but is — overall — more cost-effective.
- Spillovers from climate change to other environmental issues are dominant, especially for acidification, chemicals (i.e. heavy metals, PAHs and dioxins/furans) and primary particulate matter. It is shown that CO_2 emission reduction of 15 % leads to emission reductions of 24 % for SO_2, 8 % for NO_x, 24 % for PM_{10}, while SO_2, NO_x, and VOC control measures lead to auxiliary reduction of more than 7 % PM_{10} emissions and significant reduction of the pressures on natural ecosystems.
- If, besides the baseline policies, no climate change policies were implemented at all, an additional investment in end-of-pipe measures of EUR 6 billion per year would be needed to reduce the acidifying emissions to a level that would ensure reaching the acidification

targets. In terms of welfare loss, this would amount to nearly EUR 4 billion.
- Allowing for the Kyoto flexible mechanisms will slightly reduce the total benefit estimates of the accelerated policies scenario for climate change, mainly due to lower secondary benefits. The assessment suggests substantial cost savings to EU from trading via the Kyoto flexibility mechanisms, i.e. the trade-off between secondary benefits within the EU versus the cost advantage of trading. Considering the cost benefits, emission permit trading is more advantageous.

Study limitations
- In the framework of this study, not all spillover effects and feedback mechanisms are taken into account.
- Data and information presence is firm on air-related issues and weak in issues related to natural resources. This means that the study was not able to fully appraise all environmental issues and related costs and benefits.
- Consequently, indicators and policy targets selected in this study are mainly focused on those issues where a solid information basis is present. This means that findings on the remaining issues are less robust.
- It is assumed that all measures and policy actions will be fully implemented and enforced. Implementation failures of actions (in place or identified) have not been assessed.
- The macroeconomic effects of the benefits have not been appraised. This also counts for the distributional effects of new policies on different socioeconomic groups within the EU.
- The subsidiarity issue and the consequences of the EU enlargement have not been assessed in full detail.
- Time was too limited to fully quantify the sensitivities and uncertainties of the results.

Recommendations
In future, it will be necessary to focus on root causes emphasising an integrated and cost-benefit approach not only within issue areas, but also recognising the ecological and cost-benefit linkages between issues. For example, the interactions between climate change acidification, eutrophication, tropospheric ozone, biodiversity loss, and soil degradation. By providing an integrated economic and environmental assessment on priority setting for European policy planning, this study represents a starting point towards that direction.

Lessons for the EEA for integrated assessment development with regard to linkages between air pollution and climate change
The broad integrated assessment of many environmental topics is too complex and time consuming and presently not within the reach of the EEA. However, the EEA could see this approach as a long-term goal, which could be adopted in the future.

Availability
The report was published by RIVM.

Publications
RIVM, EFTEC, NTUA, IIASA, 2001. European environmental priorities: an integrated economic and environmental assessment. RIVM report 481505010. National Institute for Public Health and the Environment (RIVM).

Annex 2: 'Shared analysis air pollution and greenhouse gases' (ShAIR) study

Study name:	Shared analysis air pollution and greenhouse gases
Period of development:	1998–99
Institute:	RIVM, AuTh, ICCS-NTUA, IIASA and TNO
Spatial coverage:	Europe (EU-14, seven accession countries — Czech Republic, Hungary, Poland, Slovenia and the three Baltic States, Estonia, Latvia, Lithuania — 10 accession countries and the rest of Europe)
Spatial specificity:	Various European regions
Time horizon:	1990–2020
Focus (thematic coverage):	Integrated assessment on air pollution and greenhouse gases

Background information
In the recent report *Environment in the European Union at the turn of the century* (EEA, 1999a), the European Environment Agency (EEA) showed substantial development in its experience in integrated assessment, which is considered as a primary process. The EEA medium- to long-term strategy and work programme aims at improving the methodologies for integrated assessment and prospective analysis in order to produce more transparent, better documented and more scientifically sound results for the next integrated assessment report in five years' time. Therefore, the EEA initiated the 'Shared analysis air pollution and greenhouse gases' (ShAIR) study to evaluate and appraise its experience in the environmental projections underpinning the report *Environment in the European Union at the turn of the century*.

Scope and objectives
In the ShAIR study, an updated projection on air pollution and greenhouse gases has been produced on the basis of the shared analysis energy project (Capros and Mantzos, 2000). A partly updated shared analysis energy scenario has also been developed. The main objectives of the study were to:

- test and evaluate the integrated assessment infrastructure developed by undertaking sensitivity and uncertainty analysis of the so-called baseline scenario, with particular emphasis on air-related issues (air pollution and the interaction with climate change/greenhouse gases);
- build on expertise, connections and interrelations among parties involved;
- identify relevant indicators, particularly for prospective analysis and policy evaluation, and develop accessible methodologies, information flows and tools for their implementation;
- appraise, evaluate and further develop integrated assessment methodology.

In summary, the study had two main goals. One was to learn about and improve the integrated assessment methods and tools used and the other was to produce an updated projection (ShAIR) on air pollution and greenhouse gases based on the shared analysis scenario.

Methodology used
This study made use of experiences gained in recent scenario studies in the context of policy processes in the

European Union (EU). The economic and energy scenario used as a starting point in this study is the shared analysis scenario, which is a baseline scenario assuming existing agreed and adopted policies and measures. Various scenario assumptions have been updated, and the resulting scenario version, with a time horizon extended to 2020, is referred to as the ShAIR scenario. Based on these underlying trends, integrated projections have been made for emissions of greenhouse gases, long-range transboundary air pollution and urban air quality. The study used a model network that combined the models used in three policy fields.

Firstly, two different methods have been used to make the projections of emissions of greenhouse gases in this study: the Primes model for carbon dioxide (CO_2) emissions and information from scientific literature for the other greenhouse gases. The Primes model includes projections for all individual EU Member States (except Luxembourg) on energy-related carbon dioxide (CO_2) emissions. CO_2 emissions from non-energy sources (industrial processes and waste burning) are not included. No emission projection model was available for the other greenhouse gases. Projections have been based on the literature, and data for individual countries are sometimes lacking. Emissions and removals from land-use change and forestry (carbon sinks) were excluded. For the non-EU countries in Europe only limited information is available.

Secondly, the projections for precursor emissions, concentrations of ground-level ozone and acidifying and eutrophicating depositions are made with the RAINS model. A TNO model has been applied for PM_{10} (breathable particulate matter emissions). PM_{10} concentrations were not projected as part of the ShAIR scenario. The energy scenario for EU Member States, calculated with the Primes model, was used as an input to the RAINS model.

Finally, the model tools for assessment of urban air quality in the EEA's generalised exposure assessment (GEA) as applied in the Auto-Oil II programme have been, specifically for this project, further extended for application to cities in central and eastern Europe. An updated and improved version of the AuTh's OFIS model was applied to assess urban ozone levels in numerous large European cities. The RIVM's UAQAM model for urban concentrations of inert gases (NO_2, SO_2) has been extended as well.

Scenario development

The updated shared analysis energy scenario draws on the same macroeconomic and sectoral projections as the shared analysis energy project. For the shorter term (up to 2000) these are mainly the projections of the European Commission (Research DG). For the period beyond 2000, ShAIR uses aggregate assumptions for the world economy derived from the OECD linkages project. The updated scenario features an increased transport growth.

In the shared analysis energy project an attempt has been made to build a separate 'story' describing the evolution in each EU country. The projections were made in three steps:

- First, gradual conditional convergence of the EU economies by 2030 in terms of per capita income was assumed. The GDP of each EU country for the period 2000 to 2030 was derived on this basis.
- Second, the starting situation of each country, along with clearly identifiable trends and the identifiable driving forces of growth for each economy, were used to determine the growth rate in each industrial sector.
- Third, the GEM-E3 general equilibrium model of the EU economy has been used to ensure consistency of sectoral and macroeconomic projections.

The baseline scenario simulates a dynamic path for the EU economy up to 2030. This scenario is derived from exogenous assumptions on the evolution of technological progress associated with production factors, changes in the global economic and environmental context, and the continuation of the current pattern of public finance policy.

Indicators
Policy targets addressed are directed at UNECE protocols, EU directives for air pollution and the Kyoto obligation for greenhouse gases. The indicators chosen cover:

- socioeconomic indicators per sector;
- emissions;
- transboundary air pollution (ozone, acidification, eutrophication);
- urban air quality (urban ozone, urban SO_2, NO_2 concentrations).

Main findings with regard to linkages
- Emission reductions as foreseen in the ShAIR scenario result in a substantial improvement in the indicators for acidification and ozone.
- The focus in air pollution policy is now on eutrophication and health effects (ozone and particulate matter (PM)) and less on acidification.
- Energy trends and climate change policies influencing the fuel mix (less coal, more gas) have a significant effect on the emission levels of long-range transboundary air pollutants. Moreover, CH_4 emission reductions in the northern hemisphere of about 25 %, as projected in the ShAIR study for the EU countries, are expected to lower the background concentration of ozone.
- Under the assumption of the ShAIR emission scenario, urban air quality is strongly improving but exceedance of (proposed) air quality guidelines is still expected in 2020. In a limited number of east European cities the models project a major deterioration in air quality between 2010 and 2020. The estimated number of excess deaths attributed to sulphur dioxide (SO_2) exposure decreases sharply.
- Sensitivity calculations show that the modelled concentrations are sensitive to meteorological conditions. The required reduction in urban emissions needed to meet the air quality guidelines may vary up to 50–60 % depending on the selected meteorological year.
- In calculating exceedances of air quality guidelines in the urban area, hourly regional background concentrations are needed as input for those pollutants where the limit value is equivalent to a percentile. Such data are not calculated in the RAINS model.

