2 Air

Increasing energy consumption and society's emissions of greenhouse gasses will inevitably influence global climate in the twentyfirst century. Air pollution has otherwise declined substantially in recent decades. Ambient air quality in cities and towns has generally improved, and sulphur pollution has been reduced considerably. An exception is the health risk associated with increased particulate matter pollution from the growing vehicular transport.

Photo: CDanmark

2.1 Introduction

Air pollution as an environmental problem

Pollution of the atmosphere is not a new phenomenon associated with the industrial era. Early written history and literature abound with references to poor air quality in towns. Nevertheless, this problem has increased both geographically and temporally as the global population has grown and industrialization has advanced. In addition, the development and growth of transport and industry have added new pollutants.

It is well known that human activities substantially influence ambient air quality in urban areas and have had harmful effects there on people, animals, plants, buildings and materials. Particulate matter pollution in recent years has caused special concern because of the harmful health effects associated with small particles in particular.

Air pollution is not merely a local problem. The wind can transport harmful substances over long distances. Much of the pollution in Denmark originates abroad – from sources as far away as several thousand kilometres (*Section 2.4*). At the regional level, air pollution results in negative effects such as the acidification of forest ecosystems, lakes and watercourses and eutrophication of the sea. Ammonia pollution, which mostly originates from agricultural activity, is a growing problem not only for the aquatic environment but also for several types of vulnerable terrestrial ecosystems.

Human activities have gradually reached a scale at which emissions to the atmosphere change its global composition – not basic components, but the concentrations of numerous important trace substances. This results in two problems:

- Depletion of the stratospheric ozone layer caused by numerous substances that are mostly produced industrially (such as chlorofluorocarbons (CFCs) and related substances)
- Augmentation of the natural greenhouse effect – which is decisive for the heat balance of the Earth and its atmosphere and thereby for the global climate – due to the emission of greenhouse gasses, in particular carbon dioxide (CO_2), methane and nitrous oxide.

Both problems involve completely nontoxic substances that cause more indirect environmental effects than the "classical" types of air pollution.

Depletion of the stratospheric ozone layer (*Section 2.5*) will increase the level of ultraviolet radiation at the surface of the Earth and will thereby cause numerous harmful effects on nature and human health. The effects will not be uniformly distributed, but they will be negative everywhere. The main cause – the use of CFCs and similar substances – has been identified. The use of these substances can be phased out, and in many cases has been initiated pursuant to international agreements.

The increase in the greenhouse effect and the resulting climate change (*Section 2.6*) is a far more controversial problem. Even though scientific consensus on the causal mechanisms has gradually been achieved, the magnitude and distribution of the effects have not yet been determined. The changes will result in both winners and losers, and combating the greenhouse effect requires global restructuring in both the energy and food sectors. This must be accomplished at a time when the world population continues to rise and the developing countries attain a higher material standard of living. Despite international efforts to limit emissions of greenhouse gasses and expected trends towards more sustainable technologies, it must therefore be considered extremely probable that a certain degree of climate change is unavoidable.

The overall aim is still to brake this trend, but preparation for inevitable changes is required. These two global challenges are linked both scientifically and societally, as well as to the following challenges related to air pollution:

- Several substances can both deplete the ozone layer and enhance the greenhouse effect
- Depletion of the ozone layer can counteract global warming; conversely, global warming can influence ozone depletion
- Ozone pollution of the troposphere (the lowest part of the atmosphere) increases the greenhouse effect, whereas sulphur pollution counteracts global warming.

The various factors influencing the environment thus interact mutually. In many cases they will probably reinforce one another, while in other cases they will counteract one another.

Photo: Highlight

2.2 Air pollution – sources and emissions

The effects of pollutants in the atmosphere do not depend on whether the emissions are anthropogenic or natural. While it would obviously seem to be easier to regulate anthropogenic emissions, there is no clear distinction between anthropogenic emissions and natural emissions. For example, conifer forests and other types of vegetation emit volatile organic compounds (isoprenes and terpenes), and bogs and other wetlands emit methane. The emission of these substances therefore depends on the pattern of land use. Thus, a large proportion (about 30%) of the total emissions of hydrocarbons in Europe is estimated to originate from forests and agriculture. This has an important influence on the creation of photochemical air pollution.

Anthropogenic emissions

The main source of anthropogenic air pollution is the use of fossil fuels: coal, oil and natural gas and derivative products. Combustion of fossil fuels creates various substances; some are direct combustion products and others arise from impurities in the fuel. The dominant pollutants from transport include nitrogen oxides (NO_x), various volatile organic compounds (VOCs), carbon monoxide (CO) and particulate matter. Industry emits the same substances but the composition is often considerably different than transport emissions, typically including more hydrocarbons. Emissions from such sources as Denmark's coal-fired power stations include a certain amount of sulphur dioxide (SO_2), although various measures have reduced this substantially. Livestock farming emits considerable ammonia (NH_3). In addition, households use substantial amounts of VOCs, such as those contained in various solvents, paint, varnish and other products. Examples of VOCs include ethylene, propylene, acetylene, benzene and toluene, which have useful properties as solvents for lipids and glue.

Inventories and uncertainty

Determining the precise emissions of air pollutants is difficult because the sources are so diverse and multitudinous. For example, the pollutants emitted by a motor vehicle depend on the type, age, calibration of the engine, whether it is fitted with a catalytic converter, and the ambient air temperature. In addition, the pattern of driving influences emissions – both the type of trip and the temperament of the driver. Special measurement methods can be used to directly measure emissions from a specific source, such as a car or a smokestack. The number of vehicles on the road can also be counted directly. Nevertheless, emissions are usually inventoried by using emission factors: experimentally determined mean values for emission as a function of fuel consumption or the magnitude of a specific activity.

Photo: NERI/Jes Fenger

National air emission inventories

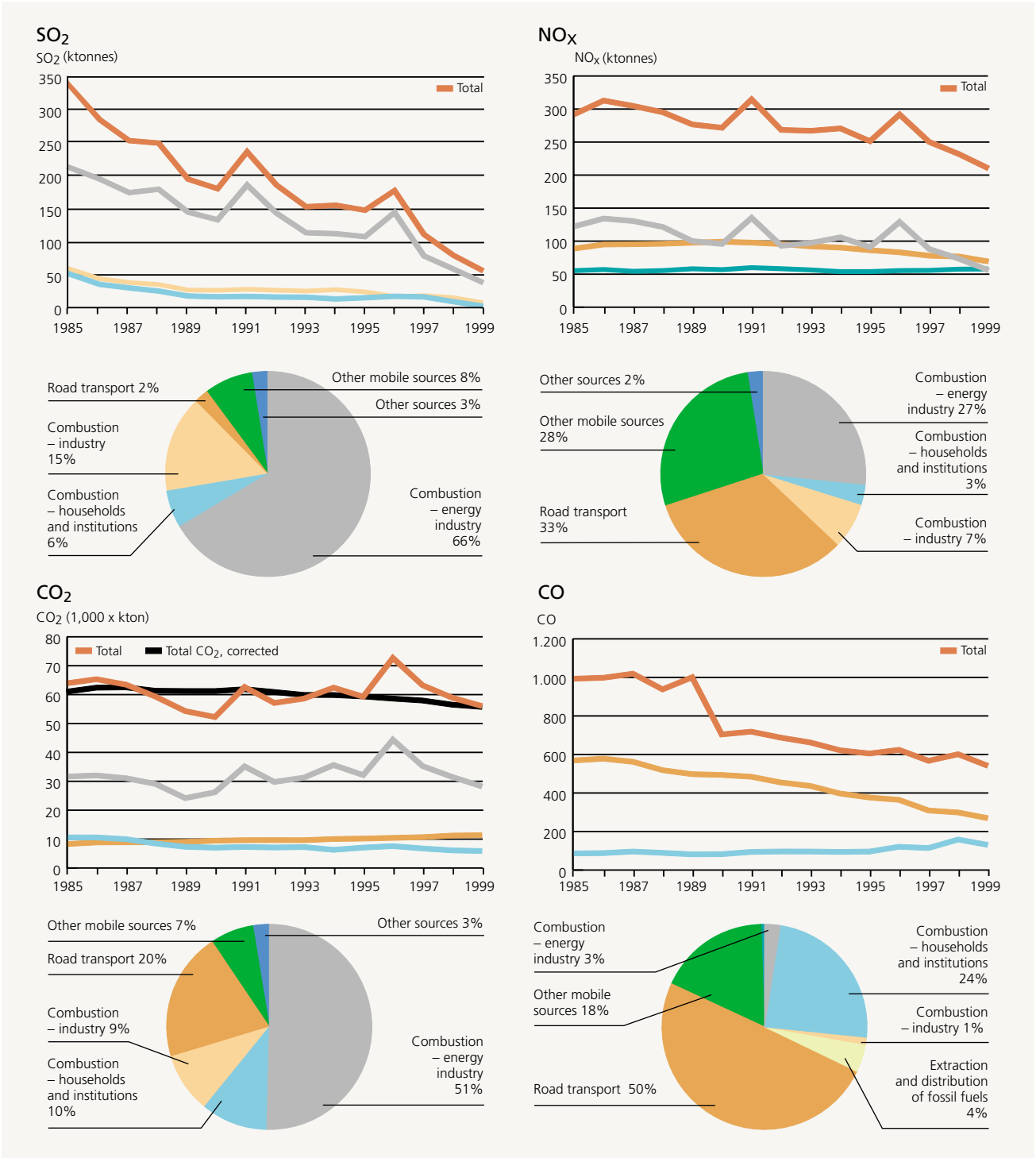
Each European country is required to prepare detailed national air emission inventories.

Figure 2.2.1
Development in Danish emissions of the main air pollutants over the period 1985–99 and apportioned by sector for 1999.
(Source: Illerup et al., 2001).

The typical result is one total figure for the annual emissions of each substance for each country. Some countries, however, present the figure in a grid that has a maximum resolution (quadrant size) of 50 km by 50 km. This is used to determine the long-range transport of air pollutants, but this is too imprecise for calculating how the local levels vary seasonally and diurnally, and what types of sources lead to the various types of emissions. This requires detailed inventories.

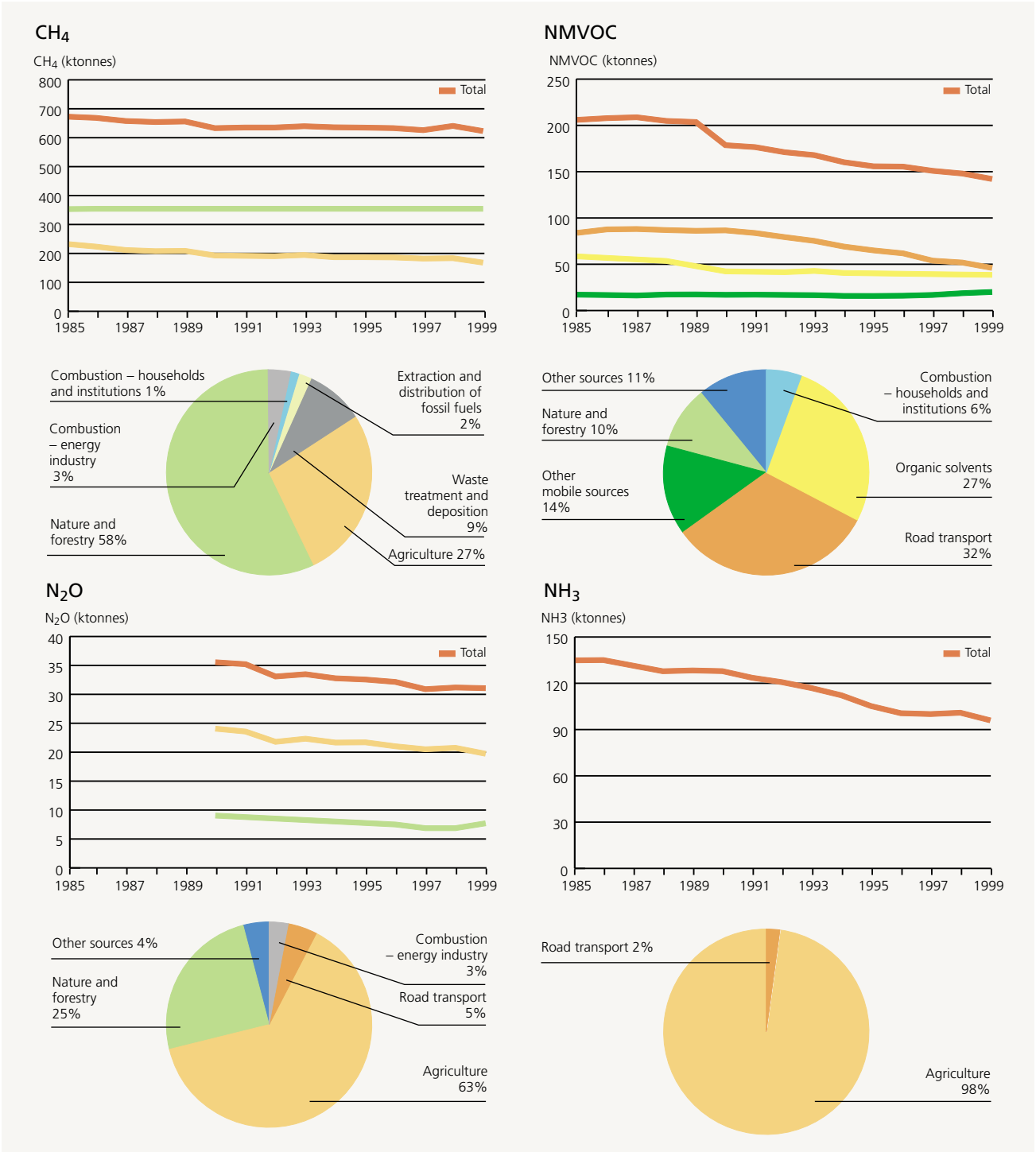
Trends in Denmark's emissions

Denmark's emissions of the most important types of air pollutants are inventoried according to sector and over time (*Figure 2.2.1*).



SO_2

Nearly all the SO_2 emissions result from combustion of fossil fuels – mostly coal and oil – at power stations and combined heat and power stations. Emissions declined considerably throughout the 1980s and 1990s owing to the use of fuels with a lower sulphur content and increasing use of flue gas desulphurization installations at the larger stations. SO_2 emissions declined by 27% from 1998 to 1999 due to less use of coal and more use of natural gas and renewable energy. Another reason for the decline was the continuing construction of flue gas desulphurization installations. The relatively large interannual variation in emissions resulted from the sale of electricity across national borders, and the high levels of emissions in 1991 and 1996 resulted from substantial export of electricity.



NO_x

Road transport and other mobile sources account for about half of Denmark's NO_x emissions. Another major source is power stations. Total emissions of NO_x have declined in recent years; similar to SO_2, emissions of NO_x declined substantially from 1998 to 1999. The reason is that emissions from both power stations and road transport declined. Reduced export of electricity and reduced use of coal caused power stations to emit 24% less NO_x. Although road transport has increased, emissions from this source have declined since 1990 in connection with the introduction of catalytic converters on all new cars in Denmark.

CO_2

CO_2 emissions mostly originate from the combustion of coal, oil and natural gas at power stations and in housing and industry. Denmark's total annual emissions of CO_2 have varied at a figure of around 60 million tonnes since 1985, but have varied by up to 15 million tonnes as a result of net imports or exports of electricity. The emissions resulting solely from domestic consumption have been declining steadily since the late 1980s (*see Section 1.3.1*). Current CO_2 emissions have declined by 5% from 1998 to 1999. The main reason is reduced export of electricity and higher ambient temperatures in 1999 than in 1998. Another reason for reduced emissions is the pattern of fuel use, shifting from coal to natural gas and renewable energy. Most CO_2 emissions now result from combustion of oil because the use of coal has declined in recent years.

CO

Although all new petrol cars in Denmark have been equipped with catalytic converters since 1990, road traffic is still the dominant source of CO. Nevertheless, similar to NO_x emissions, CO emissions declined substantially from 1998 to 1999, as an ever-increasing proportion of cars have catalytic converters. Other mobile sources and nonindustrial waste-incineration installations also contribute significantly to total emissions.

CH_4

There are two major sources of methane (CH_4) emissions: nature and agriculture. The natural sources produce more than half the total emissions, and these arise mostly from anaerobic decomposition of organic matter. Agricultural emissions result from the formation of methane in the digestive systems of livestock and the use of manure.

Non-methane VOCs

NMVOCs are emitted by many sources – anthropogenic and natural – that differ considerably and can be classified into two main types: incomplete combustion and evaporation. Incomplete combustion in road traffic and other mobile sources, such as sea vessels and off-road machinery, are the main sources of NMVOCs. Road traffic is still the largest source, although emissions have declined since catalytic converters were installed on all new petrol cars starting in 1990. Important sources of emissions from evaporation include terpenes and other VOCs from conifer forests and emissions from the use of organic solvents in industry and households.

N_2O

Agriculture is by far the most important source of nitrous oxide (N_2O), since it can be created in the soil by bacteria converting nitrogen applied as commercial fertilizer and manure. Other important sources include run-off water and coastal water bodies in which this process of bacterial conversion of nitrogen also occurs. Most of this nitrogen originates from the application of fertilizer in agriculture.

NH_3

Agriculture accounts for nearly all atmospheric emissions of ammonia (NH_3). Transport accounts for only 2%; the proportion is increasing because the use of catalytic converters is increasing, whereas the proportion caused by agriculture is decreasing.

Most agricultural NH_3 emissions derive from manure (76%). Other important sources include commercial fertilizer (7%), crops (15%) and ammonia treatment of straw (2%). Application of sewage sludge to fields also emits NH_3, but this is a minimal proportion of total emission (<1%).

Table 2.2.1
Danish emissions of heavy metals in 1990 and 1999.
(Source: Illerup et al., 2001).

	Arsenic	Cadmium	Chromium	Copper	Mercury	Nickel	Lead	Selenium	Zinc
	1,447	1,125	6,211	10,036	3,171	26,474	126,788	4,236	34,569
			2,650	9,609	1,976	15,200	7,337	3,514	22,887
Percent reduction									

Heavy metals

The most important sources of heavy metals emitted to ambient air are the combustion of fossil fuels and waste incineration. Although fuel consumption increased from 1990 to 1998, heavy metal emissions declined considerably (*Table 2.2.1*). The magnitude of the reduction ranges from 4% for copper to 94% for lead. The reduced emissions largely result from increased flue gas abatement in power stations and combined heat and power stations, including waste incineration plants. The main reason for the decline in lead emissions is the introduction of lead-free petrol, however. The reduced emissions of heavy metals in the last decade led to a parallel decline in the deposition of heavy metals from the air and in the concentration of heavy metals in ambient air (*see Section 2.4, Figure 2.4.6*).

Acidifying gasses

The emissions of acidifying gasses can be converted to acid equivalents to compare the potential acidifying effects of various substances (*Figure 2.2.2*). The greatest acidifying factor in Denmark is nitrogen from the ammonia emitted by agricultural activity. The emissions of all acidifying gasses have declined since 1990. The emissions of SO_2 have declined especially sharply, and the proportion of acidifying gasses accounted for by ammonia has increased from 39% to 47%.