Study limitations
- Lack of a model on agriculture scenarios
- Lack of a model on non-CO_2 greenhouse gases
- Greenhouse gas models not used for all European countries
- PM not integrated in the model network
- Problems with linkages of the various components (models) in the integrated assessment, creating gaps and twists in smooth data flow
- Problems with differences in assumptions of the various components creating inconsistencies in the results
- Gaps in the data flow as a result of missing components due to the lack of institutional capacity for integrated assessment.

Recommendations
This study used a model network, which needs several improvements, such as:

- adding a model on agriculture scenarios;
- adding a model on non-CO_2 greenhouse gases;
- expanding the greenhouse gas models to all European countries;
- integrating PM in the model network;
- improving the link between transboundary and urban air quality;
- improving the link between the energy model and RAINS;
- improving the consistency between energy and transport models;
- improving the module on urban emissions;

- obtaining a better understanding of the state of current policies and measures.

Improvement of models themselves is costly and time consuming. However, the support of model development could be focused on the consistency and coherence of the model and the institutional network, and the interconnections between the models used in the policy processes on climate change, long-range air pollution and urban air quality.

Lessons for the EEA for integrated assessment development with regard to linkages between air pollution and climate change

The construction of the ShAIR scenario contributes to integrated assessment studies in air pollution and climate change. In a relatively short time frame and within limited budgets, projections on transboundary and urban air quality, and greenhouse gas emissions, were made for Europe for the next 20 years based on a common scenario of economic and energy developments.

Availability

Available at: http://reports.eea.eu.int/topic_report_2001_12

Publications

EEA (2001). *The ShAIR scenario: Towards air and climate change outlooks, integrated assessment methodologies and tools applied to air pollution and greenhouse gases*. Topic Report 12/2001.

Capros P. and Mantzos L. (2000). 'The European energy outlook 2010 and 2030', *Int. J. Global Energy Issues*, Vol. 14, Nos 1–4.

Annex 3: AIR-CLIM project

Study name:	AIR-CLIM project
Period of development:	1998–2002
Institute:	Centre for Environmental Systems Research, RIVM, TNO-MEP and CIEMAT
Spatial coverage:	Europe (western Europe, eastern Europe and the European parts of the former USSR)
Spatial specificity:	European regions
Time horizon:	1990–2100
Focus (thematic coverage):	Regional air pollution, climate change

Background information
The 'Regional air pollution and climate change in Europe' (AIR-CLIM) project was an integrated assessment project funded by the European Commission, Directorate-General for Research, which assessed the linkages between regional air pollution and climate change in Europe and provided scientific information about important policy-relevant issues.

Scope and objectives
The aim of this project was to assess the linkages between regional air pollution and climate change in Europe and to provide scientific information about important policy-relevant issues. This project analyses these issues in a geographically detailed and quantitative manner. The following questions were addressed.

1. Over the long run, what is the relative importance of regional air pollution and climate change impacts in Europe?
2. What are the possible linkages between regional air pollution and climate change in Europe?

In particular:
(a) How will climate change affect the distribution of regional air pollution in Europe?
(b) How will climate change affect the sensitivity of European ecosystems to regional air pollution?
(c) How will regional air pollution in the form of sulphate aerosols affect climate change in Europe?
(d) What will be the impact of climate change policies on the costs of controlling regional air pollution?

Methodology used
The basic research tool used was an integrated modelling framework, which was part of the overall integrated approach taken in the project. This framework was integrated because it linked key elements of the problems (economy, emissions, atmospheric processes and terrestrial impacts) which were usually treated separately in long time scales and for all of Europe.

Under the AIR-CLIM framework, detailed scenarios of both air pollution and greenhouse gas emissions were developed. European scenarios of sulphur and nitrogen dioxides that are consistent with the new global IPCC scenarios (the 'SRES' scenarios) of greenhouse gases were also developed. These long-term emission scenarios make it possible to compare the long-term trends of regional air pollution with climate change in Europe.

In general, to compare regional air pollution and climate change, A1 and B1 IPCC scenarios were used as a common basis. However, the values for the driving forces (including population, economic growth and type and magnitude of energy production) assumed by the IPCC for these scenarios could not be used by AIR-CLIM in their original form because they were specified for large aggregated world regions. Therefore, the assumptions were downscaled to the level of European regions.

Besides, the framework was created from the components of two existing integrated models, RAINS and IMAGE 2. Therefore, first the TIMER model calculated the estimates of global greenhouse gas emissions including CO_2, CH_4 and N_2O in order to compute climate change. Regional concentrations of sulphate aerosol were also calculated. Finally, the TIMER model provided a consistent method for computing regional NO_x and SO_2 emissions.

After computing emissions, the resulting deposition of acidity and nitrogen to the environment was estimated. The AIR-CLIM framework used source-receptor matrices derived from the EMEP long-range transport model of air pollutants in Europe to compute the deposition. The matrices describe the deposition in different grid cells due to unit emissions from each country. Since country-scale emissions are required for these calculations, the European subregional emissions calculated by IMAGE 2 (TIMER) were downscaled to the country level using the distribution of emissions computed by the RAINS model. The question of how large the effect of climate change is on the source receptor relationships in Europe was addressed by carrying out model experiments with EMEP and comparing the results on deposition calculated for current and future climate conditions.

Moreover, to quantify the impacts of deposition on natural vegetation the concept of critical loads and critical levels was used. The critical loads were corrected for changed average climate over the scenario period. At the same time, the concept of 'critical climate change' was introduced with the aim of assessing the impacts of climate change and providing a more consistent basis for comparing them to the impacts of regional air pollution.

Finally, to evaluate the effects of climate policies on costs for reducing air pollution emissions, first the costs of climate change policies were computed. Then, the costs of reducing sulphur and nitrogen dioxide were computed with the help of cost curves.

Scenario development

The AIR-CLIM version of A1 and B1 assumed modestly increasing economic growth up to 2020 for western Europe and a decline in the second half of the century for B1. In eastern Europe, economic growth was assumed for both scenarios. Total population sinks slowly in western Europe but rises gradually in eastern Europe until around 2050, when it starts to decline.

More specifically, to compute the emission scenarios, further assumptions were made about the mitigation of emissions.

- The A1-P and B1-P scenarios assume that present air pollution policies are continued in Europe indefinitely.
- The A1-A and B1-A scenarios assume 'advanced' air pollution policies, that is, emission reductions increase over time up to a maximum value, and are achieved through end-of-pipe measures.
- The A1-550-P and A1-550-A scenarios add climate policies to the assumed air pollution policies. For these scenarios it is assumed that greenhouse gas emissions are reduced so that the atmospheric concentration of carbon dioxide stabilises at 550 parts per million in the atmosphere over the long run.
- The B1-450-P and B1-450-A scenarios include climate policies sufficient to stabilise carbon dioxide at 450 parts per million by 2100.

- No reduction policies were assumed for ammonia emissions (which contribute to total nitrogen deposition).

Additionally, in order to compute the costs of climate change policies and to stabilise carbon dioxide at 450 and 550 parts per million by 2100 according to the climate policies, a 'carbon tax' was assumed in order to stimulate a variety of actions. For example:

- investments and implementation of energy efficiency;
- the substitution of high carbon fuels with lower carbon fuels (for example, coal with natural gas);
- higher levels of world trade in lower carbon fuels; and
- investments and construction of low or non-carbon alternatives such as wind energy, solar energy, biofuels and nuclear energy.

Indicators
For climate change, the indicators chosen for the AIR-CLIM project were changes in surface temperature and precipitation because of the large number of potential impacts associated with these parameters.

For air pollution, acid deposition and nitrogen deposition with some attention to air concentrations of nitrogen oxides (NO_x) and sulphur dioxide (SO_2) were chosen. One reason is that their precursor emissions have been controlled in Europe by a series of international agreements. An additional factor is that at least one regional air pollutant stemming from sulphur dioxide emissions in Europe (sulphate aerosol) has an established link to climate change (as explained later in the text). For these reasons the study is concentrated on sulphur and nitrogen. However, it was recommended that other important regional air pollutants, e.g. persistent organic pollutants and oxidants, be given attention in any follow-up studies.

Main findings with regard to linkages
- By 2050, practically all of Europe's area outside of northern Europe and Russia will be affected by either or both regional air pollution and climate change. The areas of overlapping impacts in 2050 cover about 16–31 % (depending on the scenario) of Europe's area.
- Model experiments by the EMEP model showed a relatively small influence of climate change on the distribution of acid deposition and nitrogen deposition in Europe.
- The change in critical loads because of climate change at a particular location does not exceed 10–15 %. Forest soils, on average, will have higher critical loads. Nevertheless, some parts of western coastal regions and mountainous regions become more sensitive.
- The effect of climate change on deposition is quite small compared to its effect on critical loads. For example, under present climate conditions, the area where critical loads of nitrogen are exceeded ranges from only 55.6 to 58.1 % because of the influence of climate change on deposition patterns, but varies from 46.2 to 58.1 % because of its influence on critical loads.
- Climate change increases the sensitivity of plants to specified levels of air pollutants in the boreal forests of northern Europe, while it decreases plant sensitivity in temperate areas.
- For the highest and lowest AIR-CLIM scenarios (A1-P and B1-450-A), a wide range of SO_2 emissions causes only a small difference in temperature (0.10 to 0.20 ˚C, European annual average). Hence, for these model experiments, the influence of sulphate in the atmosphere on Europe's temperature is rather small.
- Climate policies usually aim to reduce fossil fuel use in order to reduce carbon dioxide emissions. As a side effect they also reduce emissions of sulphur dioxide and nitrogen dioxides significantly and that could make it easier for Europe

to comply with the Gothenburg Protocol. In the AIR-CLIM project this effect was found to be very significant.

- For the A1 scenarios, the annual costs of reducing sulphur dioxide emissions (without climate policies in place) are estimated to be between 0.19 and 0.31 % of Europe's GDP in 1995 (depending on the reduction level). These are the long-term (2000 to 2100) average costs.
- If climate policies are in place, then the costs of add-on technologies to control SO_2 could be reduced by about 70 % because of decreased fossil fuel use.
- Cost savings are lower (around 55 %) for the B1 scenarios, because base emissions are already much lower than under the A1 scenarios, again because of lower fossil fuel use.
- For NO_x emissions, the long-term average annual costs for emission reductions (without climate policies) are somewhat higher than for sulphur dioxide, being about 0.51 to 0.75 % of European GDP in 1995. But climate policies would also lower the baseline NO_x emissions and thereby save a substantial sum for add-on measures. The cost savings with climate policies in place are estimated to be 40 to 55 %, as compared to scenarios without climate policies.

Study limitations

The conclusions are true for sulphur and nitrogen as regional pollutants, but are not necessarily true for other important regional pollutants such as persistent organic pollutants and photo-oxidants. These other pollutants do not have the same chemical characteristics as sulphur and nitrogen, and therefore respond differently to wind, temperature, precipitation and other aspects of climate. Hence, an assessment of the connection between these substances and climate change would be interesting from both the scientific and policy perspective.

The AIR-CLIM project was comprehensive but not definitive. While it was comprehensive geographically, and in its coverage of economic, emission, atmospheric and ecological aspects of air pollution and climate change, it was nevertheless limited in scope.

- Research focused only on the impacts on natural vegetation and not on any other impacts such as the impacts on human health, crop production and aquatic ecosystems, among other categories.
- Cost calculations investigated only the side benefits of climate policies to reductions of air pollution emissions and did not evaluate truly *joint policies* having the objective of simultaneously reducing greenhouse gas and air pollution emissions.
- To include climate change in any analysis it was necessary to use climate scenarios. These scenarios have a high rate of uncertainty because they are generated by models that must make a large number of approximations to simulate global atmospheric processes. This uncertainty can be somewhat reduced by using output from the new generation of regional climate models that can better simulate finer scale meteorological processes important in Europe.

Recommendations

- While the conclusions of the AIR-CLIM project hold for sulphur and nitrogen as regional pollutants, they will not necessarily hold for other important regional pollutants such as persistent organic pollutants and oxidants. These other pollutants do not have the same chemical characteristics as sulphur and nitrogen, and therefore respond differently to wind, temperature, precipitation and other aspects of climate. Hence, an assessment of the connection between these substances and climate change would be interesting from both the scientific and policy perspective.
- Future research should focus not only on the impacts on natural vegetation, but also on the impacts

on human health, crop production and aquatic ecosystems, among other categories.

- Cost calculations should investigate not only the side benefits of climate policies to reductions of air pollution emissions, but should evaluate truly *joint policies* having the objective of simultaneously reducing greenhouse gas and air pollution emissions.
- In order to include climate change in any analysis it is necessary to use climate scenarios.
- These scenarios have a high rate of uncertainty because they are generated by models that must make a large number of approximations to simulate global atmospheric processes. This uncertainty can be somewhat reduced by using output from the new generation of regional climate models that can better simulate finer scale meteorological processes important in Europe.

Lessons for the EEA for integrated assessment development with regard to linkages between air pollution and climate change

The AIR-CLIM project introduced a new approach to carrying out regional studies of air pollution and climate change. For Europe, this method allows a comparison of future trends in regional air pollution and climate change in a consistent manner. Moreover, it made possible the building of a complex modelling framework in a short period of time and made more time available for scenario analysis and conducting model experiments, using for the first time the detailed output from a climate model, as input to a long-range transport model of pollutants.

The concept of critical climate can be a useful new tool for researchers in their assessments and analyses of climate impacts on natural vegetation. The simultaneous usage of critical loads, critical levels and critical climate in AIR-CLIM, which allows a more consistent comparison of impacts on natural vegetation due to deposition, air concentration and climate change, can also be applied to many other regional and subregional assessments.

Availability

The final report is available at: http://www.usf.uni-kassel.de/usf/forschung/projekte/airclim.en.htm

Publications

Alcamo J., Mayerhofer P., Guardans R., Van Harmelen T., Van Minnen J. G., Onigkeit J., Posch M. and De Vries B. (2002). 'An integrated assessment of regional air pollution and climate change in Europe'. Findings of the AIR-CLIM project. *Environmental Science and Policy*. 5: 257–272.

Annex 4: Approaches to analyse interactions of climate change, acidification and ozone (NRP project)

Study name:	Approaches to analyse interactions of climate change, acidification and ozone
Period of development:	2000–02
Institute:	Wageningen University and TNO-MEP
Spatial coverage:	Europe
Spatial specificity:	Ranging from country level to Europe as a whole
Time horizon:	1990–2010
Focus (thematic coverage):	Climate change, air pollution

Background information
This project was carried out within the framework of the Dutch 'National research programme on global air pollution and climate change' (NRP), a strategic and long-term scientific research programme to strengthen and support Dutch policy-making in regard to climate change as a result of global air pollution, by providing policy-relevant information.

Scope and objectives
This project focuses on the interactions of various problems of transboundary air pollution, climate change and stratospheric ozone. The objective of the present study is to examine approaches for an integrated analysis (scenario and optimisation analysis) of climate change, acidification, tropospheric ozone formation and stratospheric ozone depletion, with a focus on the European situation. The aims are:

- analysing the interactions between the four environmental themes above;
- assessing model specifications for these four themes considering limitations related to, for example, data on emissions, environmental effects and emission reduction costs' complexity of the model and limited computer resources.

To reach these aims, the following research questions have to be addressed:

- Which interactions exist between acidification, tropospheric ozone formation, climate change and stratospheric ozone depletion?
- How can these interactions be analysed either by means of existing models, or by combining parts of these models, or by new model structures focusing on these interactions?
- Which data are required at the appropriate spatial and temporal scales for these themes and how can these different scales be integrated?
- Which information is already available in existing emission inventories and existing models?

Methodology used
First an introduction of what the most important interactions are between air pollutants and environmental problems was made. The interactions that were taken into account were those that exist in sources of emissions of various pollutants and greenhouse gases, the interactions because of reduction strategies and the interactions during the formation of acidification and tropospheric ozone in the atmosphere. The impacts of climate change on the source receptor relations for

acidification and tropospheric ozone were also considered.

Then, the characteristics of existing emission databases, from the point of view of chemical compounds, spatial and temporal dimensions, emission source and emission estimation methods, were analysed. The analysis covered European databases, based on national inventories prepared for international databases on air pollution abatement. These include EMEP, Corinair and IPCC databases and the Pollutant Emission Register (PER) from the Netherlands, as an example of detailed national emission inventory. Databases that are used as input into integrated assessment models (IMAGE 2.0 and RAINS) and into an atmospheric transport model (LOTOS) were also analysed. These databases were compared to each other, and in a second stage a number of models (IMAGE, RAINS-Europe and RAINS-Asia, LOTOS, MERGE and Markal) were analysed, from the point of view of their treatment of emission reduction strategies.

In addition, the basic requirements of emission inventory databases to be used in an integrated analysis of acidification, eutrophication, tropospheric ozone and global warming related problems in Europe were identified. The hypothetical 'ideal' specification of such databases, which combine requirements for policy, economic and atmospheric analyses, was compared with the existing emission inventory databases, in order to examine to what extent they fulfil these requirements.

Furthermore, two detailed economic models that focus on multi-pollutants were discussed. Both studies deal with cost minimisation given a set of environmental constraints. This new economic method to model interactions of reduction strategies in a comparative static optimisation model determined cost-effective policies for several environmental targets simultaneously, taking into account interrelations between these policies. The model is formulated as a linear programme including a large number of sources, pollutants and abatement options.

Finally, suggestions are given for the structure of an integrated model on the basis of available emission inventories and existing models for atmospheric chemistry, taking into consideration the results of these two models. This model is able to determine cost-effective solutions at a European level for given targets of acidification, eutrophication and tropospheric ozone and for given emission targets for the emissions of greenhouse gases, either individually or aggregated by means of global warming potentials.

Scenario development

The first economic model structure, which focuses on the economic modelling of a cost-effectiveness analysis for reducing various pollutants, was applied to the agricultural sector in Europe. The model is used to analyse cost-effectiveness of strategies to reduce NH_3, N_2O and CH_4 from European agriculture taking into account interactions between abatement of these gases.

The second model structure deals with a combined cost-effectiveness approach for acidification and tropospheric ozone. Changes in energy supply were allowed. However, the demand and supply of the energy are given exogenously and stay outside the optimisation. This restricts the optimisation to end-of-pipe technologies for acidifying pollutants and precursors of ozone or some greenhouse gases in agriculture. Data from Germany and the Netherlands that qualitatively reflect some real world proportions were taken in order to provide parameters for the model. Source receptor matrices have been taken from EMEP but they have been adjusted for the two countries.

Indicators

- Future emissions of NO_x, SO_2, NH_3 volatile organic compounds, CO_2, CH_4, N_2O, several fluorinated compounds and soot.

- Other suggested indicators for integrated analysis in terms of environmental impact: CO_2-equivalent emission targets for greenhouse gases, critical levels for tropospheric ozone concentrations, critical loads for deposition of acidifying and eutrophying compounds.