Greenhouse gasses

CO_2 is the most important greenhouse gas emitted in Denmark followed by CH_4 and N_2O, based on the distribution by type of anthropogenic emissions of greenhouse gasses converted to CO_2 equivalents (*Figure 2.2.3*). The other greenhouse gasses hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sodium hexafluoride (SF_6) together account for less than 1% of total emissions. In contrast to acidifying gasses, the reduction in greenhouse gas emission is much less prominent (*see Section 1.3.1*).

Figure 2.2.2
Danish emissions of acidifying gasses in 1990, 1995 and 1999 expressed in acid equivalents. (Source: Illerup et al., 2001).

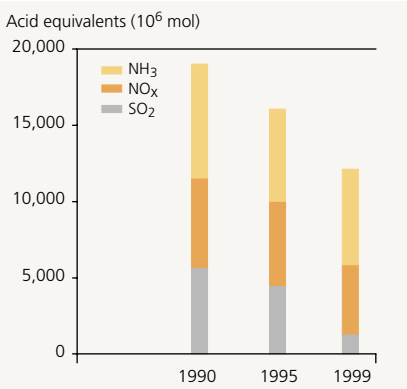


Figure 2.2.3
Danish greenhouse gas emissions in 1990, 1995 and 1999 expressed in CO_2 equivalents. The figures are based on the actual emissions, and are not corrected for electricity imports. (Source: Illerup et al., 2001).

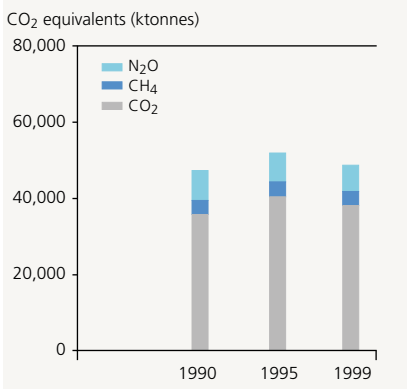


Table 2.2.2
Status for Danish emissions of substances for which reduction targets have been stipulated pursuant to international conventions on global and transboundary air pollution. (Source: Illerup et al., 2001).

Protocol	Substance	Baseline year	Measurement year	Reduction target (%)	Reduction in 1999 (%)
CLRTAP Sulphur Protocol	SO_2	1980	2000	80	88
CLRTAP NO_x Protocol	NO_x	1987	1994	0	11(1994) 31
CLRTAP VOC Protocol	VOC	1985	1999	30	35
UNFCCC Kyoto Protocol[1] (not yet ratified)	CO_2, CH_4, N_2O HFCs, PFCs, SF_6	**1990:** CO_2, N_2O, CH_4 **1995:** HFCs, PFCs, SF_6	2008-2012	21[2]	5

1) EU's burden sharing agreement on an EU reduction of 8% under the Kyoto Protocol.

2) Based on CO_2 emissions corrected for electricity imports in 1990.

Denmark's status in fulfilling targets

Transboundary air pollution is regulated by numerous international conventions under the auspices of the United Nations. The most important conventions are the Convention on Long-range Transboundary Air Pollution (CLRTAP) (*see Section 2.4*) and the United Nations Framework Convention on Climate Change (UNFCCC) under the Intergovernmental Panel on Climate Change (IPCC) (*see Sections 2.6 and 1.3.1*). *Table 2.2.2* summarizes the status for Denmark's emissions of substances targeted in accordance with these conventions.

The target in the Geneva Protocol on VOCs (signed in 1991) under the Convention on Long-range Transboundary Air Pollution was to reduce anthropogenic emissions by 30% from 1985 to 1999. Denmark fulfilled this target, as the reduction was 35%. In the Oslo Protocol on sulphur under the Convention, Denmark pledged to reduce SO_2 emissions by 80% from 1980 to 2000. This target has probably been achieved. The general target in the Sofia Protocol on NO_x was to stabilize NO_x emissions at the 1987 level in 1994. Denmark reduced emissions by 11% in that period and by 31% in 1999. In contrast, Denmark must take new initiatives if the target of the Kyoto Protocol to the Framework Convention on Climate Change is to be achieved (*Section 1.3.1*).

The most recent protocol under the Convention on Long-range Transboundary Air Pollution is the Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone. The purpose is to reduce the emissions of SO_2, NO_x, NMVOCs and NH_3 (*Table 2.2.3*). In contrast to the previous protocols, the individual countries have not been assigned reduction targets, but have been assigned emission ceilings with the aim of reducing the exceedance of ecosystem critical loads. The Protocol is currently being ratified in Denmark.

Substance	Emission reduction commitments in 2010 (tonnes)	Emissions in 1999 (tonnes)
	55,000	55,911
	127,000	210,171
	85,000	128,000
	69,000	74,751

* NH_3 emissions in the Gothenburg Protocol do not include emissions from ammonia treatment of straw and from crops

Table 2.2.3
Danish emission reduction commitments for SO_2, NO_x, NMVOC and NH_3 under the Gothenburg Protocol.
(Source: Illerup et al., 2001).

Photo: 2. maj/Sonja Iskov

2.3 Local effects of air pollution

2.3.1 Local trends in ambient air quality

Introduction

Human activity is known to substantially influence ambient air quality in urban areas and to have harmful effects on people, animals, plants, buildings and materials. Particulate matter (aerosol) pollution in particular has given rise to increasing concern in recent years. Nevertheless, air pollution in cities is not only created locally. Wind can transport harmful substances over long distances. Thus, much of the air pollution in Denmark comes from sources up to several thousand kilometres away. The combination of the air pollution transported long range and the local pollution determines the current ambient air quality.

The nationwide Danish Air Quality Monitoring Programme monitors the ambient air quality in Denmark's cities, including Copenhagen, Odense, Aalborg and Aarhus. The Programme also includes two background stations in rural districts: Keldsnor (on the island of Langeland) and Lille Valby (near Roskilde). The monitoring strategy chosen allows the pollution from vehicular transport to be differentiated from other sources of urban pollution and allows urban pollution to be distinguished from the natural background pollution and the air pollution transported long range. The Programme monitors the concentrations of the most important air pollutants: NO_x, SO_2, CO, ozone and particulates. These substances are discussed below, except particulates, which is discussed in detail in a theme section (*Section 2.3.2*).

Figure 2.3.1
Measuring station on Jagtvej in Copenhagen. The station is part of the nationwide monitoring programme LMP III. (Source: Palmgren et al., 1997).

Photo: NERI/Jes Fenger

Trends in ambient air quality

Measurements in Denmark's urban areas have shown that urban ambient air quality has generally improved in recent years. Lead has largely vanished as an air pollutant after lead-free petrol was introduced, and the measured concentration is less than 5% of the newest EU limit values (*Table 2.3.2*).

SO_2 pollution has been drastically reduced as a result of the general efforts to reduce pollution, including cleaner fuels, natural gas, flue gas desulphurization and conversion from individual household furnaces to district heating. The SO_2 concentrations are also far below the newest EU limit values (*Table 2.3.2*). The concentrations of CO and hydrocarbons, including benzene, have also declined, especially because of the catalytic converters on petrol-driven vehicles.

Nitrogen oxides and ozone

The total emissions of nitrogen oxides ($NO + NO_2$) have declined, as have the concentrations of NO. The decline in concentrations of NO_2 – the nitrogen oxide most harmful to health – has been modest, however (*Figure 2.3.2*). The reason is that cars directly emit very little NO_2. Most NO_2 is created in reactions between NO and ozone, and the concentrations of these gasses determine how much NO_2 is formed. Rural districts have virtually no NO as it has been converted to NO_2 as it disperses from urban areas. The concentration of NO_2 is similar for Aalborg and Odense but higher for Copenhagen, probably because direct emissions of NO_2 are higher in Copenhagen. The concentrations of NO are similar in Aalborg and Copenhagen, but lower in Odense.

Danish towns do not generally have excessive ground-level ozone concentrations because ozone formation is modest under the conditions prevailing in Denmark (*Table 2.3.1*). The ozone concentration has been nearly constant in Denmark over the past decade. Many areas of southern and central Europe experience episodes with very high concentrations of ground-level ozone in and near large cities. Such ozone episodes can occur in Denmark when ozone formed in central Europe is transported to Denmark.

The ground-level ozone concentration in cities and towns is generally lower than that in rural districts because ozone reacts with NO and forms NO_2. The sum of NO_2 and ozone will therefore be nearly constant in the transition between rural areas and urban areas. Only the direct emissions of NO_2 (5–10% of NO_x) will result in a larger total of NO_2 and ozone in cities.

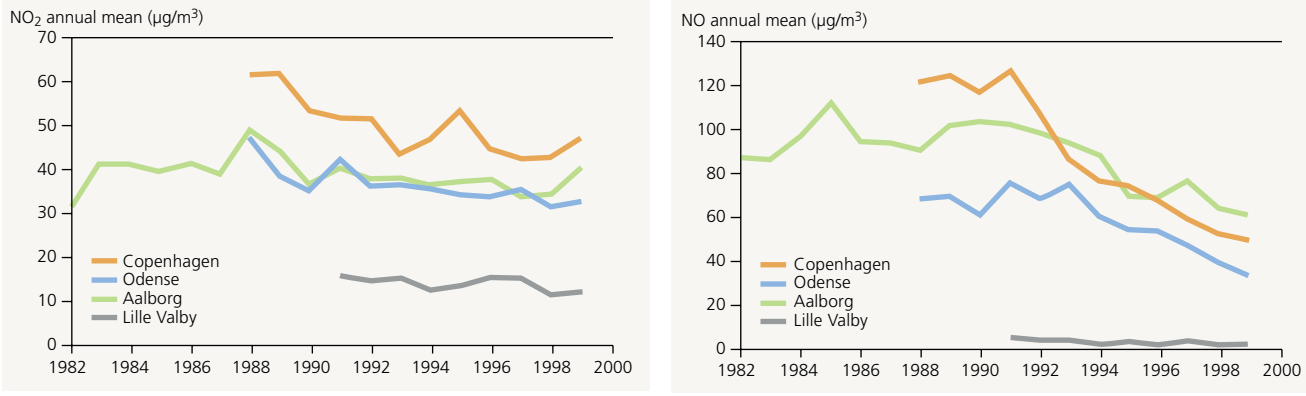


Figure 2.3.2

Concentration of nitrogen oxides in Danish towns and at a single rural measuring station over the period 1982–99.

(Source: Kemp and Palmgren, 2000).

Benzene

The concentration of benzene in air was very high in streets with considerable vehicular traffic until the mid-1990s; the streets with the most traffic and narrow streets in Denmark would not be able to comply with the newest EU limit values (*Table 2.3.2*). The source of benzene was gasoline vehicles, which emitted benzene in exhaust fumes and through evaporation from the petrol tank and engine. In the following years, oil companies with refining operations in Denmark reduced the concentration of benzene in petrol from 3–4% to 1% by 1998. From 1 January 2000, 1% is the maximum allowed in the entire EU. The gradual replacement and scrapping of cars has reduced emissions of benzene because new cars have a more tightly sealed fuel system, which reduces evaporation.

Benzene air pollution has thus declined drastically because the concentration in petrol has been reduced and because catalytic converters remove benzene. All gasoline cars registered for the first time in Denmark after October 1990 have catalytic converters. This comprises more than 60% of all the cars in Denmark, and the proportion is often even greater on streets with heavy traffic.

Limit values for ambient air quality

Limit values for ambient air quality have been in force in the EU since 1980. These have then been implemented in Denmark in the form of statutory orders. These limit values have hitherto been determined based on assessment of effects weighed up against technical, economic and political considerations.

The limit values are being revised, and new limit values will apply from 2005 or 2010 depending on the substance (*Table 2.3.2*). The revised limit values are based on the framework directive for ambient air quality assess-

Table 2.3.1

Annual mean and maximum ozone levels in 1999 compared with threshold values.

(Source: Ministry of the Environment, 1994, EEC, 1992).

	Average	Maximum 24 hrs	Maximum 8 hrs	Maximum 1 hr
Urban background level:				
• Odense	51	107	146	180
• Aalborg	51	98	125	142
Rural districts:				
• Lille Valby	59	118	174	188
• Keldsnor	66	113	130	154
Traffic:				
• Copenhagen	33	77	92	119
Threshold value	-	65	110	200
Average number of exceedances of the threshold values	-	100	10	0

Table 2.3.2

Limit values according to the daughter directives of the EU Framework Directive on Air Quality.

(Source: EC, 1996; 1999; 2000).

Substance	Limit value (µg/m³)	Sampling period (hrs)	Statistics	Protection of	Cut-off date
			18 times per yr	Man	
			Average, yr	Man	
			Average, yr	Vegetation	
			24 times per yr	Man	
			3 times per yr	Man	
			Average, yr and winter	Vegetation	
Particles			35 times per yr	Man	
			Average, yr	Man	
			7 times per yr	Man	
			Average, yr	Man	
Lead			Average, yr	Man	
Benzene			Average, yr	Man	
	10,000	8 hrs (sliding)	Maximum	Man	

ment and management adopted by the EU in 1996, which is to be completed with daughter directives for individual substances.

The limit values will now be established based on assessment of effects, primarily based on the recommendations of the World Health Organization (WHO). In addition to limit values, most of which will be stricter, the daughter directives will govern methods of measurement, publication of results and other requirements.

Daughter directives have been adopted for SO_2, NO_2, particulates (PM_{10}) and lead, as well as for benzene and CO (*Table 2.3.2*). Directives are being prepared for ozone, polycyclic aromatic hydrocarbons, mercury, nickel, cadmium and arsenic.

Assessment of ambient air quality

Box 2.3.1. Implementation of EU directives on ambient air quality.

Implementation of the EU directives on ambient air quality necessitates a preliminary assessment of the ambient air quality in Denmark with the aim of establishing a measuring programme. The principle is to identify the zones in which the limit values risk being exceeded and carry out a more thorough assessment of the ambient air quality in these zones. In accordance with this principle, one investigation in Denmark determined how the concentrations of pollutants in a street vary with the density of vehicular traffic and the width of the street. The concentrations of both NO_2 (*Figure 2.3.3*) and benzene (*Figure 2.3.4*) exceed the new EU limit values on the streets with the heaviest vehicular traffic and the narrowest streets. Nevertheless, the scenario modelling indicates that Copenhagen will be able to comply with the limit values in 2010 as required by the directives.

In addition to the preliminary assessment of pollution from vehicular transport, the pollution from point sources has also been assessed. The results show that the EU limit values are very likely to be complied with if the point sources of pollution comply with the air quality guidelines for Denmark issued by the Danish Environmental Protection Agency.

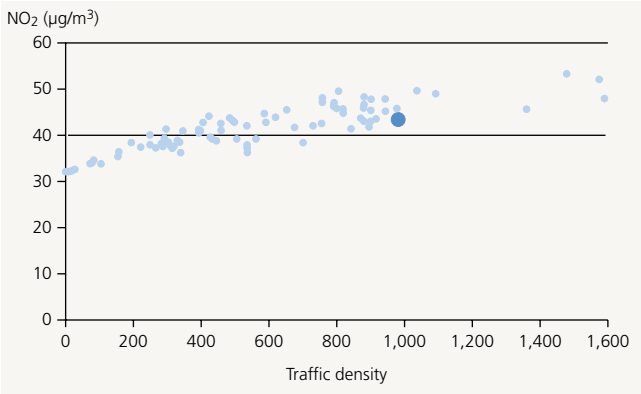


Figure 2.3.3
Model calculations of the annual mean NO_2 concentration in the air of 103 streets in Copenhagen in 2000. The abscissa indicates traffic density expressed as number of vehicles per day per metre of street width. The Jagtvej measuring station is indicated by a closed circle. The EU limit value is indicated by a horizontal line. (Source: Jensen et al., 2000).

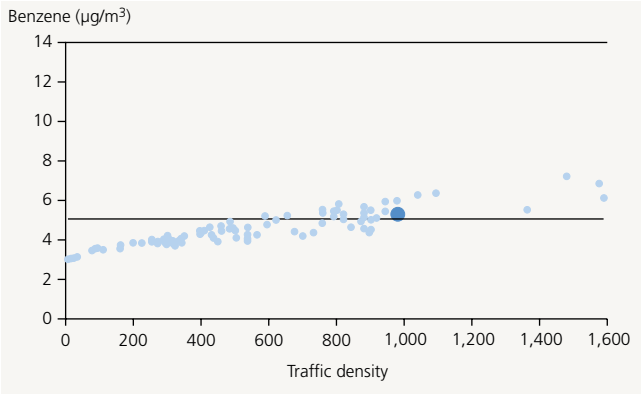


Figure 2.3.4
Model calculations of the annual mean benzene concentration in the air of 103 streets in Copenhagen in 2000. The abscissa indicates traffic density expressed as number of vehicles per day per metre of street width. The Jagtvej measuring station is indicated by a closed circle. The EU limit value is indicated by a horizontal line. (Source: Jensen et al., 2000).

Forecasting ambient air quality

Box 2.3.2
Forecasts of ambient air quality.

A modelling system enables the concentrations of pollutants to be predicted on a spatial scale as small as the individual street level. The forecasts are based on the weather forecast and on a set of physicochemical computer models for the dispersion and chemical conversion of air pollutants.

NERI's Web site (www.luft.dmu.dk) has a forecast for ambient air quality for a 3-day time horizon in specific regions of Denmark, above rooftop level in Copenhagen (urban background) and at street level in the traffic artery Jagtvej in Copenhagen. Further, the site provides forecasts for the concentrations of such air pollutants as ozone, NO_x, CO and benzene over the coming days on Jagtvej or in Denmark as a whole. The forecasts have been extended to include many other streets in Copenhagen and other large cities and towns in Denmark, and this has already been carried out for Aalborg. The forecasts are updated four times daily.

Only the concentrations of the pollutants NO_2, CO and ozone are included in the summary forecasts. However, all the forecast graphs with temporal trends (3 days) and the geographical distribution of air pollutants in Copenhagen and Denmark are available in detail on the site.

The system can be used to inform and, if necessary, warn the general public and public authorities when exceedance of critical limit values can be predicted. People with respiratory diseases and disorders such as asthma and bronchitis especially benefit from the forecasts of ambient air quality. It should be noted that the present EU limit values for individual pollutants are very seldom or never exceeded in Denmark, but these limit values are being revised (as mentioned previously) and are becoming stricter.

Figure 2.3.5
Example of the air quality forecast for three days in July 2000 for the traffic artery Jagtvej in Copenhagen, for Copenhagen as a whole and for various regions of Denmark. There are five possible forecasts: "Below normal", "Normal", "Above normal", "High" and "Pollution alert". The air quality forecast is available in Danish at www.luft.dmu.dk

Photo: 2. maj/Sonja Iskov

2.3.2 Theme – particulate pollution of the air

Pollution of the urban air with particulates causes numerous serious harmful effects on human health. These include long-term effects such as cancer and cardiovascular diseases as well as acute effects such as allergy and irritation of the eyes, nose or throat. Particles vary greatly in size, from dust and dirt of a visible size to ultrafine particles 1,000 times smaller. Studies have shown that the correlation between the concentration of particulate matter and harmful health effects increases as the size of the particles declines. It is therefore especially important to investigate the occurrence of very small particles.

The coarse fraction of particles encompasses those with a diameter exceeding 2.5 µm. They are typically created mechanically by such means as turbulence from traffic, wind erosion and sea spray. Another fraction is the fine particles between 0.2 and 2.5 µm in diameter, which are usually formed through chemical reactions (such as conversion of SO_2 and NO_x to sulphates and nitrates in the atmosphere), coagulation, condensation of gasses onto smaller particles or other slow processes. These particles thus result from such sources as the emission of NO_x and SO_2 from combustion plants and cars. The third fraction is ultrafine particulate matter smaller than 0.2 µm in diameter. Particles from petrol and diesel engines are created at high temperatures in the engines, in the exhaust pipes or immediately after being emitted into the ambient air. Other combustion processes and certain chemical processes in the atmosphere also form ultrafine particles (*Figure 2.3.6*).

The concentration of particulates in ambient air is expressed in different ways. The most common so far is total suspended particulate matter (TSP). Other expressions include PM_{10} and $PM_{2.5}$, which are the concentration of particulate matter with a diameter of less than 10 µm and 2.5 µm, respectively. All stations for measuring ambient air quality in Denmark are being converted so that they can measure PM_{10}, and this will be completed in 2010. In addition, $PM_{2.5}$ monitoring campaigns are conducted at selected stations.

TSP in urban ambient air is a mixture from various sources, but the large particles from whirled-up dust of local origin predominate in this particulate matter. As mentioned, the fine particles in Europe mainly derive from the combustion of fossil fuels. A very great proportion of these particles are ammonium sulphate and ammonium nitrate, which are created from ammonia, SO_2 and NO_x. They comprise a very large proportion of $PM_{2.5}$ in Denmark. They are typically created in the course of a few days while being transported from central Europe to Denmark. This fraction is expected to decline in the future because of reduced emissions resulting from better flue gas abatement at power stations etc., requirements for three-way catalytic converters on all new petrol vehicles and reduc-

tions in emissions from diesel vehicles. Diesel and petrol vehicles emit much of the fine and especially ultrafine particulate matter.

The air pollution in for example a street is the sum of pollution from the traffic in that street, from the traffic in other streets, from other sources in the town, from regional sources, and from other Danish and foreign sources. The composition of the sources of pollution varies over time depending on the magnitude of emissions, conversion of pollutants, deposition on surfaces and meteorological conditions such as wind direction, wind speed and stability. This naturally also applies to particulate matter. Nevertheless, describing and assessing particulate matter pollution is more complex than most other types of air pollution. One reason is that not only the concentration is required, but also the chemical composition and the size distribution of the particles.

Many sources cause the emission of various types of particles of varying size and chemical composition. Vehicular traffic is an example of a source that creates completely different types of particles depending on the formation processes. Some particles are created in the engine, in the exhaust system or immediately outside the exhaust pipe, mostly fine or ultrafine particles. Other particles are whirled up from the road surface or result from wear on the road surface and on tyres, brakes, clutch and other vehicle components; these are mostly large particles. Emissions of NO_x from vehicles in central Europe form particles during the long-range transport to Denmark, and the particles also absorb ammonia emitted by such sources as agriculture during transport.

The emission of particulate matter from transport can be reduced by such measures as installing particle filters on diesel vehicles. There are many different types and brands of filters for diesel vehicles, and measurements in Denmark and studies elsewhere in the world have shown that many of these filters are very effective (>90%) in filtering particulate matter, including the ultrafine particles. Some engine manufacturers are developing new technologies able to reduce particle emissions substantially. Catalytic converters on petrol vehicles are also very effective (>90%) in filtering particles, including ultrafine particles.

Concentrations and trends

The Danish Air Quality Monitoring Programme measures the concentrations of TSP. TSP is measured as a 24-hour mean value in Copenhagen, Odense, Aalborg and Lille Valby (*Table 2.3.3*). The limit values are not exceeded, and the measurements also show that the concentration at the Lille Valby background station is between one third and one half the level at stations in city streets (*Figure 2.3.7*).

PM_{10} has been continuously measured since July 1998 on Jagtvej in Copenhagen. The TSP concentration was generally 35% higher than the PM_{10} concentration. This is similar to the concentrations in other cities. It is the very large particles that are responsible for the difference.

The new limit values of the EU directives (such as an average annual PM_{10} concentration of 40 µg/m³ to be complied with in 2005) have probably been exceeded in several locations when TSP is converted to PM_{10}. The limit value in 2010 of 20 µg/m³ is clearly being exceeded, and is unlikely ever to be complied with; one reason is that some PM_{10} pollution is natural in origin or is whirled-up dust from various activities such as construction and agriculture.

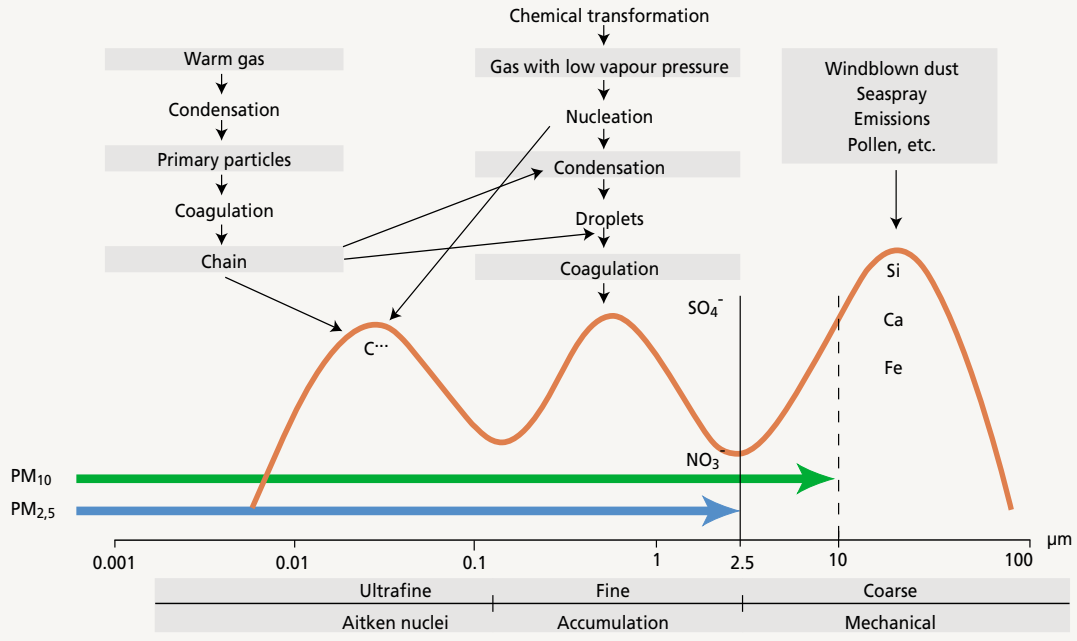


Figure 2.3.6 Schematic representation of the size distribution of particles in urban air. The ordinate scale is arbitrary. (Source: National Environmental Research Institute).

The concentration of fine particulate matter varies only slightly in Denmark (*Figure 2.3.8*). The concentration of particulate sulphur (and nitrate) in urban areas (urban background measurements) is nearly the same as in the countryside. High levels are only seen in very busy streets due to pollution from traffic (20–40% higher). The concentration of sulphurous particles in Denmark has clearly declined in the past decade. The main reason is that SO_2 emissions in Europe, and especially eastern Europe, have declined.

The concentration of ultrafine particles distributed according to size and number has been measured on streets with heavy vehicular traffic in Copenhagen (Jagtvej) (*Figure 2.3.9*) and in Odense (Albanigade) (*Figure 2.3.10*). Gasoline and diesel vehicles emit about the same total amount of particulate matter on Jagtvej because the proportion of diesel vehicles is very low there. A much higher proportion of the total particulate emission was produced by diesel vehicles than by gasoline vehicles in Albanigade in Odense, a more typical street.

In summer 1999, Denmark began to sell diesel fuel with a lower sulphur content: 50 ppm as compared with a previous maximum of 500 ppm in Copenhagen. The concentrations of ultrafine particles were measured in the same time period. Measurements in the winters of 1999 and 2000 showed clearly how the conversion to low-sulphur diesel oil strongly reduced the number of nanoparticles emitted by diesel-driven vehicles. It turns out that the amount of sulphur is not sufficient to explain the quantity of particulate matter emitted. The reason is that extremely small sulphur and sulphuric acid particles form the basis for larger particles developed as they absorb various other substances, such as VOCs. A further reduction in the sulphur content of diesel oil would not necessarily reduce the amount of particulate matter emitted, but there may be other reasons

Table 2.3.3
Mean values, 95-percentiles and maximum values for TSP in 1999. The data are based on 24-hr averages. (Source: Kemp and Palmgren, 2000).

Station	No. of measurements	Yearly average	95-percentile	Maximum
Copenhagen	356	47	97	159
Odense (I)	359	49	104	269
Odense (II)	362	44	89	125
Aalborg	358	51	99	153
Lille Valby	360	24	54	79
Limit value	**Min. 100**	**150**	**300**	**–**

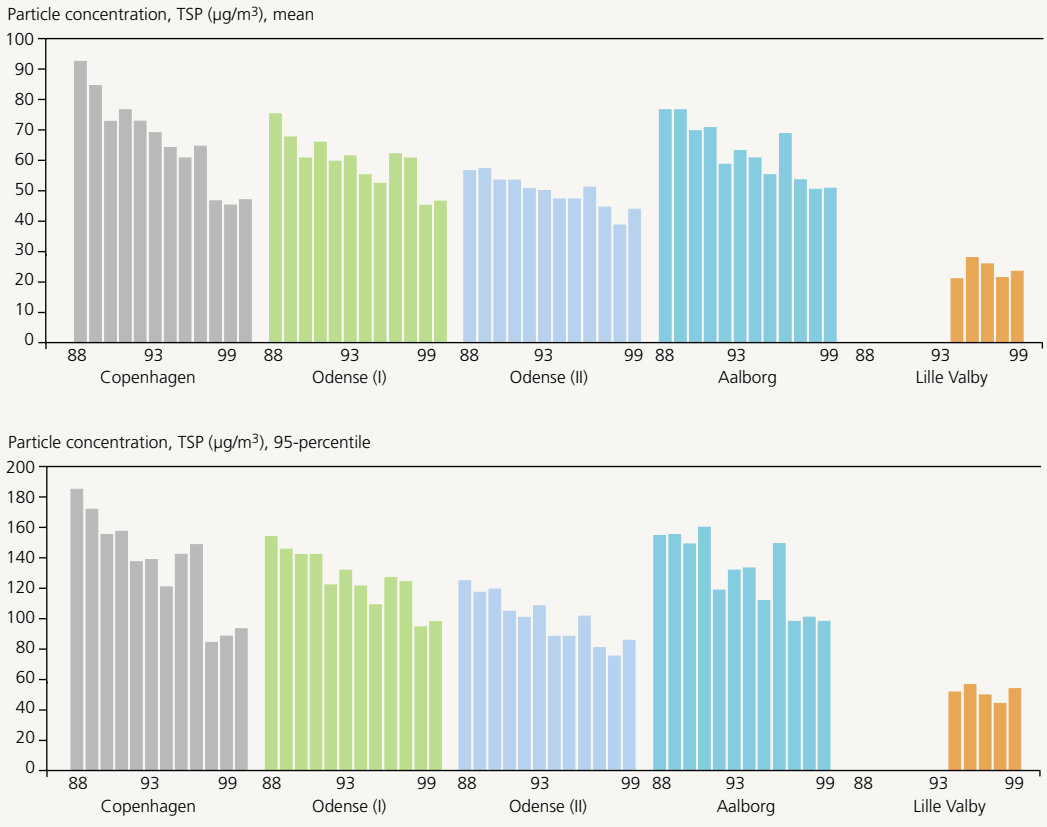


Figure 2.3.7
Development in the particle concentration (TSP) in Denmark over the period 1988–99 shown as the annual mean values and 95-percentiles. (Source: Kemp and Palmgren, 2000).

to reduce the concentration of sulphur in fuel, e.g. increasing the durability of catalytic converters or reducing corrosion on the engine and exhaust system.

The health effects of particulate matter

Studies in the USA and Europe have shown that particulates (PM_{10} and $PM_{2.5}$) adversely affect health. Nevertheless, the characteristics of the particulates that cause harmful effects are not known, although some studies indicate that ultrafine and fine particles are the most hazardous.

These studies, which demonstrated an association between the mortality rate and particulate matter concentrations in the USA and Europe, were all conducted based on a greatly simplified assessment of population exposure. The mean annual urban background concentration of PM_{10} was used. This is the concentration of pollution that can be registered in areas a certain distance from streets and point sources of pollution. Examples include parks, residential areas without substantial vehicular traffic, above rooftops or in backyards or courtyards behind streets. This assumption was based on the premise that the population is exposed to pollution equivalent to the concentration in the ambient air outside their homes rather than that in the streets. This model thus did not account for the fact that much of the population is exposed to heavy pollution from vehicular traffic during transport, such as commuting on streets with heavy traffic. Further, the model did not consider that short-term high-level exposure may cause more harm than the equivalent low-level exposure over a long time period.

Populations exposed to particulate matter have excess premature mortality compared with less-exposed populations. Studies outside Denmark indicate that life expectancy declines by 0.4 to 0.6 years for each 10-µg/m³ increase in PM_{10} concentration in ambient air. A working group on ambient air pollution has thus concluded that reducing the average particulate matter concentration in ambient air in Denmark's cities and towns by about one third would reduce the annual mortality rate by 400 deaths per million citizens. In addition, particulate matter pollution probably adversely affects the health status of a substantial number of people, including increased morbidity. An analysis of the latest studies from outside Denmark concludes that a 10 µg/m³ increase in PM_{10} concentration in ambient air increases the number of hospital admissions and consultations in emergency and accident wards for respiratory diseases and disorders by 2%, reduces lung function by 2%, increases the prevalence of bronchitis by 10–25% and leads to more people with chronic cough (*Figure 2.3.11*).

Overall, the current concentrations of particulates in ambient air in Denmark are considered to cause considerable harmful effects on health. The reasons why particulates have these effects are not fully understood. One outstanding question is the extent to

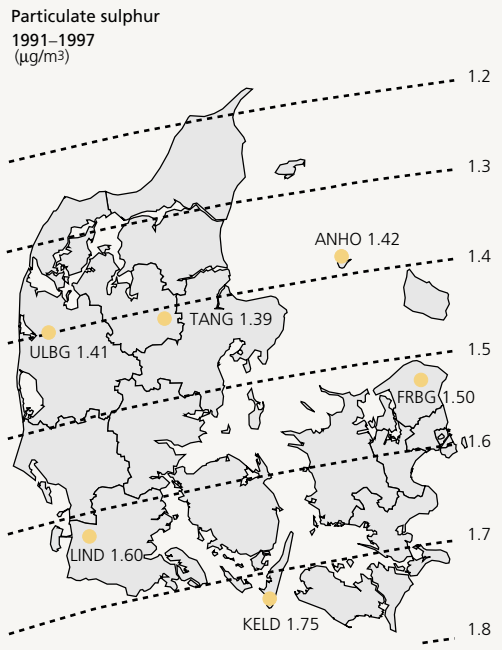


Figure 2.3.8
Geographic distribution of particulate sulphur measured at a number of background stations in Denmark.
(Source: Kemp and Palmgren, 2000).

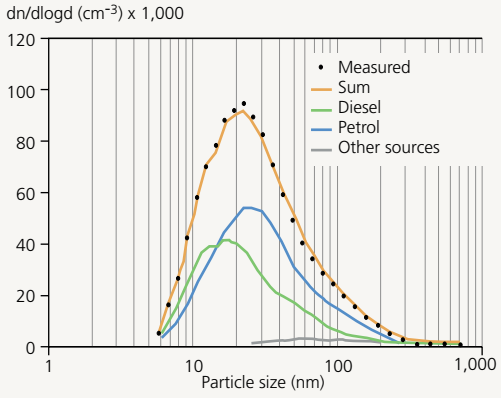


Figure 2.3.9
Particle size distribution on the traffic artery Jagtvej in Copenhagen in the morning rush hour measured on weekdays between 8.30 and 9.00.
(Source: Wåhlin et al., 2001).

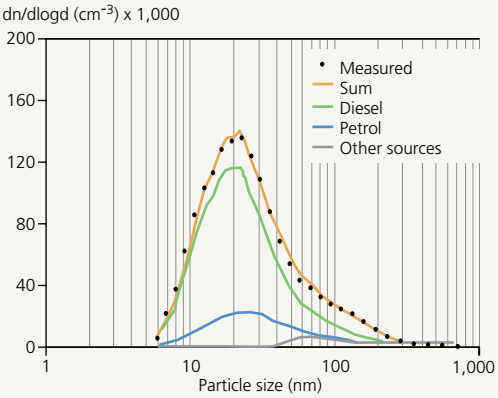


Figure 2.3.10
Particle size distribution on the traffic artery Albanigade in Odense in the morning rush hour measured on weekdays between 8.30 and 9.00.
(Source: Wåhlin et al., 2001).

which the concentration of ultrafine particles less than 0.05 µm in diameter is responsible for the harmful health effects and the role of the chemical composition of particulate matter.

The available epidemiological studies of ultrafine particles and existing knowledge on mechanisms indicate that the ultrafine fraction of transport-related particulate matter and its concentration are important for the effects on health. Thus, it is extremely likely that ultrafine particles emitted by diesel combustion play a greater role in causing negative health effects than their absolute mass would imply. This applies to exacerbation of respiratory and cardiovascular diseases, including the risk of death. Studies of healthy people exposed occupationally to diesel emissions have not found substantial excess risk for developing respiratory and cardiovascular diseases, but only an increased risk of cancer.

The proportion of the calculated health effects accounted for solely by transport-related ultrafine particles cannot be determined. The upper limit for the effect of ultrafine particles might be assumed to be equivalent to the proportion of PM_{10} caused by transport: up to 40–60% according to WHO, depending on the density of vehicular traffic. Heavy vehicles emit about 40% of the ultrafine particles. Eliminating 80% of these emissions would therefore be expected to reduce up to about 33% of the total effects attributed to PM_{10}.

Conclusion

Particulate matter pollution is one of the greatest health-related air pollution problems in Denmark. Substantial knowledge is lacking in this area internationally, but many resources have been focused on improving this knowledge. The fine and ultrafine particles seem clearly to be the most harmful, and the total number of particles may be the decisive factor. Nevertheless, no clear causal relationship between the characteristics of particles and their harmful effects on health has been determined yet.

In contrast, transport is definitely known to be the most important source of particulate matter in Denmark, especially of ultrafine particles, and people are certainly exposed when they are present in streets with heavy vehicular traffic or live or work in buildings along the streets. Vehicular transport also causes pollution with large particles arising from the road surface, tyres, brakes and other moving parts. Filters are effective in preventing the emission of particulate matter, but they only filter out the particles emitted through the exhaust system and not the gaseous substances that can lead to the formation of particulate matter. Catalytic converters on gasoline vehicles also seem to effectively reduce particulate emissions.

Effective efforts to reduce the harmful effects of particulate matter pollution require both knowing the characteristics of the particles and being able to link these characteristics with the harmful effects. Thus, reducing the emission of particulate matter as measured by mass is not useful if the number of particles is the key factor, nor is reducing the number of particles if the main factor is the presence of certain chemical substances. These issues are expected to be clarified in the coming years through extensive international cooperation.

Figure 2.3.11

Left: Deposition of particles in various parts of the respiratory tract of an adult man. The probability of deposition depends on the size of the particles and is generally greatest for small particles. The high total deposition of large particles is due to the fact that they are deposited in the upper airways, where they probably have less effect on health. Right: Size distribution of airborne particles in town air. TSP is the total amount of particles expressed in terms of weight. PM_{10} represents particles smaller than 10 µm, while $PM_{2.5}$ represents particles smaller than 2.5 µm.
(Source: Palmgren et al., 1997).