Main findings with regard to linkages

- There are at least four types of interactions between economic sectors, atmospheric processes and environmental impacts that affect emissions of air pollutants. These are the interactions between economic sectors and emitted pollutants, interactions between biogenic and biogeochemical processes and underlying emissions, between reduction strategies and related emissions and finally between emissions affected by environmental problems.
- The characteristics of an ideal emission inventory for integrated assessment have been identified, based on research aims of different types of analysis (economic, atmospheric and policy analysis). The quality of an inventory is related to its accuracy, precision, uncertainty, error, reliability, completeness, comparability and transparency. None of the existing databases met all the requirements of an ideal specification of an emission inventory database. None of the databases focuses on all four of the environmental problems that are studied in this project.
- With respect to the aggregation level, it was concluded that the LOTOS database has the most detailed spatial and temporal specification, which is closest to the 'ideal' spatial aggregation level, but only for a limited number of gases and years without detailed specification of sources.
- With respect to the source categories included, integrated models like RAINS and IMAGE are the most detailed and include several economic sectors and abatement strategies. However, they lack the temporal and spatial detail of atmospheric models.
- An emission inventory database that satisfies all these requirements for economic, atmospheric and integrated assessment models may not be easy to realise.
- Cost-effective abatement of NH_3 according to the agreements in the Gothenburg Protocol could cause an increase in emissions of N_2O.
- Although total N_2O emissions in Europe increased, total CH_4 emissions in Europe decreased due to NH_3 abatement.
- The reduction of acidification requires large reductions of both SO_2 and NO_x emissions, which may only be reached by combination of end-of-pipe technologies, energy conservation and introduction of renewables. For this particular case, reduction of NO_x may lead to an increase of ozone concentrations to the non-linearity in ozone formation.
- Multiple reduction targets for acidification and tropospheric ozone will not lead to cost savings when compared with single pollutant/single target policies.
- Renewable energy will only be used in modest quantities by the year 2010. This is mainly due to the relative high price of renewable energy compared to the price of fossil fuels and the fact that renewables are expensive related to the end-of-pipe technologies for emission reductions.

Study limitations

- Data availability: some chemical compounds are not well documented and measurements for many of them have a high rate of uncertainty.
- The time scales relevant to the climate problem are much larger than the time scales for air pollution problems; the atmospheric residence time of most climate related species is 50 years or more and for most air pollution related species one year or less. The combination in one supermodel would imply enormous computational burdens.

- Non-linear relationship between the formation of ozone and its precursors: the model used to compute the most effective abatement strategies of ozone and acidification, considering their interactions, was not detailed enough to give better insights.
- Only a small number of countries were included in the example of the analysis.
- The cost functions were not specified in any great detail.

Recommendations
A combination of information from different emission databases could be used in a series of atmospheric and environmental models. For a consistent set of scenarios, it is useful to analyse the impact on the climate change using ECHAM, for air pollution the LOTOS model, and for the potential impact of acidification and eutrophication on ecosystems the RAINS model.

Furthermore, for this combined analysis of climate change and transboundary pollution, in regards to climate change, firstly the ECHAM model could be incorporated in an economic model, based on the MERGE modelling system; for transboundary pollution, the LOTOS model could be incorporated in a model with characteristics of the RAINS system.

Besides, considering the important interactions between CH_4, N_2O and NH_3 that exist in agriculture, considerable cost savings can be obtained if the side effects of emission control options are explicitly included in the policy-making process.

Lessons for the EEA for integrated assessment development with regard to linkages between air pollution and climate change
Although the improvement of models themselves is costly and time consuming, as a first step towards an integrated analysis of different air pollution problems in Europe, the EEA could concentrate on softly linking existing models for the purpose of scenario analysis, addressing the 'what if' type of questions. A complete climate change plus air pollution model for scenario studies does not exit at the moment.

A next step could be to link models specifically designed for scenario analysis to models that have the possibility of optimisation analysis or general equilibrium modelling. It is proposed to first decouple climate change calculations from air pollution in an analysis at the global level, in order to determine emission reduction targets for greenhouse gases in Europe. Next, the optimised emission levels should be used as one of the restrictions in an optimisation analysis at the European level, using a newly developed model based on elements of RAINS and the more detailed LOTOS system for transboundary air pollution.

Availability
Available at the Dutch 'National research programme on global air pollution and climate change' (NRP) Secretary which is located at RIVM.

Publications
Van Ierland E. C., Ignaciuk A., Kroeze C., Brink C., Schmieman E., Builtjes P., Roemer M. and Mayerhofer P. (2002). Approaches to analyse interactions of climate change, acidification and ozone. NRP Report 410200105. National Institute for Public Health and the Environment (RIVM).

Annex 5: Study for *Europe's environment, the third assessment*: Exploring the ancillary benefits of the Kyoto Protocol for air pollution in Europe

Study name:	Exploring the ancillary benefits of the Kyoto Protocol for air pollution in Europe
Period of development:	2002–03
Institute:	RIVM and IIASA
Spatial coverage:	Europe (western Europe, eastern and central Europe, and Russia and western new independent States)
Spatial specificity:	Ranging from European regional level to country level
Time horizon:	1990–2010
Focus (thematic coverage):	Air pollution, climate change

Background information
The EEA has publishedan indicator-based report on the state and near-term outlook of Europe's environment for the 2003 conference of European environment ministers in Kiev: Europe's environment, the third assessment. *t*. The European Topic Centre on Air and Climate Change (ETC-ACC) has prepared background material for this report. The study presents an integrated analysis of linkages and interrelations between scenarios and mitigation options for air pollution and climate change.

Objectives
The objective of this report is to explore the emission reductions of air pollutants as well as change in control costs and environmental impacts as a result of different ways of implementing the Kyoto Protocol in Europe, including the use of Kyoto mechanisms. The report quantifies the ancillary benefits of reducing greenhouse gas emissions to meet the Kyoto targets in terms of reduction of air pollution and improvement of environmental quality.

Methodology used
The discussion focuses primarily on three country grouping/regions: western Europe (WE), central and eastern Europe (CEE) and Russia and Western NIS (R&WNIS). At this stage, the study is restricted to carbon dioxide (CO_2), leaving the remaining five greenhouse gases covered by the Kyoto Protocol not addressed.

To cover a range of potential ancillary benefits for the main region investigated, this study explores three mitigation scenarios with different usage of Kyoto mechanisms to reach the Kyoto targets.

The ancillary benefits from the mitigation scenarios are derived by comparison with a baseline scenario, which does not include any explicit climate change policies. The analysis is performed using a set of linked models that together simulate different ways of achieving the Kyoto targets for climate change and targets for controlling regional air pollution. This study integrates the different research areas by linking models that address climate change issues (FAIR and the energy model IMAGE/TIMER) and regional air pollution (RAINS).

The impacts of climate change scenarios are explored by comparing emission control costs and environmental impact indicators. The results included in the analysis are the trends in emissions, the areas of the ecosystem not protected against damage from acidification and eutrophication, and exceedances of air quality targets for ozone. Control costs of different scenarios will also be addressed, both for the policies to reduce greenhouse gases and for emission control costs for regional air pollution.

It should be noted that the results of the study should be seen as explorative for the ancillary benefits in the larger European regions, for emission control costs, for climate policies and for air pollution control. The costs calculated by different models should be compared with caution since they stem from different modelling traditions (in fact, even within each particular area, considerable ranges of cost estimates exist). Furthermore, the results presented in this report are of a descriptive 'what if' character and do not intend to be prescriptive for any future implementation of the Kyoto Protocol and air pollution policies.

Scenario development

A baseline scenario for the year 2010 was developed to assess trends in carbon dioxide emissions in the absence of explicit policies to control greenhouse gas emissions and to assess the effect of previously decided control measures on future emissions of air pollutants and ecosystem protection. The baseline scenario includes emission and fuel standards in each country according to the current legislation (CLE) *and* emission ceilings from the national emission ceilings directive of the EU and from the Gothenburg Protocol to the CLRTAP. The baseline is characterised by a continuation of trends that were dominant during the 1990s: increasing globalisation, further liberalisation and average assumptions regarding population growth, economic growth and technology development (ETC-ACC, 2002).

Furthermore, the following policy scenarios that are assumed to meet the Kyoto commitments are explored and compared with the baseline.

1. **Domestic action only (DAO).** All Annex 1 parties (countries from western Europe, central Europe as well as Russia, new independent States, Canada, Australia, New Zealand and Japan) implement their Kyoto targets domestically, i.e. without use of the Kyoto mechanisms. The exception is the trade within the regions considered, thus for instance among the current EU member countries.
2. **Trade — No hot air (TNH).** This scenario assumes full use of Kyoto mechanisms among Annex 1 parties, but without any use of hot air. This scenario explores the maximum ancillary benefits that can be obtained under a trade case.
3. **Trade with hot air (THA**). This scenario assumes full use of Kyoto mechanisms among Annex 1 parties and includes the use of hot air. However, the supply of hot- air is limited to the level that maximises the profits of Russia and Ukraine from selling the emission permits. According to calculations performed by FAIR, the supply of tradable hot air permits is 25 % of total available potential.