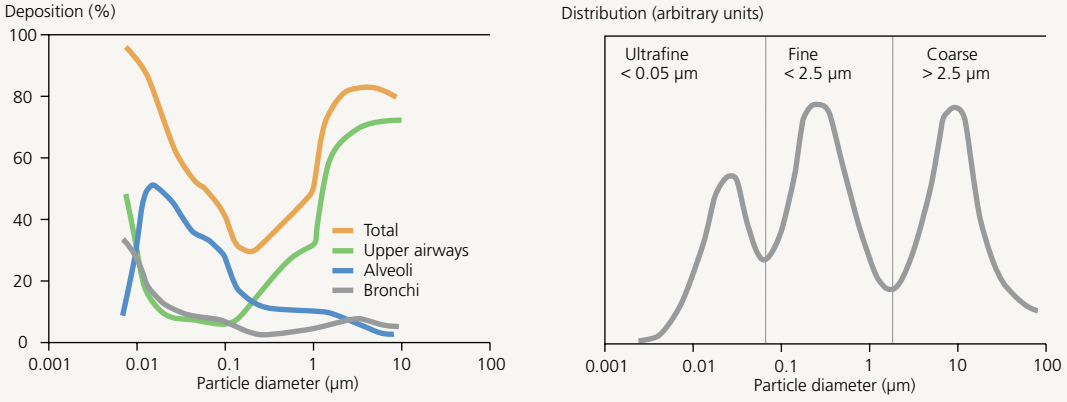


Photo: Jørgen Kjems

2.4 Regional air pollution

2.4.1 Status and trends

Introduction

The transport of air pollutants across national borders to a larger geographical area is called transboundary air pollution. The regional effects of this pollution can be roughly classified into direct effects occurring through direct contact with airborne substances at a given concentration in ambient air and indirect effects that first develop after the substances affect soil and waters through deposition. Direct effects include harmful effects on trees or crops that have absorbed high concentrations of gaseous air pollution through their leaf stomata. The indirect effects mostly comprise acidification or eutrophication caused by atmospheric deposition of sulphur and nitrogen compounds.

It has been known for decades that nitrogen and sulphur compounds transported long range have led to acidification of precipitation in such countries as Sweden and Norway, although other parts of Europe account for the greatest emissions. The Convention on Long-range Transboundary Air Pollution was the first instrument to regulate this regional air pollution in an internationally binding agreement. It entered into force in 1983, in association with the United Nations Economic Commission for Europe (UN-ECE). The EU has also begun numerous important initiatives in this field, including the framework directive for ambient air quality assessment and management.

Effects of regional air pollution

Air pollutants may be deposited on soil or vegetation surfaces (dry deposition) or may be deposited with precipitation (wet deposition). The direct effects include harmful effects on trees, crops or natural vegetation through direct contact with a specific air pollutant. Indirect effects arise when pollutants are deposited on land and change its state and quality, or when groundwater, watercourses and lakes are subsequently affected through leaching or runoff.

The efforts to regulate air pollution are based on the fact that nature can only tolerate a total maximal load either in the form of a maximum amount of deposition or a maximum concentration in air without altering ecosystems or affecting plants. The critical level is defined as the concentration of pollutants in the atmosphere above which direct adverse effects on plants and other receptors may occur. Similarly, exceedance of the critical load is defined as the amount of air pollution deposition on an ecosystem that the system is unable to turn over or tolerate without resultant changes in its function or structure.

The critical loads for indirect effects differ for different ecosystems. The sensitivity to a specific air pollutant depends on such factors as the species composition of the plant community and the type of soil. Acid sandy soil and peaty soil typically have low critical loads. The critical loads for forests can be assessed on the basis of the load that causes nitrate leaching and acidification of the soil, but critical loads can also be determined based on the diversity of forest floor vegetation or the stability of the forest or ecosystem. The critical loads for forests and dry grasslands are modelled, whereas the critical loads and levels for nutrient-poor habitats such as heaths, raised

bogs and oligotrophic fens are based on expert assessment and are thereby less certain and more qualitative.

In Denmark the critical loads and levels for direct effects are only relevant as regards ozone. Ozone mainly causes harmful effects when the concentration exceeds 40 ppb in air. The ozone index used internationally is AOT_{40}: accumulated exposure over a threshold of 40 ppb of ozone. For example, if three mean hourly concentrations of ozone exceed 40 ppb, e.g. 45, 50 and 55, the AOT_{40} for that day is 5 + 10 + 15 = 30 ppb × hours. The sensitivity to ozone of different types of vegetation varies, for example due to differences in the growing season. The critical load for ozone exposure for trees is 10,000 ppb × hours during the period April to September.

Acidification

Deposition of sulphur and nitrogen compounds can lead to acidification due to formation of sulphuric acid and nitric acid. Nitrogen in the form of ammonia and ammonium can be converted to nitrate through biological processes and then leached and thereby contribute to acidification.

Ecosystems vary in their stability to deposition of acidifying substances. Among the most sensitive are nutrient-poor lakes and watercourses in Norway, Sweden and Canada, where the soil has a low buffering capacity for acid. Acidic precipitation accumulates during the winter as snow, and the spring melt can suddenly liberate large quantities of acid accompanied by a decline in pH, which affects the fauna in the watercourse or lake.

A survey of acidification of forests in Denmark was started in the mid-1980s. Forest dieback had been observed at that time in various parts of Europe, and the reasons for these harmful effects were linked with the effects of air pollution (*Figure 2.4.1*). Throughfall deposition can be used to indicate the total deposition of SO_2, sulphurous particulate matter and sulphur deposited through precipitation. Sulphur deposition in Denmark has declined since the early 1990s as sulphur emissions have declined in Denmark and elsewhere in Europe; this trend seems to be similar at all three stations measuring deposition in Denmark.

Eutrophication

Eutrophication is defined as effects on the state of ecosystems resulting from the input of nutrients in greater quantities than the ecosystems can metabolize naturally. This section describes the contribution of air pollution to this input, especially emphasizing the deposition of nitrogen. Terrestrial ecosystems can accumulate organically bound nitrogen in the soil organic matter and in vegetation as increased biomass. The ecosystem as a whole has an upper limit for the total nitrogen load that can accumulate in the system, and if this critical load is exceeded, nitrogen will leach out. Leaching of nitrogen in the form of nitrates is accompanied by leaching of positively charged basic cations, which acidify the soil and cause loss of plant nutrients. Increased nitrogen uptake by vegetation may influence the stability of the ecosystem; for example, this may increase the sensitivity to stress factors such as drought, frost and insect infestations and influence the development and species composition of the plant community.

Photo: NERI/Morten Strandberg

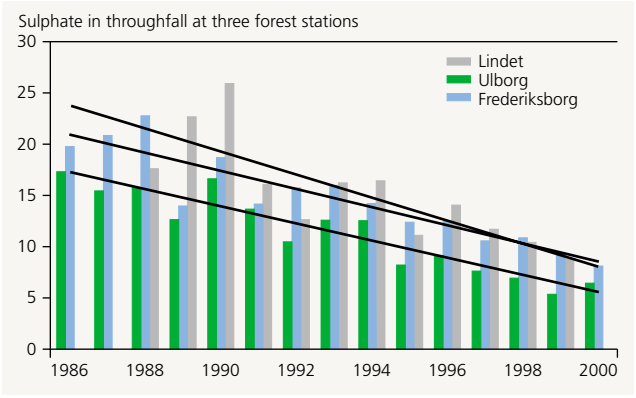


Figure 2.4.1

Sulphur deposition measured as throughfall beneath common spruce trees (kg SO_4-S/ha per yr). The measurements are from Ulborg, Frederiksborg and Lindet forest districts and record the anthropogenic sulphur deposition, i.e. they are corrected for sulphur deposition derived from marine salts. (Source: Hovmand, 2001).

High concentrations of nutrient salts in coastal waters have led to increased algal growth. This growth is nitrogen limited. The decomposition of dead algae requires large quantities of oxygen and in severe cases may lead to very low concentrations of oxygen in the bottom layer. Lack of oxygen and the subsequent death of fish and benthic animals have been common in Denmark's coastal waters in recent decades. Another serious phenomenon has been episodes of high concentrations of algae that can be toxic to humans and animals. Both phenomena are believed to be associated with increased input of nutrients from human sources.

The deposition load is assessed by measurement or modelling. Modelling allows a finer spatial resolution than does measurement. Modelling is used to determine the deposition of atmospheric nitrogen on all Denmark's marine waters and is performed for 212 receptor points in a grid with a resolution of 30 km by 30 km (*Figure 2.4.2*). These data are subsequently distributed according to primary and secondary marine waters based on geographical information. These results are continually reported and also presented on the Internet.

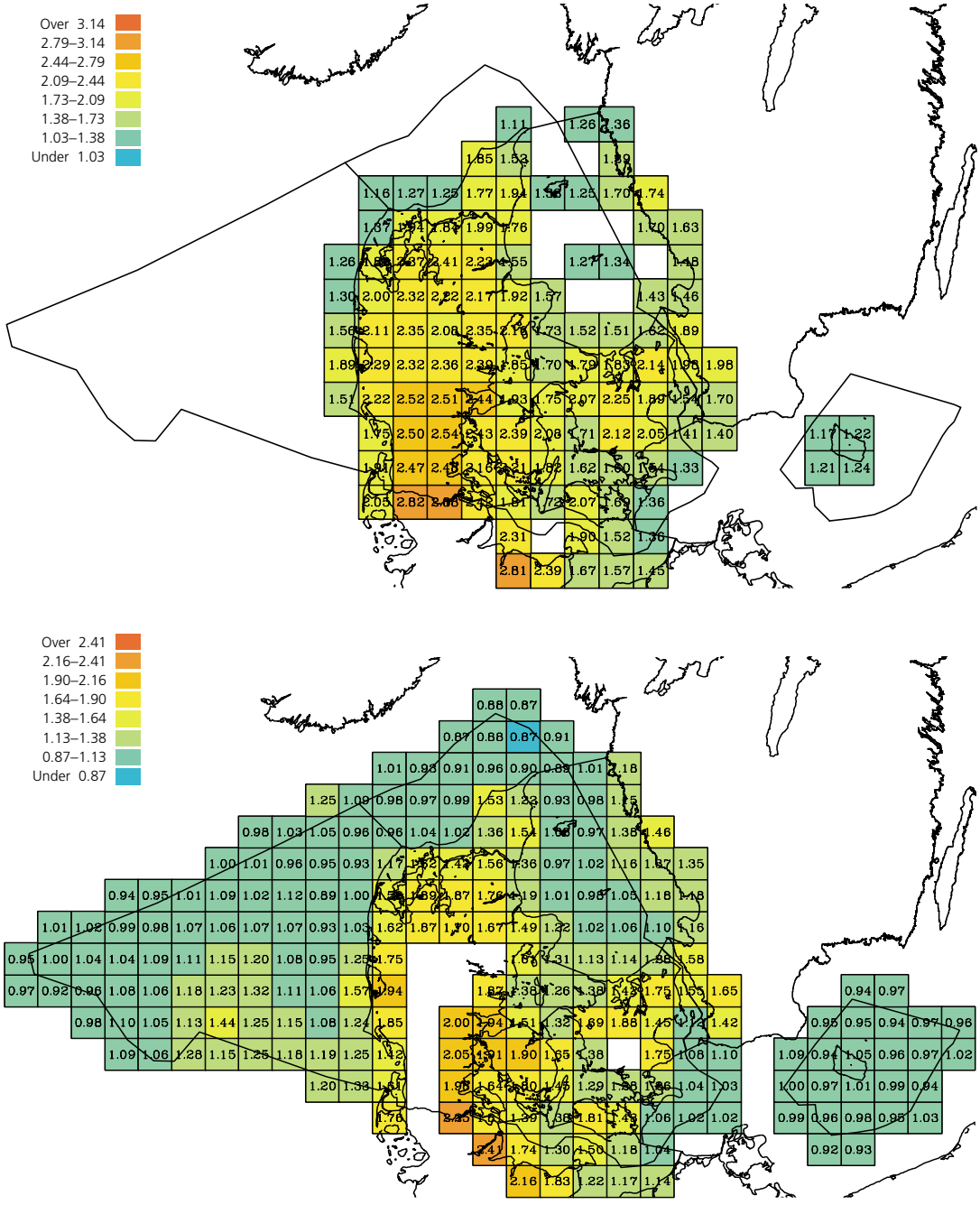


Figure 2.4.2
Calculated total deposition (dry and wet) of nitrogen compounds in 1999 on the Danish land mass (upper panel) and Danish marine waters (lower panel). Unit: tonnes N/km². (Source: Ellermann et al., 2000).

Two groups of compounds contribute to the atmospheric deposition of nitrogen in the marine environment: Ammonia and ammonium (NH_x), as well as NO_x and its reaction products (NO_y). Ammonia originates mostly from manure application in agriculture, whereas NO_x is produced during combustion processes associated with such activities as transport, industry and generating electricity and heat (*see Section 2.2*). Ammonia is mainly deposited close to the source, but can be transported long range as ammonium bound to particulate matter and be deposited very far away from the source (*see Section 2.4.2*). The situation is somewhat different for NO_x, little of which is deposited on land surfaces. It is primarily removed from the air by deposition following conversion to nitric acid and particulate nitrate, which are deposited relatively far from the sources.

The atmospheric load of nitrogen to marine waters in Denmark is estimated to be 0.8 to 1.5 tonnes of nitrogen per km^2 per year. The majority is deposited in the areas closest to agricultural activities on land in Denmark, i.e. fjords, coves and bays. These areas also have the largest runoff from watercourses, however, and the atmospheric load is therefore generally less important for these areas compared with more open marine waters such as the Kattegat Sea and the Danish part of the Baltic Sea.

The calculations indicate that NO_x accounts for slightly more than half the total nitrogen deposited on Denmark's marine waters. The situation is different for coastal marine waters, such as the Limfjord because of the substantial deposition of ammonia from sources in Denmark.

For the primary marine waters, the atmospheric deposition of nitrogen is usually dominated by wet deposition of nitrates and ammonium, which typically comprises two thirds of the atmospheric deposition. Since precipitation on Danish marine waters is fairly evenly distributed between seasons, the atmospheric deposition of nitrogen is similarly relatively uniformly distributed on an annual basis. Runoff of nitrogen via watercourses in Denmark very clearly peaks in the spring and declines somewhat in the summer. This means that the atmospheric deposition of nitrogen exceeds the leaching runoff in the summer and may therefore play an important role in the previously mentioned episodes of algal blooms that occur in the summer. The deposition of atmospheric nitrogen turns out to comprise much of the input of nitrogen to Denmark's marine waters.

More nitrogen is usually deposited on land surfaces than on water. The amount deposited on land varies between 1.5 and 2.5 tonnes of nitrogen per km^2 per year. The high deposition is partly attributable to ammonia, which dominates dry deposition of nitrogen. The deposition of reduced nitrogen (NH_x) on land surfaces in Denmark accounts for slightly less than 60% of the total nitrogen deposited. Sources of ammonia within Denmark account for about 34% of the total nitrogen deposited.

Exceedance of critical loads

Not all types of forests and natural and seminatural ecosystems are sensitive to acidification and atmospheric deposition of nitrogen. The types of habitats that are known to be sensitive to increased input of nitrogen include heaths, dry grasslands, raised bogs and lobelia lakes. Exceedance of the critical loads for eutrophication in particular has caused the species composition of many plant communities to change and has also reduced the number of species. The endangered

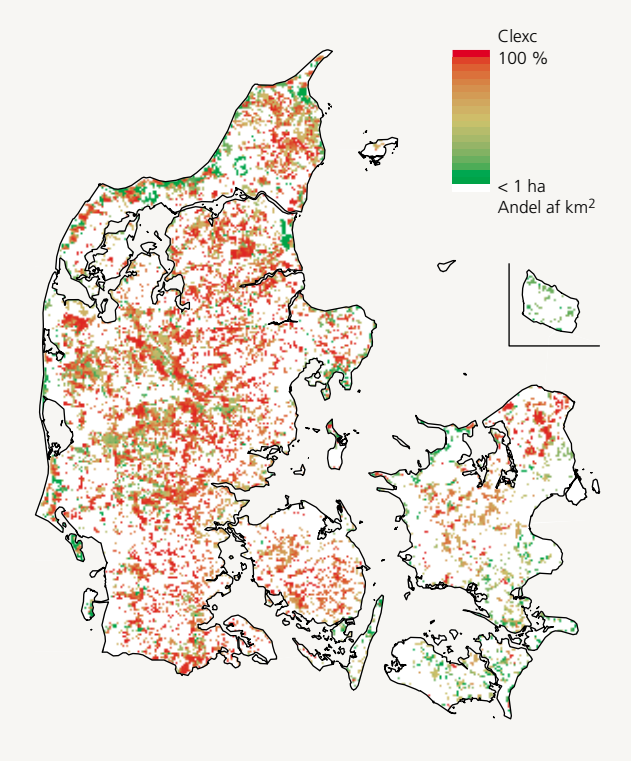


Figure 2.4.3
Percentage of area of natural ecosystems in Denmark where the critical load for acidification and/or eutrophication limit is exceeded. The area is calculated for all of the natural ecosystems indicated in Table 2.4.1 and is expressed in percent of the total area of these ecosystems in a 1 km^2 grid covering the whole of Denmark. White cells indicate that the area with critical load exceedance is less than 1 ha. (Source: Bak, 2001).

Ecosystem type	Area with exceedance (%)
Permanent grasslands	57
Heath	42
Dune heath	7
Fens	11
Lobelia lakes	100
Raised bogs	100
Broad-leaved forest	63
Conifer forest	94

Table 2.4.1
Percentage of area of natural ecosystems in Denmark where the critical load for acidification and/or eutrophication limit is exceeded. NB: The critical loads and exceedance of them are based on model calculations. Confidence intervals for exceedances have not been calculated, but the level of uncertainty is great. The uncertainty in the critical loads alone is in the order of 30–40%. The calculations are based among other things on the average annual deposition for the years 1997 and 1998 and calculations of ammonia volatilization from Danish agriculture in 1996. The latter derives from the report "Ammoniakredegørelse nr. 1". The figure has since been revised downwards in connection with the Action Plan on the Aquatic Environment II.
(Source: Bak, 2001).

plant species are mostly hardy ones associated with nutrient-poor and often stable environments such as raised bogs. Hardy plants that require a nutrient-poor habitat were previously very common and have thus been reduced, whereas competitive species that were previously rare have become more common (*see Section 4.3*).

Figure 2.4.3 shows the percentage of area of natural ecosystems in Denmark where the critical load for acidification and/or eutrophication limit is exceeded. The area is calculated for all of the natural ecosystems indicated in *Table 2.4.1* and is expressed in percent of the total area of these ecosystems in a 1 km^2-quadrant grid covering the whole of Denmark. This was calculated based on the mean annual deposition for the years 1997 and 1998.

Table 2.4.1 presents the percentage of area with exceedance of critical loads for several types of habitat. The present burden particularly exceeds the critical load for sensitive habitats such as lobelia lakes and raised bogs. Raised bogs are the type of habitat in Denmark that is most sensitive to nitrogen. The greatest deposition and exceedance of the critical loads primarily occur in areas affected by local and regional sources of ammonia. The reason for the relatively low figure of 7% for dune heaths is the relative lack of local sources of ammonia near the coast, where this habitat type is located. Dune heaths are defined here as all heaths located within 3 km of the coast and not only as an especially sensitive type of heath.

Only the sensitive fens and lakes (lobelia lakes) are included in the calculations (*Table 2.4.1*). In general, only a few Danish lakes, meadows and bogs can be expected to be sensitive to atmospheric deposition of nitrogen, partly because other nutrients can be limiting factors, e.g. phosphorus pollution of lakes, and partly because input of nitrogen from other sources may exceed atmospheric deposition.

The "Theme" on ammonia (*Section 2.4.2*) also discusses exceedance of the critical loads for acidification and eutrophication and further explains the extent to which a 50% reduction in Denmark's ammonia emissions would influence this exceedance.

Direct effects of ground-level ozone

Ozone is the air pollutant found in the highest concentrations in Denmark's forests and rural districts. The concentrations are highest during the summer when the wind blows from the southeast. The reason is that high concentrations of ground-level ozone can build up during high-pressure episodes in central and eastern Europe, whereafter this air mass is transported long range to Denmark. Ozone is formed in photochemical reactions between VOCs and NO_x in the presence of sunlight. Photochemical smog, which produces high ozone concentrations, was registered for the first time in Los Angeles, USA in the 1940s and later in southern Europe and other areas. Photochemical smog is a purely urban phenomenon. In contrast, ozone mostly decomposes in urban areas in Denmark upon reacting with NO (*Section 2.3*). This is why concentrations are usually lower in urban areas than in the countryside.

Ozone is the gaseous air pollutant that most harms the vegetation at the concentrations prevalent in Denmark. The most important harmful effects are caused when ozone is absorbed through the leaf stomata. The AOT_{40} values are higher at the Ulborg forest measuring station than at the Frederiksborg forest measuring station, and the trees in Ulborg (western Jutland) are exposed to an average ozone load very close to the critical load of 10,000 ppb × hours (*Figure 2.4.4*).

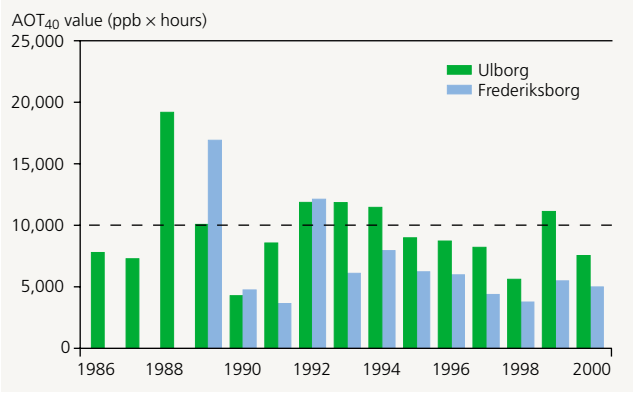


Figure 2.4.4
AOT_{40} measured at the two background measuring stations Ulborg and Frederiksborg over the period 1986–2000. The critical level for harmful effects is 10,000 ppb × hours. (Source: Hovmand, 2001).

It has been agreed internationally that the future work on the critical loads and levels for ozone is to be focused on developing a flux-based critical level index that includes the influence of climatic conditions on ozone absorption. For example, modelling indicates that a forest in southern Scandinavia absorbs the same quantity of ozone in one growing season as a forest in southern Europe, even though the concentrations of ozone are much higher in the south. The reason is that forests have a more plentiful supply of water in northern Europe and the stomata are therefore generally open for longer and hence can absorb more ozone.

Heavy metals

The atmospheric deposition of heavy metals has declined in the past decade (*Figure 2.4.5a*), and the concentrations of heavy metals in ambient air have also dropped sharply (*Figure 2.4.5b*). This trend is especially pronounced for lead after lead-free petrol was introduced, but applies to several other metals. The reason is improved flue gas abatement at coal-fired power plants in Europe, closure of less efficient power plants and a shift to natural gas as a fuel. In addition, the closure of old installations for primary and secondary production of metal in Europe has been especially important in reducing the emissions of heavy metals. Production from these installations has been moved to a few, modern installations with improved flue gas abatement technology.

Objectives and measures

In 1976, the Nordic Ministers responsible for the Environment proposed a European convention to reduce air pollution, especially sulphur compounds. The Nordic countries established a working group that submitted a draft Convention on Long-range Transboundary Air Pollution to the United Nations Economic Commission for Europe in 1978.

After negotiations within the Economic Commission for Europe, 34 countries and the European Commission signed the Convention in November 1979. At the same time, a resolution was signed to implement the Convention on an interim basis until the Convention had been ratified, mainly because of the urgent need to reduce the emission of sulphur compounds. The Convention entered into force on 16 March 1983.

Forty-eight Member States have now ratified or are in the process of ratifying the Convention, including all the countries of the Baltic region and the European Community. The Convention is a framework convention to be implemented with operative provisions. Eight protocols have been prepared and signed, of which five have been ratified.

EMEP

The Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP) was established in 1977. The Geneva Protocol on Long-term Financing of the EMEP was signed in 1984 and entered into force in 1988. The main purpose of the EMEP is to provide information to Member States on the deposition and concentrations of air pollutants and the quantity and significance of long-range transport of air pollution. The EMEP has three main elements:

- Gathering data on emissions
- Measuring the quality of ambient air and precipitation
- Modelling and calculating the atmospheric dispersion of air pollutants.

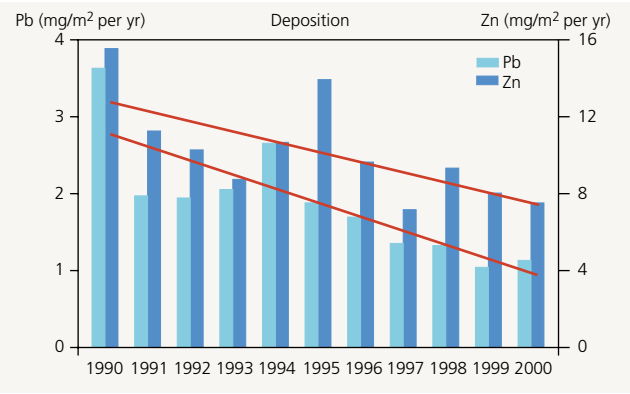


Figure 2.4.5a

Temporal development in deposition (wet) of lead (Pb) and zinc (Zn) over an 11 year period. Units: mg metal/m² per yr, which corresponds to kg/km² per yr. The solid lines indicate the simple linear regression. (Source: Hovmand et al., 2001; Hovmand and Kemp, 2000).

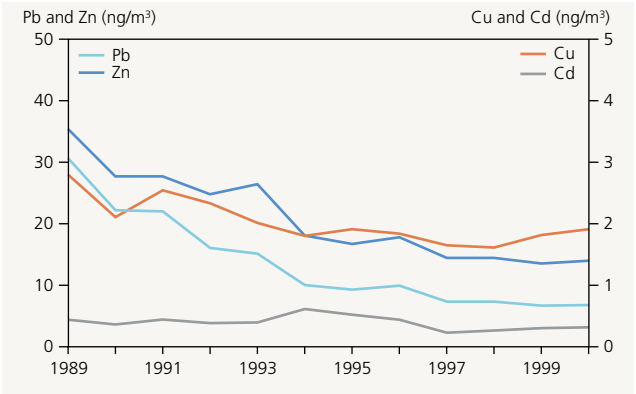


Figure 2.4.5b.

Annual mean concentration of copper (Cu), zinc (Zn), lead (Pb) and cadmium (Cd) expressed in ng/m³. For Cu, Zn and Pb the results shown are the averages of the annual means recorded at all six measuring stations. For Cd the values are the average of the means recorded at Tange and Keldsnor. As the majority of the results for Cd are beneath the detection limit, the values are subject to considerable uncertainty. (Source: Hovmand et al., 2001; Hovmand and Kemp, 2000).

• **The Helsinki Protocol**
on the Reduction of Sulphur Emissions or their Transboundary Fluxes by at least 30% from 1980 to 1993 was signed in 1985. The 22 countries that ratified the Protocol reduced their total sulphur emissions by 52% from 1980 to 1993. Denmark's emissions declined by 65% in this period. Denmark declared as it signed the Protocol that it would reduce emissions by 50% by 1995 at the latest.

• **The Oslo Protocol**
on Further Reductions of Sulphur Emissions was signed in 1994 and entered into force in August 1998. To date it has been or is in the process of being ratified by 23 countries. It is based on the concept of critical load and the use of the best available technology as a means of reducing sulphur emissions. The Protocol contains basic commitments regarding emission ceilings of 30–87% of SO_2 emissions in 1980. The target year was 2000, but further targets were added for some countries for 2005 and 2010. The long-term objective of the Protocol is to reduce deposition to a level that does not exceed the critical load. The Protocol requires Denmark to reduce SO_2 emissions by 80% from 1980 to 2000. In 1999, Denmark had reduced its SO_2 emissions by 88% compared with the 1980 level.

• **The Sofia Protocol**
concerning the Control of Emissions of Nitrogen Oxides or their Transboundary Fluxes was signed in 1988 and has now been or is in the process of being ratified by 28 countries, including the European Community. Of these, 18 countries including Denmark have complied with the requirements of the Protocol on stabilizing their NO_x emissions in 1994 compared with the 1987 level. Denmark signed a declaration on further reduction with ten other countries. Denmark's target was to reduce emissions by 30% from 1986 to 1998, and this has largely been achieved with a decline of 28%.

• **The Geneva Protocol**
concerning the Control of Emissions of Volatile Organic Compounds or their Transboundary Fluxes was signed in 1991. The Protocol entered into force in September 1997 and has been ratified by 20 countries. It requires countries to reduce VOC emissions by 30%. Denmark was supposed to achieve this from 1985 to 1999, and the actual decline in this period was 32%. The main reason for this Protocol is that VOCs contribute to creating ozone in the presence of sunlight and NO_x.

• **The Aarhus Protocol**
on Persistent Organic Pollutants (POPs) was signed in June 1998 by 36 countries. The Protocol has not yet entered into force. The purpose of the Protocol is to control, reduce or eliminate the emission of persistent organic pollutants to the environment. The production and use of some substances is prohibited. The use of other substances is severely restricted; emission ceilings will be implemented that are related to a reference year for the persistent organic pollutants formed inadvertently in combustion or industrial processes. The Protocol covers 16 persistent organic pollutants. In connection with the Protocol, 18 countries and the EU adopted a declaration that places restrictions on two additional persistent organic pollutants.

• **The Aarhus Protocol**
on Heavy Metals was signed in June 1998 by 36 countries. The Protocol has not yet entered into force. The purpose of the Protocol is to reduce the emission of lead, cadmium and mercury from numerous industrial sources and combustion processes. The Protocol lays down limit values for stationary sources and guidelines for the use of the best available techniques. Further, the Protocol requires the lead added to petrol to be phased out and includes instruments for reducing heavy metals in certain products, such as mercury in batteries.

• **The Gothenburg Protocol**
to Abate Acidification, Eutrophication and Ground-level Ozone was signed in 1999 by 31 countries. The purpose of the Protocol is to reduce acidification and eutrophication and to reduce the concentration of ozone in ambient air. Similar to the Oslo Protocol, the targets are based on the principle of critical loads for ecosystems and human health. One of the original targets was that the area in which the critical load for acidification had been exceeded in 1990 should be halved. This target was not achieved. Under the Protocol, each Member State is assigned and accepts emission ceilings applying to 2010 for SO_2, NO_x, VOC and NH_3 (*see Section 2.2*). It is believed that Denmark's emission ceilings can be met through measures that have been implemented or are already planned.


Photo: NERI/Morten Strandberg

Photo: NERI/Knud Tybirk

2.4.2 Theme – ammonia

Nitrogen is a growth-limiting nutrient for many natural plant communities in northern Europe, and increased input of nitrogen will therefore change the plant community and the species composition of many ecosystems. Ammonia is a nitrogenous nutrient and therefore contributes to eutrophication. Ammonia, which is deposited from the air onto vegetation and water surfaces, can be further converted to nitrate through biological processes in the soil. When this nitrate leaches, the upper soil layers can become acidified.

The most important source and cause of the input of nitrogen to the environment is current agricultural practices. A smaller quantity comes from the discharge of wastewater, and the deposition of NO_x and other oxidized nitrogen compounds from the atmosphere also contribute to the nitrogen load. In 1998–1999, agricultural nitrogen inputs totalled 575 kilotonnes, while the annual output in the form of crops and animal products was equivalent to about 190 kilotonnes of nitrogen. This means that the difference between the input and output of nitrogen (nitrogen surplus) is about 385 kilotonnes of nitrogen per year. The nitrogen lost to the environment in this balance comes from leaching from the root zone, denitrification in the soil and subsequent loss of nitrogen gas (N_2) and nitrous oxide (N_2O), and the volatilization of ammonia (NH_3) to the atmosphere.

The nitrogen loss is the net result of a complicated process controlled by the relationships between the type of crop, the soil conditions, agricultural practices and climate, and hence varies markedly over time and between locations. In 1999, an estimated 94 kilotonnes of ammonia volatilized in Denmark, equivalent to 77 kilotonnes of ammonia–nitrogen (NH_3-N). Ammonia volatilization thus accounted for about 20% of the total nitrogen loss in agriculture.

Environmental policy initiatives were taken in the mid-1980s to study the input into the environment of plant nutrients such as nitrogen and phosphorus as well as organic matter. It was recognized that there

was a need for more knowledge and better understanding of the relationships between discharge of nutrients and trends in the state of the aquatic environment. In 1985, the Danish parliament adopted an action plan on nitrogen, phosphorus and organic matter, and the first Action Plan on the Aquatic Environment followed in 1987. Later the input of nitrogen to sensitive terrestrial ecosystems has also come into focus; one reason is the effects of increasing input of nitrogen to forests and natural ecosystems. An action plan on ammonia was prepared in 2000–2001 to reduce ammonia volatilization.

The atmospheric cycle of ammonia

Ammonia is one of the many nitrogenous gasses in the atmosphere that contributes to eutrophication, but ammonia is also the dominant alkaline gas in the atmosphere. Ammonia thus plays a very central role in the chemical reactions occurring in the atmosphere because ammonia neutralizes a large proportion of the oxidized sulphur and nitrogen compounds in ambient air, thereby contributing to the formation of particulate matter in the atmosphere containing ammonium, sulphates and nitrates (*see Section 2.3*).

Model calculations show that ammonia sources comprise slightly more than 40% of the atmospheric input of nitrogen to Danish marine waters versus 60% on land. Of the total atmospheric nitrogen input, ammonia sources within Denmark account for 11% of the total input to Danish marine waters versus 34% for land areas in Denmark.

Emissions of NH_3-N to the atmosphere from Danish agriculture amounted to about 77 kilotonnes per year in 1999, corresponding to 98% of the total emissions. Much of this ammonia is dry deposited, very little is deposited with precipitation and much of it is converted to particulate ammonium, which is mostly wet deposited (*Figure 2.4.6*). Ammonia stays in the atmosphere for a relatively short time compared with SO_2 and NO_x because ammonia is very soluble in water. SO_2, NO, NO_2 and ammonia are all converted into particulate matter to some extent. All particulate ammonium in the atmosphere derives from ammonia.

Small particles of anthropogenic origin remain airborne as aerosols because they have a low rate of deposition. This means that the reaction products of these emissions are transported over very long distances, and the pollution thereby becomes transboundary. These anthropogenic particles last about 3–5 days. At a wind speed of 5 m/s, the particles can potentially move about 1,000 km during their short lifetime.

Denmark emitted about 77 kilotonnes of NH_3-N in 1999. Model calculations show that about 27 kilotonnes of NH_3-N was deposited on Denmark's land areas; of this, about 3 kilotonnes originated outside Denmark (*Table 2.4.2*). In addition, 22 kilotonnes of derivative ammonia compounds (NH_4^+-N) in precipitation and particles were deposited on Denmark's land areas. About 17 kilotonnes of this deposition originated from sources outside Denmark. Terrestrial areas in Denmark thus have a net export of ammonia and derivative compounds (28 kilotonnes of nitrogen), but if deposition on marine waters is included, Denmark is a net importer of ammonia and derivative compounds (22 kilotonnes of nitrogen).

Figure 2.4.6

Fate of ammonia in the atmosphere. Following emission in gaseous form (NH_3) ammonia is either deposited by dry deposition or converted to particulate ammonia (NH_4) and deposited by wet deposition. The width of the arrows indicates the relative quantitative distribution of the various processes.

(Source: Asman, 2001).

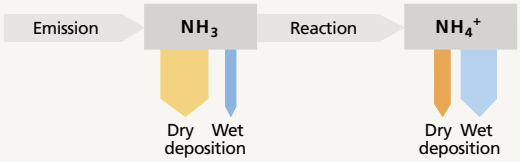


Table 2.4.2
Deposition and emission estimates for the NH_x balance for Denmark in 1999. The deposition is subdivided into deposition on land and marine waters for both ammonia and ammonium-related compounds.
(Source: Hertel, 2001).

		Foreign origin	Danish origin	Total
Deposition, land	ktonnes	3.0	24.1	27.1
	ktonnes	16.9	4.8	21.7
Total		**19.9**	**28.9**	**48.8**
Deposition, sea	ktonnes	3.4	6.5	9.9
	ktonnes	32.4	7.8	40.2
Total		**35.8**	**14.3**	**50.1**
Emission, land	ktonnes			
Denmark's land area: Net export (77–48.8) ktonnes N = 28.2 ktonnes N				
Denmark's land and sea area: Net import (77– (48.8 + 50.1)) ktonnes N = 21.9 ktonnes N				

Emissions

Atmospheric ammonia mainly derives from agriculture, with volatilization from manure being the predominant source. Some of the nitrogen in fodder is converted to milk and meat, but a relatively large proportion is excreted with urine in the form of urea. Solid manure contains other forms of organic nitrogen. Microorganisms can use the enzyme urease to convert urea into ammonia and CO_2.

The amounts of reduced nitrogen compounds (ammonia and derivatives) and NO_x emitted are approximately equal both in Denmark and in Europe as a whole (*Table 2.4.3*). Denmark accounts for slightly less than 2% of the total ammonia emitted in Europe, but Denmark's emissions per unit of land area are relatively high in Europe. The distribution of emissions clearly varies geographically, being maximal in Jutland (*Figure 2.4.7*).

Agricultural production in Denmark resulted in the emission of 77 kilotonnes of NH_3-N to the atmosphere in 1999 versus 111 kilotonnes in 1985, a decrease of 34 kilotonnes.

Calculations show that 76% of the agricultural ammonia emissions derive from manure, with the ammonia volatilizing from livestock housing, when the manure is spread on fields, during storage and when the livestock graze (*Figure 2.4.8*). About 15% of ammonia derives from crops, and 7% from commercial fertilizer. Ammonia treatment of straw is responsible for 2% of emissions, and sewage sludge and crop burning accounts for less than 0.5% of

Table 2.4.3
Emission of reduced nitrogen (NH_x-N) and oxidized nitrogen (NO_x-N) in Europe (incl. Russia) and Denmark in 1998. (Source: EMEP, 2000).