Indicators

CO_2 emissions
Air pollutant emissions (SO_2, NO_x, VOC and PM_{10})
Emission control costs
Ecosystems with deposition exceeding critical loads for acidification (percentage of ecosystem area)
Ecosystems with deposition exceeding critical loads for eutrophication (percentage of ecosystem area)
Population exposure to ozone
Vegetation exposure to ozone

Main findings with regard to linkages

- *Implementation of climate change policies to comply with the Kyoto Protocol is likely to induce significant ancillary benefits for air pollution in Europe.* The results of the domestic action scenario for western Europe can be compared to those of the earlier studies, with ancillary benefits being slightly less as result of the fact that the CO_2 baseline projection of this study is slightly lower — and some new (more stringent) policies for regional air pollutants have been introduced under the baseline. Interestingly, the 'coupling' between reductions in CO_2 emissions and reduction of regional air pollutants is the strongest in central Europe, followed by Russia/ western NIS and finally western Europe.
- *In case of the trading scenarios, the ancillary benefits of climate policies are partly 'traded' to other European regions*. In case of the trading scenario without hot air, sulphur emission reduction in central Europe and the former Soviet Union are in the order of 20 %. In the more realistic scenario with 25 % use of hot air (banking scenario) this emission reduction is about 10–15 %. Interestingly, as the linkage between sulphur emissions and carbon dioxide emission reduction is stronger outside western Europe, the ancillary benefits for Europe as a whole can be higher in the trading scenarios than in the domestic action case — depending on the question of how much hot air is used (more hot air use limits climate policy implementation costs in western Europe but reduces ancillary benefits).
  In terms of acidification impacts, similar trends can be observed. For Europe as a whole, emissions trading can lead to more reduction of acidification impacts — but only in case the amount of hot air that is used is limited (in the scenario with 25 % use of hot air the impacts between the trading scenario and domestic action are more or less similar). In fact, even in western Europe itself the differences in ancillary benefits in terms of acidification impacts between the domestic action and trading scenario are relatively small despite the fact that most of the CO_2 emission reduction takes places outside western Europe. The reason for this is that sulphur reduction in central Europe also has an impact on acidification in western Europe.
- *Climate policies can lead to large cost savings in reducing air pollution emissions.* This is caused by structural changes in energy systems induced by climate policies. It should be noted, however, that there are a number of difficulties in comparing the cost estimates for climate policies and regional air pollution policies mentioned in this study. The results suggest that for the domestic action scenario about a fifth of the total costs to implement the Kyoto scenario are regained in terms of reduced costs for air pollution control. Implementation of Kyoto mechanisms (emissions trading) result in a smaller reduction of air pollution control costs in western Europe (EUR 2–3 billion), but from the perspective of total costs this is clearly compensated in reduction of climate policy costs (EUR 11–12 billion). Trading decreases the air pollution control costs in the other regions, but these gains are considerably lower due to the fact that environmental policies are less strict.
- *Climate change policies also impact emissions of particulate matter.*
  A relatively new concern in air pollution policies is the emissions of particulate matter. Also the emissions of PM_{10} are strongly coupled to climate policies. The flat rate 10 % reduction of carbon dioxide emissions shows that the link is particularly strong in central and eastern Europe, with reductions of PM_{10} being even stronger than those of CO_2. As a result, implementing the Kyoto Protocol by means of emissions trading can

result in a much stronger reduction of European PM_{10} emissions (7–8 % than domestic action (2 %)). Interestingly, there is growing interest in the role of emissions of particulate matter directly on climate change (both in terms of cooling and warming).

- *The results can be important in designing climate policies.* In view of the financial and environmental benefits of climate policies, including emissions trading, it might be attractive to make sure that the use of hot air in climate policies indeed remains limited (as assumed in these scenarios). Moreover, it was shown that, for western Europe, using flexible instruments with central and eastern Europe can have several attractive side effects, such as a stronger improvement in the overall environmental situation in Europe, and, as a result of the transboundary nature of regional air pollution, even some improvements in the western European environment. Using CDM with developing countries foregoes these benefits, and as a result a higher 'carbon price' for JI/emissions trading compared with CDM may be justifiable from a western European perspective. Although not analysed here, the opposite is obviously true for Japan in view of transboundary air pollution from China.

Study limitations

- The study is restricted to carbon dioxide (CO_2), leaving the remaining five greenhouse gases covered by the Kyoto Protocol not addressed.
- The costs calculated by different models should be compared with caution since they stem from different modelling traditions (in fact, even within each particular area considerable ranges of cost estimates exist).

Recommendations

Overall strategies for climate change and regional air pollution can lead to cost savings and larger environmental benefits, but further analysis of the interactions, and in particular of the different costing methodologies, could help to further define strategies that fully harvest the potential synergies.

Lessons for the EEA for integrated assessment development with regard to linkages between air pollution and climate change

This technical report underpins the pan-European environment report produced by the European Environment Agency for the ministerial conference to be held in Kiev, May 2003. The integrated analysis of linkages and interrelations between scenarios and mitigation options for air pollution and climate change used in this report shows that implementation of climate change policies to comply with the Kyoto Protocol is likely to induce significant ancillary benefits for air pollution in Europe. Therefore, it could support the effort of identifying policies, which look at the cost- and environmental effectiveness of proposed solutions in an integrated way, preventing inefficient use of resources and implementation of sub-optimal solutions.

Availability

The report is available on Internet at http://reports.eea.eu.int/technical_report_2004_93/en

Publications

EEA (2004). Van Vuuren, D. P., Cofala J., Eerens H. C., Oostenrijk R., den Elzen M. G. J., Heyes C., Klimont Z. and Amann M. *Exploring the ancillary benefits of the Kyoto Protocol for air pollution in Europe*. Technical report No 93.

Annex 6: Ancillary benefits and costs of greenhouse gas mitigation (proceedings of the OECD workshop)

Study name:	Ancillary benefits and costs of greenhouse gas mitigation
Year of development:	2000
Institute:	IPCC, OECD
Spatial coverage:	World
Spatial specificity:	Ranging from world level to country level
Focus (thematic coverage):	Climate change, case studies

Background information
In March 2000, an international workshop was held to consider the development of systematic methods for creating and assessing policies and programmes to mitigate the direct and indirect impacts of climate change and for estimating costs and benefits of these policies. It is generally understood that policies which tend to reduce GHGs can have positive and negative 'ancillary effects' on public health, ecosystems, land use and materials, and that such effects can appropriately be subtracted from (or added to) mitigation costs to assess the social cost of such policies.

The workshop brought together many experts in this field to discuss and identify key issues for further analysis. The workshop was organised by the IPCC and was co-sponsored by OECD, RFF, Statistics Norway, USDoE, US EPA and WRI. This publication includes many of the papers presented at the workshop.

Scope and objectives
The workshop, results of which are presented in this publication, was designed to:

- establish a common basis of understanding about the conceptual and empirical elements of ancillary benefits and costs of climate change policies;
- identify options for integrating ancillary benefits/costs into policy design and analysis;
- identify research gaps and fruitful areas for further research to narrow uncertainties about this issue and make the analysis more useful for policy-makers.

Furthermore, the workshop facilitated a dialogue between analysts in this field and highlighted recent case studies from developed and developing countries. It also highlighted some continuing areas of debate, including valuation of health impacts and differences in approach between industrialised and developing countries.

In summary, it confirmed that positive and negative ancillary effects could be crucial to the development of effective and efficient policy-making on greenhouse mitigation.

Methodology used
The different terms used to depict ancillary effects reflect differences in their entry into the policy process. Thus, the term **co-benefits** (sometimes also referred to as multiple benefits) signals effects that are taken into account as an explicit (or *intentional*) part of the

development of GHG mitigation policies. The term **ancillary benefits** indicates impacts that arise *incidental* to mitigation policies. This publication uses the term ancillary effects to denote those impacts that occur as an incidental consequence of changes in GHG emissions. This should be understood to include negative impacts, or costs, and does not imply that the ancillary effects are necessarily of lesser importance than greenhouse gas abatement. The terms 'ancillary effects' or 'ancillary benefits and costs' are used in this paper when addressing literature that primarily looks at climate change mitigation, but also recognises there may be benefits in other areas.

In addition, it introduced the general approach to ancillary effect analysis, where climate mitigation policies operate through an economic and institutional system within a country that leads to reductions in GHGs, changes in other pollutants, and mitigation costs.

One vital element in this analysis of ancillary effects is the development of the analytic baseline — which includes projections of many of these institutional and socioeconomic parameters — since these baseline issues determine the environment in which climate change policies will have their effects. Morgenstern (2000) identifies five issues where baselines could be significant in assessing ancillary effects. The first three of these issues — non-greenhouse policies, technology and economic development — are all very closely interconnected. Changes in any of these will generally have direct implications for the others. The final two — demography and natural activities — also have such linkages, but of a far smaller order, so these can usefully be treated as exogenous to GHG policy evaluation.

There are also other key issues that need to be considered in the analysis of ancillary effects. For example, ancillary effects should be understood and estimated in geographic and time-specific contexts. As their examination is extended into developing countries, a number of difficulties arise. For many developing countries the problem is not simply ignorance about the existence of ancillary effects but rather that decision-makers have to weigh the potential ancillary effects of proposed GHG mitigation policies against other priorities, such as the satisfaction of the basic needs.

Furthermore, in order to ensure that analyses of potential ancillary effects are integrated into the policy process, it is important to consider as many types of ancillary effects as practicable. Four categories of ancillary effects could be identified: health, ecological, economic and social. Comprehensive coverage is also important within classes of ancillary effects as well as between them. Often only a subset of the relevant pollutants is considered in ancillary pollutant studies. It is now widely recognised that multiple pollutants may yield significant ancillary effects and that the benefits of emission reductions can vary tremendously depending on the spatial location of emission reductions vis-à-vis the proximity of the exposed population.

Moreover, much of the controversy surrounding ancillary effects really concerns the issue of valuation, especially the risks to human health and loss of life. Participants at the workshop raised the option of performing cost-effectiveness analysis of alternative policies instead of cost-benefit analysis as a way to improve policy-making while avoiding the controversies and uncertainties of valuation.

A further potential source of ancillary costs is the 'ancillary leakage effect.' Though there is debate about the significance of the effect, it is widely observed in modelling the impacts of Annex I actions to reduce GHG emissions that carbon emissions in non-Annex I countries may rise, due to changes in relative factor prices. The resulting increase in coal use (and in use of other fossil fuels) in non-Annex I countries — the carbon leakage — brings with it an ancillary cost of greater air pollution and other negative externalities. However, the issue is not well studied and the significance of the effect is not known.