1,000 tonnes per yr	Europe	Denmark	Denmark's share of Europe
	6,205		1.4%
	6,923		1.0%

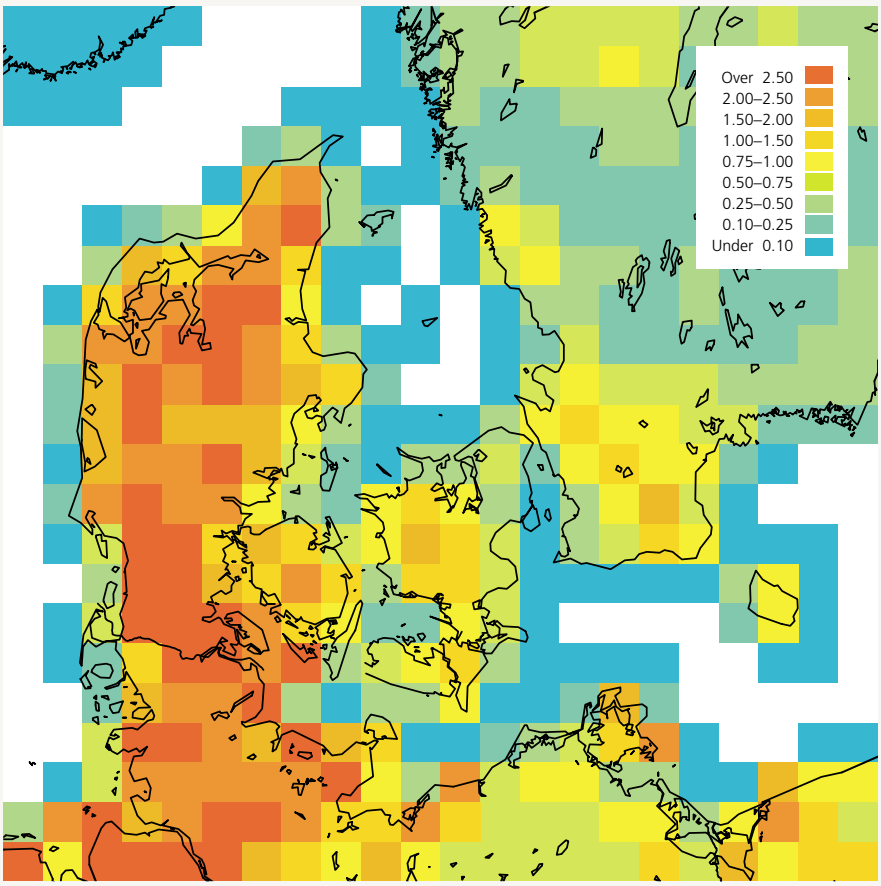


Figure 2.4.7
Ammonia emissions in Denmark and adjacent areas in 1998 in tonnes NH_3-N/km^2 per yr in a 25 × 25 km grid. (Source: Brandt and Hertel, 2001).

emissions. The proportion of total emissions accounted for by these sources has not changed substantially since 1985.

The loss of ammonia from manure was reduced by 26 kilotonnes of NH_3-N from 1985 to 1999; 20 kilotonnes of this reduction resulted from changed manure application practices.

Nitrogen excretion from livestock farming has changed as a result of a reduction in excretion per livestock unit through optimization of fodder composition and by changing the number of animals. The main reduction has been achieved in cattle holdings where both total production and excretion per unit of production have declined. The excretion of nitrogen by pigs has also declined, but this has largely been counteracted by an increase in the number of pigs raised. In 1999, cattle accounted for an estimated 34% of ammonia emissions from livestock farming and pigs accounted for 54%. The figures for 1985 were 42% for cattle and 52% for pigs.

Ammonia emission from growing crops can be considerable, but there have been very few studies of this in Denmark. The loss mainly seems to depend on the plant species, the stage of maturity and the nitrogen status such that a high nitrogen content in plants causes increasing loss to the environment. Emissions from crops were reduced by an estimated 2 kilotonnes from 1985 to 1999 through set-aside schemes reducing the fertilized area, by increasing the area of land farmed organically and as a consequence of a general reduction in agricultural acreage. The ammonia emissions from commercial fertilizer have been reduced by 2 kilotonnes of NH_3-N per year due to the decline in the use of commercial fertilizer in the 1990s.

Deposition of nitrogen on natural ecosystems

The deposition of atmospheric nitrogen only has important ecological effects on forests and natural ecosystems and on the aquatic environment. The atmospheric input to agricultural land is of minor significance relative to the other nitrogen inputs to fields. The Danish stations for measuring atmospheric deposition are therefore mostly located in forests and natural ecosystems. Deposition is also referred to as flux, defined as the amount of nitrogen per unit of land area per unit of time, e.g. kilograms of NH_3-N per hectare per year.

The regional variation in the concentrations of nitrogen compounds in precipitation from 1990 to 1995 was determined based on 17 measuring stations throughout Denmark. The ratio between ammonium and nitrates in the precipitation sampled at background stations in Denmark was very close to 1:1. The deposition of nitrogen with precipitation is evenly distributed throughout Denmark, peaking in central and southern Jutland. The reduced deposition in coastal regions and in the sea results from reduced local pollution concentrations and the generally reduced amount of precipitation in these areas. The geographical variation is small: About ±15% in relation to the mean.

Nitrogen compounds can also be deposited in dry weather, including both gasses and particulate matter. Direct determination of the dry deposition of most substances is difficult. Further, knowledge of the environmental factors that determine the magnitude of deposition is still limited. For ammonia, the ability of vegetation to absorb or emit ammonia is particularly poorly studied.

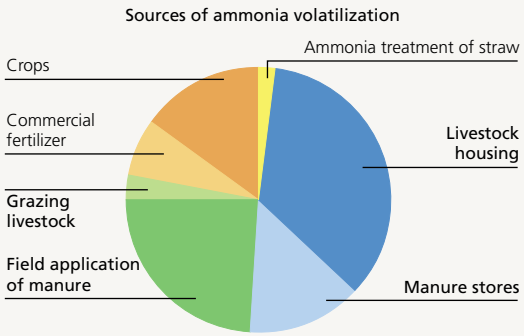


Figure 2.4.8
Sources of ammonia volatilization in Denmark in 1999. Emissions from livestock production are indicated by bold typeface. (Source: Andersen et al., 2001).


Photo: CDanmark

Dry deposition of ammonia on forests has been measured experimentally for various periods of time in the Ulborg State Forest District in western Jutland (*Figure 2.4.9*). The measurements showed that the flux in forests varies widely, in part because concentrations and weather change and in part because the absorption on vegetation surfaces varies strongly over time.

Thus it transpires that with forests located near agricultural areas, the flux of ammonia goes in both directions: not only is ammonia deposited in the forest, but the forest emits ammonia in certain situations. Deposition generally occurs under low temperature and high humidity, whereas warm and dry weather seems to reduce deposition or even leads to emission. The nitrogen status of the ecosystem also influences this process, as some of the measurements indicate that the level of ammonia volatilization is the same as for crops. Similar observations for ammonia flux have been made in forests in the Netherlands and in other natural ecosystems in England.

The dry deposition of a substance is often estimated based on the atmospheric concentration and the rate of deposition, i.e. the rate at which the substance is deposited on the surface. The concentration can often be measured, but the rate is estimated, often based on meteorological observations and assumptions about deposition on the surface.

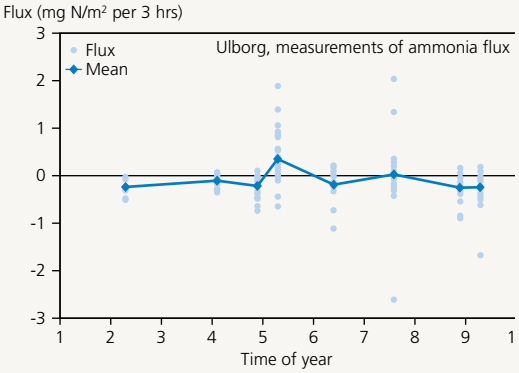


Figure 2.4.9

The flux of ammonia to forest measured in Ulborg Forest District during various times of the year during the period 1991–96. Negative values indicate a downward flux, i.e. net deposition, while positive values indicate an upward flux, i.e. net emission. Each data point represents a 3-hr measurement. (Source: Andersen et al., 1999).

Figure 2.4.10 presents an example of regional variation of nitrogen deposition in forests by showing the deposition of various nitrogen compounds at three forest locations in Denmark. The estimates are based on the concentrations measured at the three forest measuring stations Ulborg, Frederiksborg and Lindet, meteorological parameters and the estimated deposition rates for the substances. Ammonia comprises a large but regionally variable proportion of the nitrogen deposition. The deposition of the other nitrogen compounds is relatively similar at the three forest stations because the pattern of concentration is more uniform for these compounds. Deposition can vary somewhat from year to year.

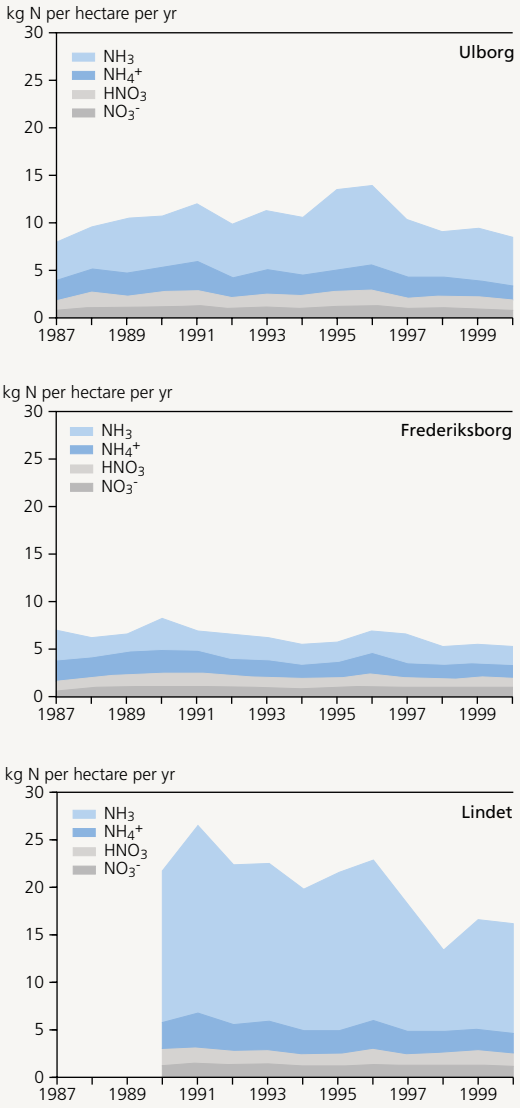


Figure 2.4.10

Dry deposition of various nitrogen compounds expressed in kg NH_3-N/ha per yr at the three forest measuring stations. NB: It should be noted that the Lindet measuring station was moved 1 km further away from the local source at the beginning of 1997.

(Source: Hovmand et al., 2001).

Ammonia emissions within the local area vary for each of the three measuring stations. High ammonia deposition results if the emissions in the area are high. Thus, the emissions from the agricultural land near Lindet Forest total 30–40 kg of nitrogen per hectare per year. This tract of forest in the Sønderjylland State Forest District is further affected by a large pig farm located 1.5 km southeast of the measuring station. The measuring point was located 0.5 km southeast of the pig farm before 1997. Ammonia deposition is especially high at this location. The Frederiksborg station in northern Zealand has the lowest ammonia emissions, being located in an area with relatively little livestock farming. The tract of forest in the Ulborg State Forest District in western Jutland has an intermediate position, the emissions in the surrounding agricultural land amounting to about 20–40 kg of nitrogen per hectare per year.

The atmospheric concentration of ammonia and the resulting deposition in forests and natural ecosystems are much more dependent on the local conditions than is the dry deposition of particulate matter and wet deposition. Despite the great local variation in the concentration of ammonia, some regions of Denmark generally have a higher concentration of ammonia than do others. These regions also tend to have greater deposition of ammonia. The regions with high deposition of ammonia on natural ecosystems thus coincide with the parts of Denmark in which the deposition of ammonia is high because of intensive livestock farming. It is therefore often not only a single source of ammonia that decisively affects the concentration of ammonia in natural ecosystems, but the total of all sources in a larger area depending on the wind direction.

Local concentration and deposition

The local atmospheric concentration of ammonia is closely associated with the current local ammonia emissions, which vary over time and according to location. The ammonia concentration in ambient air thus depends especially on the distance to livestock housing and manure storage facilities and on the conditions under which manure is spread on fields. The concentration also varies according to the humidity of air and the soil, temperature, wind speed and to some extent on the chemical composition of the particles. Thus, the concentration of ammonia varies diurnally and seasonally. The concentration is usually highest in the spring (when manure is spread) and in the late summer.

The local pattern of ammonia dispersion is very important in assessing the effects on natural ecosystems. When air containing ammonia passes over an area with no sources of ammonia, such as a forest or a natural ecosystem, the concentration declines as a function of the distance from the edge. Declining concentration normally produces declining deposition. The magnitude of the decline in concentration and thereby deposition depends strongly on the distance from and the types of sources in the catchment area located upwind of the area with no sources. Thus, sources up to 10–30 km away can influence the concentration in a given area.

The more local variation of ammonia deposition around a point source can also affect the development of nitrogen-sensitive habitats. Large livestock farms increase the local ammonia concentration and thereby also deposition. Local vegetation damage can also occur. A study in the Netherlands concludes that emissions of 10,000 kg of nitrogen per year pose a great risk of harming plants within 100 m from the livestock housing regardless of the wind conditions and some risk within 200 m depending on the wind conditions. A study of various types of vegetation in Scotland located near four livestock farms (chickens, pigs and cattle) emitting between 4,000 and 14,000 kg of nitrogen per year found clear associations between increasing ammonia concentrations and deposition and the increasing concentration of nitrogen in various parts of the plants. Ammonia deposition clearly affected the forest floor vegetation 50–300 m from the livestock facilities, equivalent to deposition exceeding 20 kg of nitrogen per hectare per year.

Modelling of nitrogen deposition on a local scale in a small part of Vejle County can illustrate the association between emissions, deposition and the location of natural ecosystems. It also illustrates the difficulty in determining the deposition on these ecosystems, which often comprise small areas in a mosaic of agricultural parcels (*Figure 2.4.11*). The map indicates the location of the livestock housing and the magnitude of the emissions from the livestock housing and manure storage facilities.

The simplified model calculations assume that the rate of deposition is identical for cultivated land and for natural ecosystems. In reality, forests and natural ecosystems have greater capacity to absorb ammonia than does intensively cultivated land, which emits ammonia for long periods of time. The emission coefficients used for the calculations are overestimated as the national estimates of ammonia emissions were revised in 2000; calculations using these new figures are not yet available. As the map shows, the model finds a considerable ammonia load near the sources, due to dry deposition of ammonia. The natural ecosystems are located in a dispersed pattern around the sources. The ones located near the sources are exposed to a greater nitrogen load that increases with the size of the livestock holding.

Temporal trends

Concentrations of gaseous ammonia and particulate ammonium in ambient air have been measured at six stations in Denmark since the late 1980s.

The concentration of ammonia varies according to time and place *(Figure 2.4.12*). Except for the Tange measuring station in central Jutland, the ammonia concentration measurements for the period 1987 to 2000 do not exhibit any decline, even though emissions in Denmark declined by 30% from 1985 to 1999 and those in Europe by about 17% from 1985 to 1998. Any decline could be difficult to identity because the concentration varies substantially from year

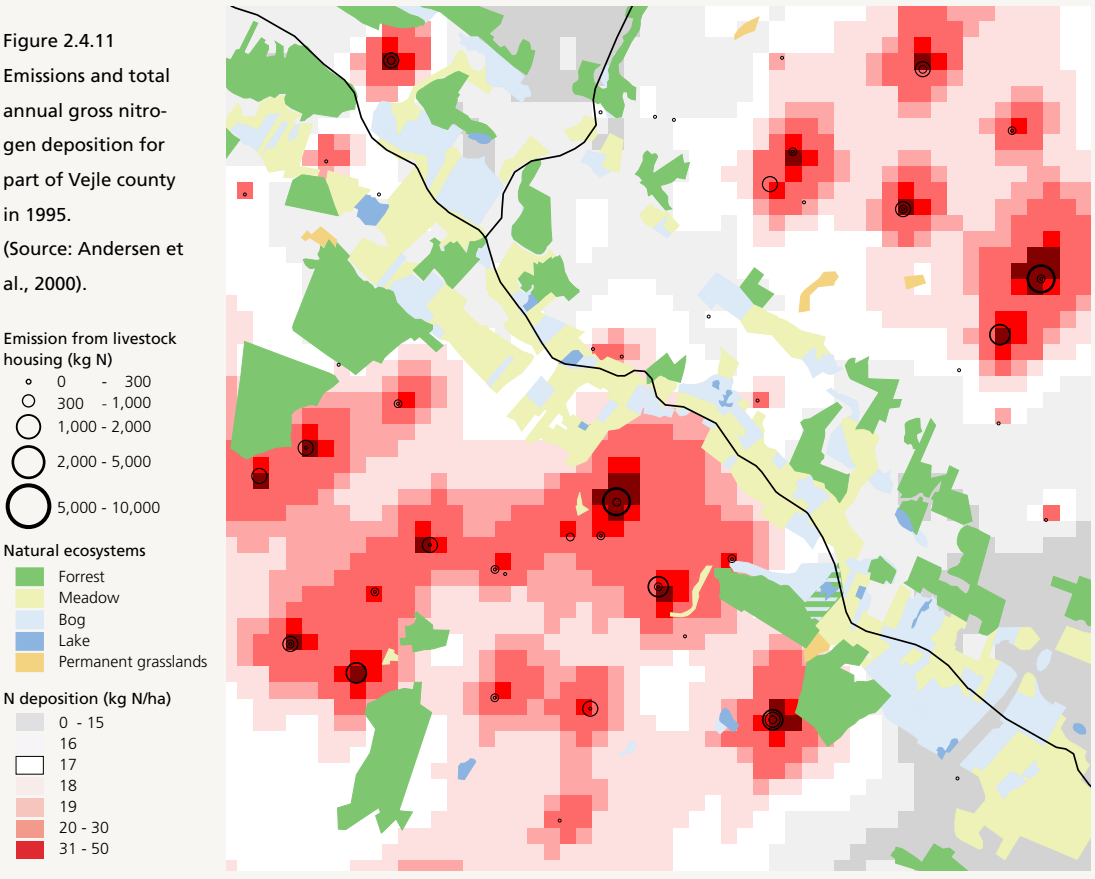


Figure 2.4.11
Emissions and total annual gross nitrogen deposition for part of Vejle county in 1995.
(Source: Andersen et al., 2000).

to year, but the lack of decline could also result from changes in the characteristics of the atmosphere as the sulphur emissions have declined. This could very well influence the conversion of ammonia to ammonium such that this reaction may occur more slowly because ambient air contains fewer sulphuric acid particles. Further, the measurement method is subject to limitations and should be assessed solely based on the combined concentrations of gaseous ammonia and particulate ammonium. The concentration of the part measured as particulate ammonium has clearly declined by more than 30%, and thus the sum of gaseous ammonia and particulate ammonium has also declined. In addition, the ammonia concentration measured in the Netherlands using more ammonia-specific methods did not decline either despite reduced emissions. Wet deposition of ammonium and nitrate declined moderately from 1987 to 2000 (*Figure 2.4.12*).

If the rate of conversion of ammonia to ammonium has declined as sulphur emissions have declined, this will affect the local dispersion of ammonia because the ammonia remains in the atmosphere for a longer time, with local emissions thereby influencing a larger area.

Exceedance (%)

	Oak	Beech	Spruce	Pine
Acidification	38	30	44	47
Eutrophication	51	40	81	81

Exceedance in percent assuming a 50% reduction

	Oak	Beech	Spruce	Pine
Acidification	28	22	35	40
Eutrophication	35	26	70	73

Table 2.4.4 (above)
Estimates of the percentage of forest area where the critical load for acidification and eutrophication is exceeded.
(Source: Bak et al., 1999).

Table 2.4.5 (below)
Estimates of the percentage of forest area where the critical load for acidification and eutrophication would be exceeded assuming a 50% reduction in ammonia emissions.
(Source: Bak et al., 1999).

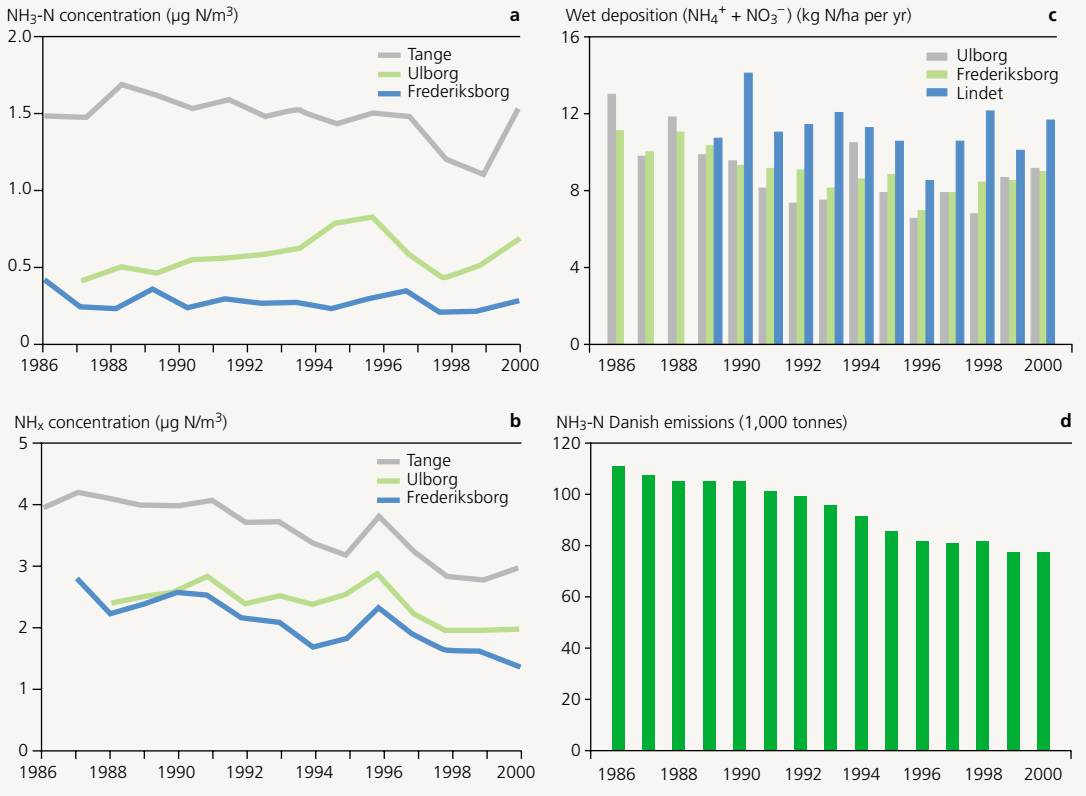


Figure 2.4.12
Annual mean concentration of gaseous ammonia (NH_3) (a), the sum of gaseous and particulate ammonia (NH_x) (b), and wet deposition of ammonium and nitrate ($NH_4^+ + NO_3^-$) (c).
(Source: Hovmand, 2001 b).
In addition, the figure shows the annual Danish emissions of ammonia (d).
(Source: Andersen et al., 2001).

Reduction scenarios

A 1999 report on ammonia from NERI estimates the exceedance of critical loads for acidification and eutrophication in Denmark's forests and natural ecosystems. Estimates were also made for a scenario in which Denmark's ammonia emissions were reduced by 50%. *Tables 2.4.4* and *2.4.5* show the current proportion of specific types of ecosystem exceeding the critical loads for eutrophication and acidification and the projected proportions based on a 50% reduction in Denmark's ammonia emissions. The critical loads and deposition were calculated using modelling and have an expected uncertainty of about 30–50%. A mean value and a 90% confidence interval have been calculated based on the estimated uncertainty.

The calculations show that exceedance of the critical loads for acidification and eutrophication cannot be eliminated to any great extent since transboundary pollution from other countries will continue to cause exceedance of critical loads. The exceedance is least pronounced for beech and oak forests, and a 50% reduction scenario would reduce this problem substantially.

Denmark's critical loads for the eutrophication of terrestrial habitats are empirically established for sensitive ecosystems such as heaths, dune heaths, raised bogs and dry grasslands. The uncertainty of the critical loads has only been assessed qualitatively, and the established critical loads are assessed as being reliable for heaths or very reliable for dune heaths, raised bogs and dry grasslands. The following critical loads were established:

Ecosystem type	Critical load (kg N per ha per year)
Inland heaths	15 – 20
Dune heaths	10 –15
Dry grasslands	10 –15
Raised bogs	5 –10

Reducing ammonia input would reduce the proportion of ecosystems that are threatened, although the critical load for raised bogs is so low that a 50% decline would not improve the situation noticeably, even if the exceedance is calculated for the upper limit of the critical load range. For inland heaths, a 50% reduction would virtually eliminate the threat of eutrophication. Between 0 and 40% of heaths are calculated to exceed the critical load for the highest and lowest limits. A 50% reduction would reduce this to less than 1%. For dune heaths, the threatened area would be reduced from 1–37% to 0–3%.

It should be noted that these model calculations are subject to some uncertainty in both setting the critical loads and calculating the deposition. The estimates of emissions on which the calculations are based were revised in 2000, but the new figures are not yet available.

Objectives and initiatives

In connection with the political agreement on Denmark's second Action Plan on the Aquatic Environment in 1998 it was decided that an action plan would be prepared for reducing ammonia emissions from agriculture. The action plan on ammonia was presented in May 2001. The overall objective is to reduce the input of nitrogen to Denmark's aquatic environment, but another objective is to contribute to conserving and protecting Denmark's vulnerable ecosystems with their associated plant and animal species. The action plan on ammonia focuses on optimizing the various stages of fertilizer management and includes such measures as prohibiting ammonia treatment of straw. Another measure is limiting the local ammonia volatilization from livestock farms near vulnerable ecosystems. The effect of implementing the action plan would be an additional decline in ammonia emissions from the 77 kilotonnes of NH_3-N in 1999 to 68.3 kilotonnes in 2003. The Wilhjelm Committee on biological diversity and nature protection, which prepared a proposal for a national action plan on biological diversity and nature protection, proposes designating buffer zones of up to 300 m around vulnerable ecosystems in which ammonia emissions would be reduced.

The action plan on ammonia should also be viewed in connection with Denmark's accession to numerous international agreements, as expressed in the United Nations Convention on Biological Diversity, the EU Habitats Directive, the EU strategy to combat acidification and the Convention on Long-range Transboundary Air Pollution. In relation to the EU strategy to combat acidification and the Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (to the Convention on Long-range Transboundary Air Pollution), Denmark has committed itself to an emissions ceiling in 2010 of 69 kilotonnes of ammonia (equivalent to 56.8 kilotonnes of NH_3-N) from manure, commercial fertilizer and wastewater. The current initiatives under the second Action Plan on the Aquatic Environment and the proposed action plan on ammonia would reduce Denmark's emissions from these sources to 55.8 kilotonnes of NH_3-N. Denmark will thus fulfil its international commitments to reduce ammonia emissions by 2003. Denmark is in the process of ratifying the Gothenburg Protocol.

Photo: NERI/Morten Strandberg

2.5 Depletion of the ozone layer

Introduction

Anthropogenic emissions of ozone-depleting substances, especially chlorofluorocarbons (CFCs), have thinned the atmospheric ozone layer. About 90% of the ozone is concentrated in the stratosphere (upper atmosphere) located between 10 and 50 km above the surface of the Earth. The ozone layer absorbs most of the harmful ultraviolet radiation from the sun (ultraviolet B radiation), so that thinning of the ozone layer will allow more ultraviolet B radiation to reach the Earth. Increased ultraviolet radiation over a long period can increase the risk of human skin cancer and cataracts and reduce the immune response. Organisms other than man can also be affected. Thus the production and reproduction of plankton in the sea can be affected, and increased radiation can also affect the growth of agricultural crops.

Anthropogenic pressure on the ozone layer

Even though the existence of an ozone layer in the stratosphere had long been recognized, a measuring campaign in the International Geophysical Year (1958) was the first to investigate this thoroughly and the first to provide evidence of permanent depletion of the ozone layer (*Figure 2.5.1*). The fact that the ozone layer could periodically deplete was known, but this was considered a short-term phenomenon in which ozone would naturally be regenerated and the concentration over a period of years was considered to be constant.

In 1974, the scientific theory was proposed for the first time that chlorine from CFCs released through photolysis could deplete the stratospheric ozone layer. CFCs are chemically inert compounds with a high vapour pressure at room temperature, and this means that they go directly to a gaseous phase upon emission. Bromine released through the photolysis of halons (chlorofluorobromocarbons) has the same effect. These character-

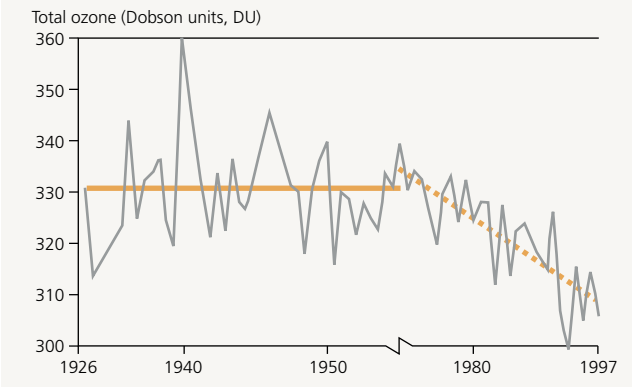


Figure 2.5.1
Measurements of ozone over Arosa in Switzerland over the period 1926–97. Until 1973 the level fluctuated around a mean of 326 DU. The total amount of ozone above a given spot is called the ozone column. This is the height of the ozone layer adjusted to standard conditions (i.e. 0°C and 1,013 hPa.) and expressed in hundredths of a millimetre – so-called Dobson units (DU). The height is also commonly expressed in "millimetres" adjusted to the same conditions. Typical values are around 300 DU. In 1973, the thickness of the ozone layer started to decrease by an average of approx. 0.03% per year.
(Source: IACETH, 2001).

istics make these substances well suited for several technical uses, but are also decisive for their harmful environmental effects. The long lifetime in the atmosphere (40–150 years) means that they can be transported to the stratosphere, where they are exposed to the ultraviolet light that catalyses the depletion of ozone, especially at a height of 35–45 km above the surface of the Earth. Since the greatest quantity of ozone is present at lower altitudes (15–25 km), CFCs were only expected to cause a small decline in the total quantity of ozone. This turned out to be a mistake!

The ozone hole over Antarctica

In the early 1980s it became clear that the effects would be much more serious. Surprisingly, the most serious effects began in Antarctica, where up to 50% of the total ozone disappeared in a few weeks in the spring. The reason was heterogeneous chemical reactions on the surface of particles in the stratosphere.

In the winter a vortex is created over Antarctica in which the winds circulate around the South Pole. The inner part of this vortex is very cold, and clouds of particles are created that act as a reservoir for ozone-depleting substances. When the temperature rises in the spring (autumn in the Northern Hemisphere), these compounds are released and lead to an ozone hole over Antarctica, which now recurs every year. The most recent measurements of the ozone layer over Antarctica and updated documents on this theme are available on the Internet.

Ozone over the Arctic region

One might think that ozone depletion would be greater in the Northern Hemisphere where most sources of ozone-depleting substances are located, but in fact the ozone layer is not depleted as rapidly in the stratosphere over the Arctic region as in Antarctica. The reason is that the Earth's two polar regions are different. Antarctica is a continent surrounded by oceans, whereas the Arctic region is an ocean surrounded by continents. This means that the Arctic region is not as cold in the winter; the ozone hole often only lasts a few weeks, and the mean annual concentration of stratospheric ozone is 7–8% less than in other comparable areas. Substantial increases in mean ultraviolet radiation have not yet been registered; one reason is that the ultraviolet B radiation varies naturally by as much as ten-fold from the Lofoten Islands in Norway (78°N) to Kenya (at the equator).

The ozone layer over Denmark

The Danish Meteorological Institute regularly measures the total amount of ozone (ozone column) over Denmark. The mean value for Denmark is 350 Dobson units (range 200–450). As mentioned previously, the quantity of ozone in the stratosphere varies greatly (*Figure 2.5.2*), being highest in the spring and lowest in the autumn. The ozone column over Denmark is declining by a mean of 0.4% per year, slightly more in the spring and slightly less in the autumn.

Regulation of CFCs

The first international agreement on regulating ozone-depleting substances, the Vienna Convention, was signed in 1985. A total of 161 countries have ratified the Montreal Protocol, which followed the Vienna Convention in 1987:

The Montreal Protocol regulates seven groups of ozone-depleting substances:

- Since 1995, the use of CFCs has only been allowed in medical products and for laboratory analysis
- Halons (chlorofluorobromocarbons) have been prohibited from being produced and imported in industrialized countries since 1995
- Carbon tetrachloride and tricholoroethane have been limited to laboratory use since 1995
- The use of hydrobromofluorocarbons (HBFCs) has been prohibited since 1996
- The use of hydrochlorofluorocarbons (HCFCs) and methyl bromide will be phased out over a period of years.

Denmark has been a leader in phasing out ozone-depleting substances. Thus, in 2000, the only permitted uses were HCFC's in refrigeration units and special exceptions for other substances for medical use or in laboratories.

Just as the effect of greenhouse gasses relative to CO_2 can be assigned a global warming potential, ozone-depleting substances can be assigned an ozone depletion potential. This is calculated relative to the ozone-depleting effect of CFC-11 ($CFCl_3$), which is (or was) the most important substance in this context. Denmark's use of ozone-depleting substances declined by 98% from 1986 to 1998 (*Figure 1.5.28*). The phase-out has also been successful in the rest of the world. The decline in the world production of CFCs has been accompanied by increasing production of CFC substitutes such as HCFCs and hydrofluorocarbons (*see Section 1.5*).

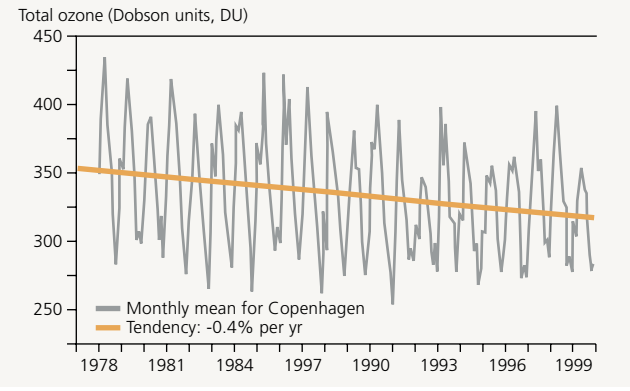


Figure 2.5.2

Change in the ozone column above Denmark since the end of the 1970s. (Source: Danish Meteorological Institute, 2001).

Photo: Unknown

2.6 The greenhouse effect and anthropogenic climate change

The historical background

It was already known in the mid-nineteenth century that the atmospheric concentration of CO_2 is decisive for the heat balance of the Earth, and in the late 1930s the effects of the anthropogenic emissions of CO_2 were estimated for the first time. This did not arouse great interest, however – the effects were considered more positive than negative, and the world was more focused on economic crisis and the threat of world war. Scientific attention was first aroused in the mid-1950s, and systematic measurement of the concentration of CO_2 in air began as part of the International Geophysical Year (1958).

It was not politically recognized that the concentration of carbon dioxide could be a problem until after the 1987 publication of ***Our common future***, the report of the UN World Commission on Environment and Development. This lead to the establishment of the Intergovernmental Panel on Climate Change (IPCC), which compiles and assesses all scientific literature on climate change and regularly publishes reports.

The IPCC published large comprehensive assessments in 1992, 1996 and 2001; these form the basis for the international efforts in relation to the United Nations Framework Convention on Climate Change. Although the IPCC's assessments have become more certain, the basic message has not changed: severe anthropogenic climate change is a risk if the growth of global emissions of greenhouse gasses is not severely restricted and subsequently reduced. Nevertheless, the IPCC has recognized that some climate change is now inevitable, and this should be assessed in relation to other environmental effects and the economic consequences.

Effects on climate

The main greenhouse gas responsible for the anthropogenic influence on the heat balance is CO_2. The atmospheric concentration of CO_2 has increased from 280 to 370 ppm (about 30%) since the pre-industrial era in the nineteenth century. The main cause is the use of fossil fuels, but changing land use, including forest clearance, has also been a significant factor. The concentrations of the greenhouse gasses methane and N_2O, which are highly linked to agricultural production, have increased by 150% and 16%, respectively. The

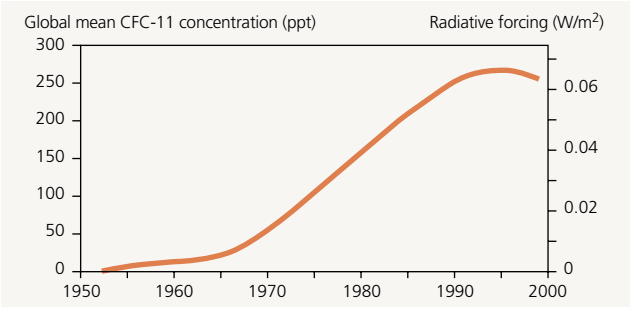


Figure 2.6.1
The global mean atmospheric concentration of CFC-11 together with radiative forcing expressed in watt per m². (Source: IPCC, 2001a).

CFCs and related compounds, which are both ozone-depleting substances and greenhouse gasses, were largely unknown before 1945 (*Figure 2.6.1*).

Sulphur pollution plays a dual role. It causes acidification (*Section 2.4*), but sulphate aerosols in the atmosphere counteract the greenhouse effect by reflecting solar radiation. These effects vary locally and are therefore difficult to quantify. The effects also vary regionally as demonstrated by measurements on ice cores in Greenland. The concentration of sulphate increased from 50 mg/tonne in the late nineteenth century to more than 200 mg/tonne in about 1980. Thereafter it has declined. This pattern corresponds approximately to the trends in global emissions of sulphur. Similarly, recent studies in North America and Europe show that sulphur deposition on these continents is declining, mainly because of improved flue gas desulphurization and cleaner fuels. The cooling effect of sulphur compounds in the atmosphere is expected to be reduced further as a result of general environmental efforts in this area.

Changes in the concentrations of greenhouse gasses are not simply related to these effects on the heat balance, however. The various gasses absorb radiation at different wavelengths and with different efficiency. Moreover, the concentrations of some gasses are so high that the radiation at some wavelengths is already nearly fully absorbed. An increasing concentration will therefore have a limited effect. This must be considered in assessing the effects of changes in the concentrations of various gasses. Further, the lifetime of the gasses in the atmosphere needs to be taken into account – the longer they remain in the atmosphere, the greater their overall effects.