Finally, there is general agreement that the uncertainty surrounding the estimates of ancillary impacts is at least as great as the value of those estimates as that associated with other mitigation costs. At the least, ancillary benefit studies should provide similar qualitative information about uncertainty.

Scenario development
Almost all the studies of ancillary effects reviewed here analyse the effects of a GHG reduction policy through a tax on carbon. Only two studies consider alternative programmes: a national efficiency programme, and energy efficiency improvements, based on the adoption of existing technologies. The level of abatement of these two studies is relatively modest.

As far as the other policies, which were assumed in the different study approaches, are concerned, there are some key differences related to assumptions about baseline regulatory policies. For instance, the abatement cost savings from reducing SO_2 emissions in response to a carbon tax is counted because SO_2 emissions are capped in the US. Similar adjustments are not made for SO_2 taxation (or taxation of other pollutants) in Europe, where large differences exist in regulatory policy.

Furthermore, several of the developing country studies relate the values for health impacts with future income growth. In general, developed country studies do not. On the other hand, the majority of the ancillary effect studies do not incorporate the potential impacts of changing demographic profiles. The level of spatial detail varies very widely, from the fine detail to national level evaluations including the international summation of national figures.

Most of the studies in this publication use static or dynamic CGE models. One employs an econometric model, which provides top-down and sectorally aggregate estimates of ancillary effects/costs. The modelling of carbon reductions as a result of a policy intervention, such as a tax, is credible though subject to key choices about energy substitution and demand elasticities. Although restricted to the electricity sector, there is only one study that provides the sole example of location specificity of an economic model. Other studies do not use an economic model, but follow a bottom-up approach, positing some increase in energy efficiency or reduction in carbon and estimating the ancillary effects that would result, at a reasonably detailed spatial level. Finally, most of the studies try to quantify uncertainties. In addition, many conduct sensitivity analyses on key economic, health and valuation parameters to estimate the range of possible ancillary effects.

Indicators

- Avoided deaths and illness tied with exposure to particulate matter in developed countries.
- Mortality and morbidity associated with ozone and particulate matter.
- The amount of willingness to pay (WTP)/willingness to accept (WTA) for avoiding such health impacts.
- Avoided costs (e.g. cost savings for meeting the SO_2 cap in the United States). If the SO_2 cap is binding, moderate policies to reduce GHG emissions from the power and industrial sectors will not lead to further reductions of SO_2 emissions. As these emissions are capped, the result is abatement cost savings to those purchasing or otherwise acquiring SO_2 permits freed up by the GHG policy induced SO_2 reductions).

Main findings with regard to linkages
From the case studies reviewed some main conclusions were highlighted:

- Changes in assumptions about the future price of oil could drastically change the measurement of ancillary benefits as higher prices would

themselves drive many of the improvements which climate change policies might support.
- Avoided costs may be an important and growing source of ancillary benefits; it is important to identify and quantify their range.
- Preliminary analysis of extant modelling results suggests the possibility of ancillary costs resulting from increases in conventional pollutants in developing country regions as a consequence of the 'leakage effect' of carbon reductions under the Kyoto Protocol.
- Meteorology and other factors, including the potential for a non-linear relationship between emissions and pollutant concentrations, or between concentrations and health effects, further enhance the value of complex, location-specific models.
- Health effects typically account for 70–90 % of the total value of ancillary benefits in places where the unemployment rate is high, the amount of willingness to pay (WTP)/willingness to accept (WTA) for avoiding such health impacts may be lower or the estimate of loss of earnings due to illness may be lower.
- The 'Value of a statistical life' (VSL) routine values used in the literature could lead to a difference of 300 % in ancillary benefit estimates.
- Ecological ancillary benefits will arise from reductions in airborne emissions, although these have not yet been specifically modelled.
- Some studies find that the benefits of the health effects avoided by mitigation measures, per tonne of carbon, are roughly equal to the carbon tax/tonne needed to meet those goals or even exceed the tax. Others find relatively small ancillary benefits. Thus, it is difficult to generate broad, general estimates of the magnitude of ancillary effects relative to mitigation costs.
- The broad divergence in the value of ancillary effect estimates, even within the same country, is evident. Where studies include uncertainty bounds, these are often quite large relative to the central estimate.
- Inclusion of ancillary effects is likely to make *design* of GHG abatement policies more complex, especially in adding a geographic dimension which need not otherwise exist. In terms of *selecting* policy instruments, different instruments do differ in their ability to incorporate ancillary effects. However, all instruments appear capable of building in ancillary effects to some degree.
- Inclusion of ancillary effects can affect not just the type of policy instrument put in place, but the sectoral targets of policies. Where policies are aimed at specific technologies, they may also affect the choice of technological options.
- If congestion is the overriding ancillary effect (at least in peak hours), then measures which reduce traffic will have far greater ancillary effects than those which reduce the emission intensity of traffic.
- In the case where ancillary benefits outweigh abatement costs, as found in some studies, the relative cost assessment could be completely switched around unless there are comparable ancillary costs in non-energy sectors.

Study limitations (from the case studies reviewed)
- The differences in policy scenarios, modelling and parameters in addition to the real differences across countries, such as population size, regulatory differences, technological sophistication and baseline emissions of conventional pollutants, lead to different estimates of the size and scale of ancillary effects.
- Most of the studies were concentrated on health ancillary effects.
- The dominance of health impacts in ancillary effect analysis can qualitatively alter the analysis.
- Lack of available studies on ecological ancillary effects and land use impacts is an important gap in the knowledge base.
- There was a lack of indigenous data in developing countries and it was

not possible to asses how accurate benefit transfers from developed countries really are.
- Aggregate models, which have many advantages for the study of GHG mitigation policies, are not well suited to capture the important detail or non-linearities involved in estimating ancillary effects.
- None of the studies reviewed in this assessment reported estimates of ancillary costs.

Recommendations
High priority areas for further research:

- more targeted case studies on non-health ancillary effects, especially ecological impacts, some of which are related to air pollution;
- more comprehensive generation and use of health information on morbidity and mortality tied to the array of air pollutants of interest;
- more sophisticated assessments of baseline health and social conditions as these influence susceptibility to pollution in various regions;
- transparent and reasonable specification of regulatory baselines, particular with respect to future air pollution regulation;
- development of integrated modelling which allows simultaneous consideration of macroscale and geographically specific impacts;
- better modelling to incorporate avoided costs and integrated achievement of multiple policy goals;
- analysis that attempts to capture ancillary costs;
- consideration of the time frame over which ancillary effects are realised, and the relationship to GHGs policy timeframes.

Lessons for the EEA for integrated assessment development with regard to linkages between air pollution and climate change
This publication is part of the effort to assess potential ancillary effects. It is important to follow the efforts to find suitable costing methods to quantify these effects as they could further help to understand how ancillary effects can influence choices about the stringency and types of GHG mitigation policies that may be adopted.

Availability
Papers and presentations of the workshop are available at http://www.oecd.org/env/cc

Publications
Pearce, D. (2000). *Policy frameworks for the ancillary benefits of climate change policies, ancillary benefits and costs of greenhouse gas mitigation*, Proceedings of an IPCC co-sponsored workshop, March 2000, OECD, Paris.

Annex 7: Workshop of the Task Force of Integrated Assessment Modelling (TFIAM) of UNECE on 'Linkages and synergies of regional and global emission control'

(This text is taken from the conclusions of the workshop on 'Linkages and synergies of regional and global emission control', 27–29 January 2003, EMEP Centre for Integrated Assessment Modelling, Laxenburg, Austria, as presented to the Task Force on Integrated Assessment Modelling at its 28th meeting on 7–9 May 2003 in Haarlem, the Netherlands).

Introduction

1. The workshop was attended by 75 experts from Austria, Belgium, Denmark, Finland, France, Germany, Italy, the Netherlands, Norway, Poland, Portugal, Sweden, Switzerland, the United Kingdom, the United States of America and the European Community, as well as the Coordination Centre for Effects (CCE), the UNECE secretariat, the World Health Organisation (European Centre for Environment and Health), the European Environment Agency, the European Community Joint Research Centre (Institute for Environment Sustainability), the European Chemical Industry Council (CEFIC), the Union of the Electricity Industry Eurelectric) and the World Conservation Union (IUCN).
2. The workshop was organised by the Task Force on Integrated Assessment Modelling and the EMEP Centre for Integrated Assessment Modelling (CIAM). It was supported by the Topic Centre on Air and Climate Change of the European Environment Agency (ETC-ACC).
3. The conclusions of the workshop and an informal report with extended abstracts will be presented to the Task Force on Integrated Assessment Modelling at its 28th meeting on 7–9 May 2003 in Haarlem (Netherlands). The presentations of the workshop can be found at: www.iiasa.ac.at/rains/meetings/AP&GHG-Jan2003/announcement.html.
4. Many of the traditional air pollutants and greenhouse gases have common sources, their emissions interact in the atmosphere, and separately or jointly they cause a variety of environmental effects on the local, regional and global scales. Thus, emission control strategies that simultaneously address air pollutants and greenhouse gases could be beneficial on all scales. The executive body at its 20th session noted with interest the plans of the Task Force on Integrated Assessment Modelling to examine the links and synergies between regional air pollution and climate change, recognising the importance of these links. Welcoming the work initiated to explore such links, it requested EMEP to address all relevant aspects of these links in its future work.
5. Through a series of brief overview presentations, the workshop reviewed from the air pollution perspective the scientific knowledge on the physical linkages between the control of air pollution and greenhouse gases (atmospheric chemistry, impacts, emission control options) and examined possible synergies addressing sectoral emission control options, multi-pollutant strategies and economic instruments. The objective was to identify future directions for integrated assessment modelling under the Convention on Long-Range Transboundary Air Pollution so that the policy-relevant linkages and synergies could be

systematically explored. While the focus of the workshop was on the linkages and synergies from a scientific perspective, the discussion also covered aspects relevant for policy-making in developing air pollution control strategies.

6. The workshop recognised that the numerous linkages and synergies provide a strong argument for developing programmes that address air pollution and climate change simultaneously or at least in parallel. The first step is to encourage the development of analytical tools to be able to analyse such a comprehensive programme. At the same time, policy analyses of air pollution control should consider the air pollution effects on climate change, and vice versa.

I. The physical linkages

A. Atmospheric chemistry

7. The impact of gases and aerosols on climate is usefully expressed as radiative forcing. Radiative forcing is a measure (expressed in watts per square metre) to estimate, to a first order, the relative impact on climate due to radiatively induced perturbations. The concept assumes a general relationship between global mean forcing and the global mean equivalent temperature response. While the concept of radiative forcing is useful, it does not encompass all the important impacts of changing atmospheric composition on climate, especially at the regional scale and in relation to variables other than surface temperature, such as precipitation.
8. Radiative forcings of the six long-lived trace gases covered by UNFCCC (greenhouse gases — GHGs) have received much attention. Also some short-lived air pollutants, notably ozone and fine particles, exert climate impacts. While GHGs are uniformly distributed at the global level, for ozone and fine particles there are some high concentration regions, which are not necessarily close to the sources of the precursor emissions. In some parts of the world, significant reductions of traditional air pollutants have been achieved, which is not the case for GHGs.
9. The radiative forcings of ozone and fine particles are different, both in space and time, from those of the greenhouse gases. Model simulations have shown that short-lived air pollutants can lead to significant regional climate perturbations, especially affecting seasonal precipitation patterns, which may contribute regionally to floods and droughts. Climate control strategies are usually examined at long time horizons, sometimes up to 100 years or more. Air pollutants may affect climate much more quickly and such impacts can also be addressed by policy on shorter time scales.
10. Particulate matter (PM) is a diverse group of substances with different physical-chemical properties and different climate impacts. The effects of aerosol forcing on precipitation patterns may be very important. Some of these effects are very uncertain, in particular the indirect effects of aerosols (via cloud coverage and cloud optical properties).
11. Sulphate, nitrate and organic carbon particles in the atmosphere affect the climate in the opposite direction than GHGs, i.e. they tend to have a cooling effect and can lead to reduced precipitation. Other carbonaceous particles (black carbon, soot) are thought to have a positive forcing on the climate, although the magnitude of this effect is uncertain. Hence, while the reduction of black carbon will be beneficial in reducing climate change, this is not the case for the reduction of other aerosols.
12. In Europe, black carbon constitutes only a small share (10–15 %) of total $PM_{2.5}$ emissions. Emission reductions necessary to reduce health effects of PM will have to reduce not only black carbon but also other components of PM. The net effect of a PM reduction strategy to cut health effects substantially may therefore

be an increase in radiative forcing. To reach any given climate targets, such PM reductions will have to be compensated by further measures on other climate gases. At the same time, strategies to reduce PM should be developed so that they place more emphasis on bringing down black carbon emissions than measures do at present. Such strategies will target diesel emissions, biomass burning as well as residential combustion of solid fuels and should place greater emphasis on non-road mobile sources. Preliminary estimates suggest that especially ships contribute increasingly to black carbon concentrations.

13. Tropospheric ozone has a relatively strong radiative forcing and therefore measures to reduce it will be beneficial in reducing climate change. The influence of tropospheric ozone on climate change is better understood than the role of aerosols. Regional ozone levels build up on top of a considerable hemispheric background ozone baseline. Hemispheric ozone baseline concentrations have been increasing by about 0.5 ppb per year and are projected, in some scenarios, to increase in the future. One of the important factors contributing to this increase is the rise in global methane emissions.
14. Methane is important both in building up the hemispheric background of ozone and in enhancing intercontinental ozone transport. Methane also exerts direct radiative forcing and is a GHG with a relatively short atmospheric lifetime (12 years). A methane emission reduction strategy will therefore be very effective in reducing both climate change and ozone concentrations. While natural methane emissions are important, the larger (and growing) share is anthropogenic. Preliminary results of work on introducing methane into the RAINS model 1 show that there is significant potential for controlling methane emissions.
15. Climate change is likely to affect regional circulation and wind patterns. This may affect the accuracy of source-receptor relationships developed on the basis of historic meteorological data. For a relatively short time horizon, such as up to 2020, this effect is not likely to be important and it would be very difficult to quantify.

B. Environmental impacts

16. There are a number of linkages between climate change and air pollution effects, but they can go in different directions and are not yet fully understood. Model results suggest, for example, that: (1) a temperature increase through climate change may reduce ecosystem sensitivity to acidification damage and tends to change deposition patterns so that there will generally be less critical load exceedance; (2) an increase in nitrogen deposition (through air pollution) may raise the ability of plants to store carbon diminishing radiative forcing; (3) many air pollutants tend to weaken plant growth thereby reducing carbon storage capacity; (4) both climate change and air pollution may adversely affect biodiversity.

II. Synergies of multi-objective strategies

17. Many measures to cut air pollution also benefit the climate through reduction of GHG emissions and vice versa. Understanding these synergies in emission controls and addressing local, regional and global objectives simultaneously, rather than separately, is needed to achieve overall cost-effectiveness. As marginal costs of further air pollution abatement measures tend to increase rapidly once a certain reduction level has been achieved, any potential for cost savings for strategies to reach air quality objectives must be explored. Synergies may free resources that

allow reaching more ambitious targets. Many of the driving forces underlying air pollution and climate change are identical: economic growth, consumption and production processes, and demography. A sustainable development strategy must address these issues in an integrated manner.

18. While there are many synergies in emission control for air pollution and climate change, there are also trade-offs. Some air pollution abatement measures tend to increase energy consumption thereby causing increases in CO_2 emissions. Nitrous oxide (N_2O) emissions may increase through nitrogen oxide (NO_x) reducing catalytic converters.
19. At the global level, a stabilisation of GHG emissions will lead to a reduction of SO_2 emissions. The extent of this depends on the type of CO_2 measures applied, on SO_2 control measures in place, and on the energy scenario assumed. Single sector measures, may lead to an increase in SO_2 or PM emissions. For instance, moving out of coal into renewables in the electricity sector in Asia may lead to higher use of coal in some other sectors increasing SO_2/PM emissions. Also a regional strategy to enhance natural gas infrastructure may increase SO_2 emissions regionally, while reducing global CO_2, due to the risk of switching to coal in gas-exporting countries. The use of biomass (e.g. fuel wood) has been promoted in the EU. While reducing CO_2, this has tended to increase PM, CO and VOC emissions in the domestic sector. In the industry and power sector this does not apply, as such emissions can be effectively controlled.
20. The regulatory structure can facilitate multi-emission strategies in the power sector. Multi-pollutant approaches can provide more certainty and reduce costs. For instance, a power company may decide to apply different emission control measures (e.g. a switch in fuel or process instead of some end-of-pipe technology) when addressing multiple substances simultaneously than it would if it addressed emitted substances sequentially.
21. IIASA calculated that the costs of reaching the Gothenburg Protocol emission ceilings could be reduced more than EUR 5 billion per year by implementing the changes in the energy system necessary to achieve the reductions required by the Kyoto Protocol domestically (i.e. without international CO_2 emissions trading).
22. For China, it has been estimated that the cost of cutting CO_2 emissions by 5–10 % would be offset by the benefits resulting from reduced health effects through air pollution. Including the effects on crop-yield increase (via reduced NO_x) increases the 'no-regret' level of CO_2 emission cuts to 15–20 %.
23. Synergies and trade-offs are also present in agriculture. For instance, certain ammonia abatement measures related to manure application can increase emissions of nitrous oxide (N_2O), which is an important GHG also covered by the Kyoto Protocol. There are, however, abatement techniques that can reduce this negative impact. Scenario analysis has shown that it is possible to cut ammonia emissions significantly and at the same time reduce nitrous oxide and methane emissions. An integrated approach tends to achieve such synergies at much lower cost.
24. Change in agricultural policy may be an efficient structural measure to reduce environmental effects of agriculture, although not all structural changes will reduce ammonia emission. Air pollution may not be a major driving force to bring about such structural change, but knowledge of the air pollution and climate impacts of agriculture has influenced the political process. For integrated assessment modelling, a clear political signal on feasible policy options is important to determine the boundaries of the modelling work.

III. Strategic aspects: The way forward

A. Emission ceilings and carbon trading

25. GHG emissions trading systems can have significant effects on the distribution and levels of air pollution emissions. While trading reduces the overall costs of emission reductions for given targets, it tends to shift the significant co-benefits of abatement measures from western Europe to other regions. Unconstrained trading of GHG may not be cost-effective, if air quality objectives are taken into account. In some countries, GHG trading may not make sense, as the structural measures for CO_2 abatement may be necessary to achieve the emission reduction (e.g. for NO_x) required to meet the national emission ceilings.
26. In practice, the effects of carbon trading are uncertain. Regional air pollution studies should therefore use different assumptions about the baseline energy consumption (as affected by the Kyoto Protocol), including different assumptions on scope and order of magnitude of international carbon trading and, possibly, as an extreme case, a situation without the Kyoto Protocol.
27. In developing GHG emissions trading, the effects on regional air pollutants (NO_x, SO_2, PM) should be taken into account so as to give realistic estimates of the net cost and the net environmental impacts of trading.

B. Modelling linkages and synergies of regional and global strategies

28. A combined analysis of air pollution and climate change requires bridging different temporal (from a 10 to a 100 year perspective) and spatial (from local/urban to global) scales. To capture the feedbacks from climate change, air pollution modelling needs to incorporate sufficiently long time horizons in order to take account of the inertia in climate change and the time required for structural measures and technology development to take effect. At the same time, climate research should examine changes that may occur over the next 10–20 years.
29. The linkages between air pollution and climate change are manifold and not homogenous. Modelling such effects that go in different directions is possible, as long as they can be quantified. Including these effects in integrated assessment models allows determining strategies that minimise the cost of reaching a given set of objectives.
30. It may be challenging to bring together very different targets, such as health targets expressed in terms of years of lost life expectancy and targets related to climate change, but integrated assessment modelling can assist the policy process in this task. This has already been done in a multi-effect framework before, using a gap closure approach, and such an approach could be extended to link to climate change targets.
31. By incorporating the most important linkages and synergies with climate change, air pollution-focused integrated assessment modelling will have to be extended to incorporate some aspects of sustainable development strategies, in particular to model structural change. This might, for instance, require general equilibrium macroeconomic modelling. The Task Force on Integrated Assessment Modelling may have to discuss whether new criteria, possibly going beyond a simple cost-effectiveness approach, should be pursued and how to address equity considerations.
32. In further developing integrated assessment modelling to cover these issues, it is important not to lose focus. Rather than incorporating all into one unmanageable modelling framework, other ways of linking results should be explored. Growing complexity of models poses challenges for quality assurance and quality control (QA/QC). This will require an active approach to uncertainty analysis and management. As the level of

complexity makes the use of model optimisation more difficult, an emphasis should be to find robust results and to communicate the results.

33. CIAM should conduct this work closely, following discussions of the IPCC to make appropriate assumptions about the parts of the world and the issues not covered by the RAINS model. At the same time, efforts should be made to inform the IPCC about EMEP's work to encourage global modelling work to adequately cover air pollution related issues.

C. The way forward

34. Focusing on the abatement synergies, CIAM will develop cost curves for the six GHGs (CO_2, CH_4, N_2O, PFC, HFC, SF_6) included in the Kyoto Protocol and incorporate them into the RAINS model. As for the air pollutants included in RAINS, this will be done on a country-by-country basis for the EMEP region with a time horizon of 2030. In parallel, CIAM will develop methodologies for introducing structural change into the model and for addressing the physical linkages. This work will be completed in 2004.
35. The objective of the work on linkages and synergies between regional air pollution and climate change should be to provide policy-makers with the information necessary to make the right choices: (1) to reduce pollutants maximising the positive linkages and minimising the negative ones; and (2) taking those measures that are the most cost-effective in view of the objectives in both policy areas.
36. At this stage, work should first concentrate on the scientific issues of linkages before addressing the policy process. This will be to the benefit of both policy processes. The Gothenburg Protocol review can take some of the abatement synergies into account, while just addressing the air pollutants responsible for acidification, eutrophication, ground-level ozone and PM pollution. The direct benefits of climate change policies tend to be far away. Highlighting the additional benefits of certain climate mitigation measures on air pollution will make such policies more attractive in bringing the benefits closer both in space (e.g. to the local scale) and in time.
37. Contacts between experts in the fields of air pollution and climate change should be enhanced. The approach of the EEA in linking climate change and air pollution in one framework (the European Topic Centre on Air and Climate Change) is a good example. There is a need for further workshops like this one to bring the different scientific communities closer together. Also at the policy level, closer contacts between those responsible for air pollution and climate change, both at the national and international level, would be beneficial. In this connection, it is interesting to note that the Directorate-General for the Environment of the European Commission decided to bring its air quality and climate change units together under the same directorate from March 2003 onwards to further enhance policy coherence.
38. In pursuing the work, EMEP should cooperate with the IPCC. The linkages and synergies between air pollution and climate change should be examined both from the air pollution perspective and from the climate change perspective. While EMEP should cover the work from the air pollution side based on relevant findings of the IPCC, the IPCC could address the relevant scientific question from the climate change perspective. The secretariat and national experts, including the national focal points for integrated assessment modelling, should establish the necessary contacts so that relevant IPCC bodies are informed about this suggestion prior to deciding on the topics to be covered by the fourth assessment report.

D. Further research

39. Further research on how air pollutants (ozone and PM) affect the climate is important in view of the significant uncertainties. More research is especially needed to get a better understanding of how the different components of PM impact climate, and this is also important for their effects on human health. Part of this research must aim at improving the observational basis. Measurements are also required to improve emission inventories.
40. The relevant aspects of the effects of air pollution on the regional climate should be further examined and this should be considered in connection with the work on hemispheric air pollution. As far as possible, this should also involve scientists from Asia.
41. Concerning the options to reduce emissions (of air pollutants and GHG), the workshop presentations and discussions focused on structural measures and energy saving. Further work should also explore technical measures for multi-pollutant abatement.
42. The IPCC has established a Task Group on Scenarios for Climate and Impact Assessment that operates a Data Distribution Centre (website: http://ipcc-ddc.cru.uea.ac.uk/). The DDC provides a broad set of climatic, socioeconomic and other environmental data that are consistent with published IPCC scenarios and are intended for use in assessing the impacts of climate change. These data may be useful to air pollution modellers.

Annex 8: Overview of a selected number of workshops addressing the interaction of climate change and air quality

2000, March	Workshop on 'Ancillary benefits and costs of greenhouse gas mitigation', OECD, IPCC, RFF, CI, WRI workshop, Washington, D.C., USA.
2001, September	International expert workshop on the 'Analysis of the economic and public health impacts of air pollution': Garmisch-Partenkirchen, Germany, 6 September 2001. Organised by the US Environmental Protection Agency, World Bank, US Agency for International Development, World Health Organisation, Organisation for Environmental Cooperation and Development, United Nations Environmental Programme, Health Effects Institute, and National Renewable Energy Laboratory. *Summary results* Forty-nine experts from 18 industrial and developing countries met to discuss the economic and public health impacts of air pollution, particularly with respect to assessing the public health benefits from technologies and policies that reduce greenhouse gas (GHG) emissions. Such measures would provide immediate public health benefits, such as reduced premature mortality and chronic morbidity, through improved local air quality. These mitigation strategies also allow long-term goals, for example reducing the build-up of GHG emissions.
2002, May	'Air pollution as a climate forcing', APCF workshop, 29 April–3 May, Honolulu, Hawaii. The workshop, held at the East-West Centre of the University of Hawaii, was sponsored by the National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, National Science Foundation, Hewlett Foundation, California Air Resources Board, California Energy Commission, International Pacific Research Centre, and East-West Centre. *Summary results* The workshop brought together the topics of air quality and climate change. The chosen scope emphasised the impact of air quality on climate change, and on air pollutants that cause substantial climate forcing. The aim was the description of what we know and what we need to know about the commonalties between the two phenomena and the communication of this status of understanding among the participants.
2002, September	ESF exploratory workshop on 'Atmospheric pollution effects on local, regional and global scales — An integrated approach': Oslo, Norway, 26 September 2002. The workshop was sponsored by the European Science Foundation, Research Council of Norway, and NORAD (the Norwegian Agency for Development

Cooperation), and was arranged by Cicero and the Department of Chemistry, University of Oslo.

Summary results
An integrated approach to mitigating climate change and local and regional environmental problems may have important advantages, but it also poses methodological challenges. At this workshop, 25 scientists from China, USA, Chile and several European countries discussed relevant issues.

2003, January **Workshop of the Task Force on Integrated Assessment Modelling (TFIAM) of UNECE on 'Linkages and synergies of regional and global emission control', 27–29 January 2003, at IIASA, Laxenburg**

Annex 9: Internet addresses containing information on the linkage of Climate change and air quality

http://gssd.mit.edu/Gssd/startgssd.nsf/startgssd Global system for sustainable development

http://icg.harvard.edu/~espp10/Readings Science, policy and environment

http://ucrevelle.ucsd.edu UC Revelle programme on climate science and policy

http://web.mit.edu/globalchange/www/structure.html MIT global change joint programme structure

http://www.airimpacts.org/ Health and economic impacts of air pollution

http://www.cgenv.com/Narsto/frame1new.html

http://www.csa.com/routenet/cnie/pop/air/airbib.html Air, climate and atmospheric change bibliography

http://www.giss.nasa.gov/meetings/pollution02 NASA Goddard Institute: Air pollution as a climate forcing

http://www.igbp.kva.se/cgi-bin/php/first_page.php IGBP — International geosphere–biosphere programme

http://www.jhu.edu/~climate/index.html Climate change and human health integrated assessment web

http://www.lib.kth.se/~lg/climate.htm Climate

http://www.ornl.gov/ORNL/Energy_Eff Oak Ridge National Laboratory: Energy efficiency and renewable energy

http://www.sei.se/climate/activities.html Stockholm Environment Institute (SEI) — Climate and energy programme

http://www.tellus.org/seib/publications Tellus Institute online publications

http://www.tyndall.ac.uk/publications/publications.shtml Tyndall Centre

http://www.4cleanair.org

http://www.oecd.org/env/cc Organisation for Economic Cooperation and Development, Paris

http://www.rff.org Resources for the Future, Washington, D.C.

http://www.epa.gov Environmental Protection Agency, USA

http://www.esf.org European Science Foundation

http://ipcc-ddc.cru.uea.ac.uk/ The IPCC has established a Task Group on Scenarios for Climate and Impact Assessment led by Imperial College, which has established a data distribution centre

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