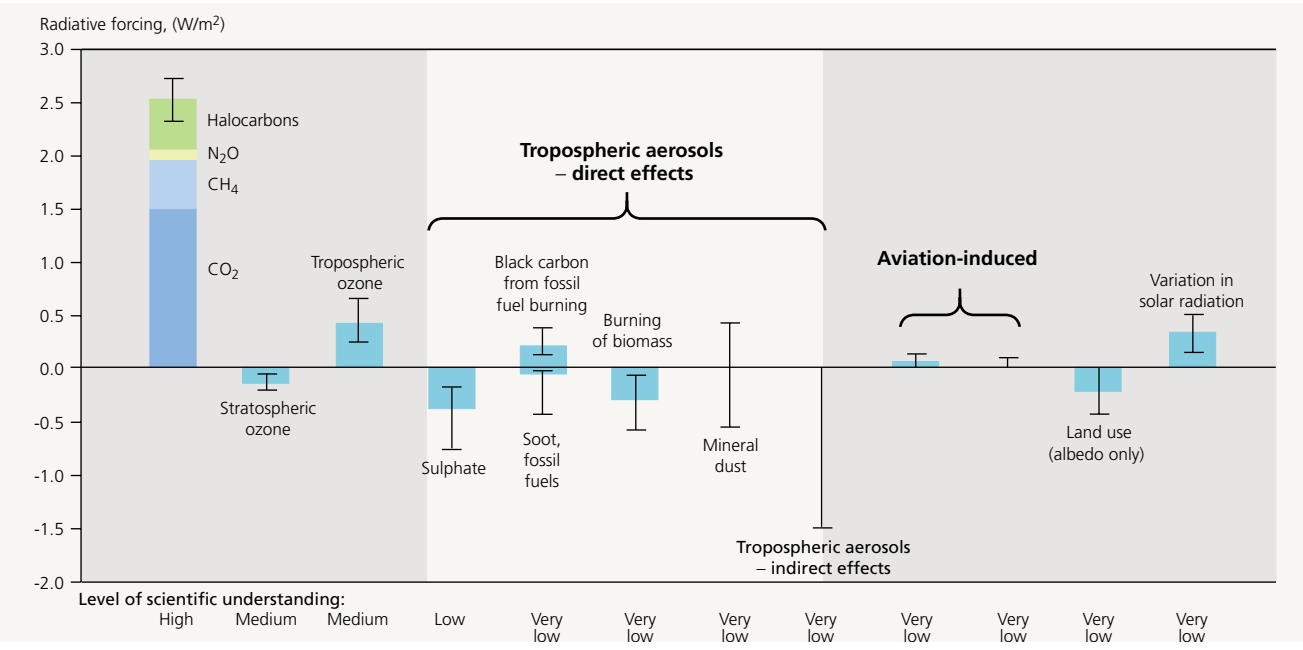
The global warming potential of various gasses has been defined as the warming effect of a given weight of a specific substance relative to CO_2. The purpose of this is to be able to compare and integrate the effects of individual substances on the global climate. The typical lifetimes are 100, 10 and 300 years for CO_2, CH_4 and N_2O, respectively, and the time perspective clearly plays a decisive role. The lifetime chosen is typically 100 years. Then the effect of the various greenhouse gasses can be converted into the equivalent quantity of CO_2, i.e. the quantity of CO_2 giving the same effect in absorbing solar radiation. According to the IPCC, the most recent global warming potential values for a 100-year time horizon are:

- CO_2: 1
- Methane (CH_4): 21
- Nitrous oxide (N_2O): 310.

Based on weight and a 100-year period, methane is thus 21 times more powerful a greenhouse gas than CO_2, and N_2O is 310 times more powerful. Some of the other greenhouse gasses (hydrofluorocarbons, perfluorocar-

Figure 2.6.2

Annual mean radiative forcing of the global energy balance over the period 1850 to the present. The columns indicate the mean values, while the vertical bars represent the uncertainty interval. The level of scientific understanding of the underlying mechanisms is also indicated as high, medium, low or very low. The individual contributions differ in nature. It should therefore be noted that the various contributions cannot simply be added to yield a net forcing.
(Source: IPCC, 2001a).



bons and sulphur hexafluoride) have considerably higher global warming potential values. For example, sulphur hexafluoride has a global warming potential of 23,900. Given the substantial variation in global warming potential, some substances can thus have a measurable effect at minute concentrations. Their combined proportion of the total emissions of greenhouse gasses is modest, however (*see Section 2.2*).

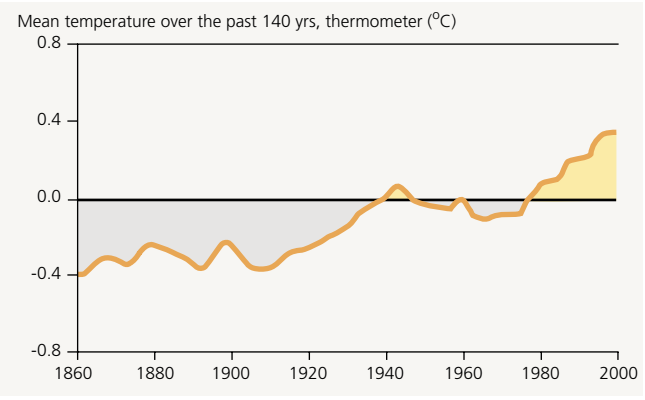
The average solar radiation reaching the Earth is 342 W/m^2, and according to the heat balance the same amount should be reflected back into outer space. Effects on this energy balance are called thermal forcing and are similarly expressed in W/m^2. The IPCC has calculated the global means of the thermal forcing caused by changes in the concentrations of greenhouse gasses and aerosols from the pre-industrial era until the present and the effects of changes in solar radiation since 1850 (*Figure 2.6.2*). The height of the columns indicates the estimated mean values, while the vertical bars indicate the uncertainty in the mean values. The direct positive effects on global warming of CO_2, CH_4, N_2O and halocarbons predominate. The depletion of stratospheric ozone produces negative but uncertain effects, while the increasing ozone concentration in the lower atmosphere produces a correspondingly positive effect. The effects of various types of particulate matter are very uncertain. The effects of changes in land use are expected to be negative and changes in solar radiation positive, but these effects are also poorly understood. Overall, the anthropogenic changes comprise only a few percent of the natural effects, but can still decisively influence the global climate. The short-term effects of such phenomena as volcanic eruptions, which emit particles with cooling effects, have not been included.

Climate change so far

Temperatures have been measured since the seventeenth and eighteenth centuries, but systematic and reliable measurements covering the entire planet first began in about 1860. Assessing whether climate has changed poses the problem that many stations were originally located in rural areas that have now become urban areas, in which the temperature can be about 2°C higher. Measurements of seawater temperatures are similarly subject to changes in the measuring conditions in the form of larger and more rapid ships. The water temperature was previously measured in a bucket that was hauled on deck, whereas modern measurement is conducted in the cooling water intakes. The trends in the mean global temperature can be determined after appropriate correction for these artefacts (*Figure 2.6.3*). The global temperature has risen significantly during two periods: from 1920 to 1940 and since the mid-1970s; 1998 was the warmest year in the period. The warming has not been uniformly distributed across the globe, and some areas around the North Atlantic have even cooled. All interannual variation cannot be explained, but short-term cooling in 1992 and 1993 is attributed to the eruption of Mount Pinatubo in 1991.

The climate in the broadest sense is decisive for nature and for numerous human activities. During the twentieth century the mean global temperature has increased by 0.6°C, and this has caused environmental changes, both positive and negative, in the form of melting polar ice and glaciers, changes in plant growth and animal populations and other effects. Several of these changes have resulted from the effects of human activities on climate, and it is assumed that they will accelerate in the future.

Figure 2.6.3
10-year sliding mean of the global mean temperature over the period 1860–2000 expressed as deviation from the average for the period 1961–90. (Source: IPCC, 2001b).



Temperature measurements from Denmark, the Faeroe Islands and Greenland show that the temperature has increased between 0.3°C and 0.6°C since the end of the nineteenth century, but the interannual variation is substantial (*Figure 2.6.4*). The decline in temperature between 1950 and 1970 is noteworthy.

The temperature in Nuuk, Greenland has also declined in recent years. The annual variation in temperature in Tórshavn, Faeroe Islands is less because the thermal capacity of the sea stabilizes the temperature.

Global trends in precipitation have been poorly determined because oceanic observations are lacking and precise measurements are difficult to make on land. The observed precipitation increased from 1900 until about 1960; since 1980 it has declined. The precipitation observed in Denmark has declined by 10% since the end of the nineteenth century (*Figure 2.6.5*). The trends in total annual precipitation may hide changes in seasonal patterns. The wettest year so far in Denmark was 1999.

Rising sea levels

The global sea level has risen as a result of the increase in mean global temperature. One reason is the expansion of water as it is heated, and the other reason is the melting of glaciers and polar ice caps. Based on measurements of sea level, the IPCC concludes that the sea level has risen by an estimated 10 to 25 cm within the past 100 years. The confidence interval is relatively large because of the vertical movement of the Earth's crust, which has to be controlled for in the measurements.

The sea level in Danish marine waters has generally risen in the past 100 years and especially in the past 30 years. Since Denmark is tilting – the land is raised in the northeastern part of the country and lowered in the southwestern part – the relatively largest rise is occurring in southern Denmark: about 1 mm per year.

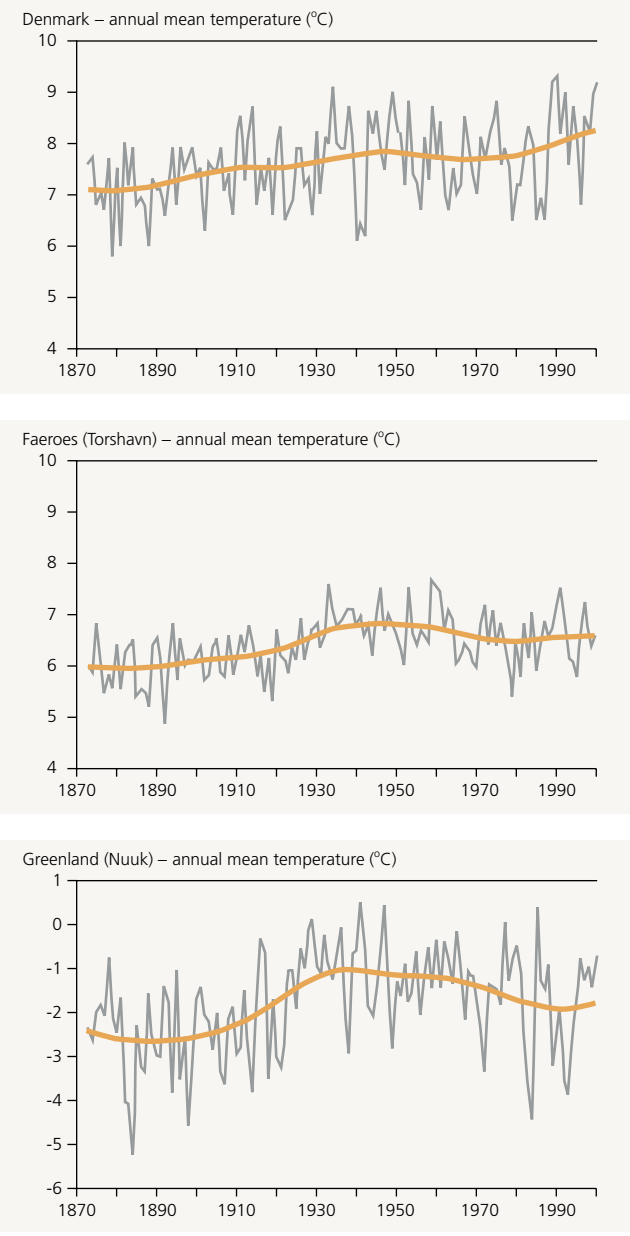


Figure 2.6.4
Temperature trend in Denmark, Faeroes (Torshavn) and Greenland (Nuuk) since 1873. Sliding means are shown. The individual years can deviate more than 1°C.
(Source: Danish Meteorological Institute).

The climate of the future

The third main assessment from the IPCC concludes that about half the observed increase in temperature is probably the result of human activities, and the IPCC presents reinforced arguments advocating that the increase in the anthropogenic greenhouse effect will inevitably result in some climate change. The magnitude of the changes, the time frame and the distribution around the globe are still uncertain and will depend on the extent to which the global emissions of greenhouse gasses can be reduced.

The climate is generally expected to become warmer, but with great regional differences. The greatest changes will occur at high latitudes. The pattern of precipitation is also expected to change. Since warmer air can contain more water vapour, the total global precipitation is expected to increase. The distribution of the precipitation according to season is more important than the absolute quantities. Several models indicate that the frequency of dry summers and wet winters will increase. In addition, the frequency of episodes of heavy precipitation is expected to increase, and this has already been observed in part.

Continuing global warming will be accompanied by an increase in the sea level. This will also differ according to region because of changes in atmospheric wind systems. In practice, the local, relative sea level and the risk for extreme values are the key factors in determining the effects of a global rise in sea level.

Emission scenarios

Moving from observations of the past to scenarios for the future makes the conclusions more hypothetical; they have to be based on complex modelling.

The preparation of the latest IPCC assessment (2001) therefore included numerous scenarios for global development towards the year 2100. They are categorized under four families of storylines depending on whether the main emphasis is on economic versus environmental development and global versus regionally oriented development (*Figure 2.6.6*) and describe the following:

- **A1**: A future world of very rapid economic growth, a global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies
- **A2**: A very heterogeneous world with continuously increasing global population and technological change that is more fragmented and slower than in other storylines
- **B1**: A world similar in certain ways to A1 but with rapid changes in economic structures toward a service and information economy and the introduction of clean and resource-efficient technologies
- **B2**: A world with continuously increasing global population at a rate lower than A2 and less rapid and more diverse technological change than in the B1 and A1 storylines.

As a whole, these storylines cover various combinations of growth in world population (the population ranging from about 7 billion to 15 billion), growth in global gross national product (by a factor of 11 to 26), distribution of energy production according to fossil and non-fossil energy sources and other parameters.

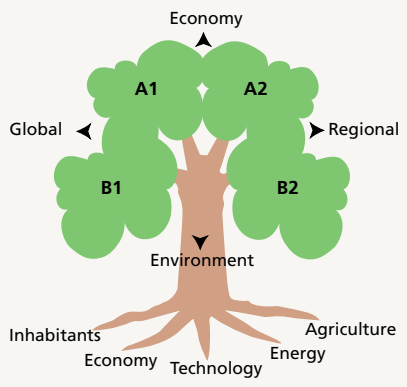


Figure 2.6.6
The IPCC's four families of storylines and the driving forces behind them.
(Source: IPCC, 2001c).

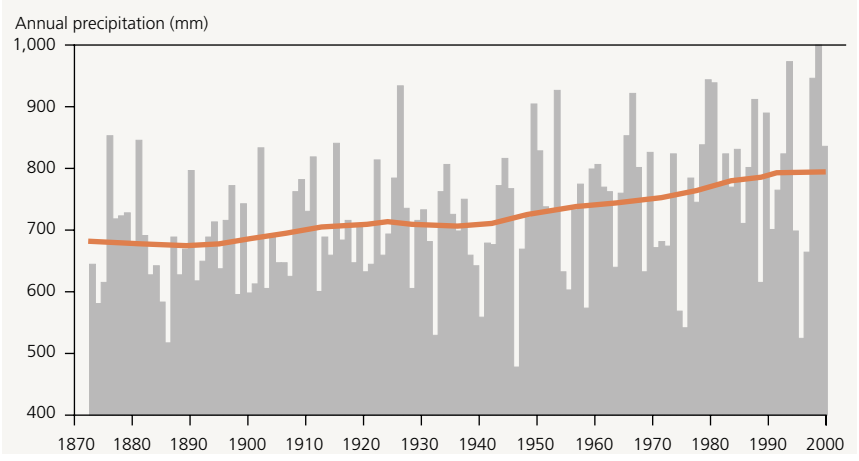


Figure 2.6.5
Observed annual precipitation in Denmark since 1874. Although there is considerable interannual variation, the smooth curve, which represents a 30-yr sliding average, indicates a general trend towards increasing precipitation.
(Source: Danish Meteorological Institute).

Although a few unrealistically optimistic scenarios include a decline in CO_2 emissions, all imply an increasing concentration from the present 370 ppm to 500–1000 ppm towards the year 2100.

Global climate scenarios

The corresponding increases in global mean temperature are calculated to be 1.4°C to 5.8°C towards 2100; this is the global mean but regional variation will be great. Precipitation is expected to increase in the winter and decline in the summer outside the tropics. Subtropical areas may be particularly affected by reduced precipitation. Further, the seasonal distribution of rain will change. Finally, more precipitation will fall as rain and less as snow, which will change the runoff pattern and thereby the pattern of water use. Very special conditions therefore pertain in areas where part of the water resources derive from melting of glaciers in the summer. The range of the projected mean global temperature and the potential resulting environmental effects is great (*Figure 2.6.7*).

If the concentrations of CO_2 and other greenhouse gasses are stabilized, the climate will probably reach a new thermal balance in the course of about a couple of hundred years. The rising sea levels would be a different situation, however. The various scenarios produce further rises in the global mean of between 9 and 88 cm towards 2100, but because glaciers melt slowly and especially the oceans warm very slowly, the sea level will continue to rise for several hundred years after the global warming began.

Although climate change can thus not be fully avoided, any slowdown in emissions will make adaptation easier. One possible course is a new climatic balance after a few hundred years (*Figure 2.6.8*).

It has been discussed in various contexts whether increasing global warming could cause substantial and abrupt climate change, such as by changing the great ocean currents. This does not seem likely, and most climate projections show that the Gulf Stream in the North Atlantic is only likely to be slightly weakened. This could mean that northern Europe might not experience as strong greenhouse warming as might otherwise be the case. Because current climate modelling still cannot reproduce the already observed changes in climate, it cannot be excluded that the deep water circulation system in the Nordic seas will be affected to a degree never previously seen.

Figure 2.6.7
Projected temperature increases for the IPCC's scenarios. The grey area represents the overall range of all combinations of many models and scenarios.
(Source: IPCC, 2001d).

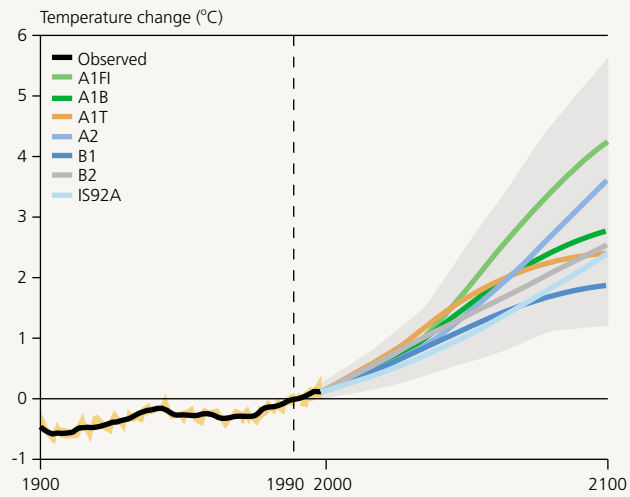
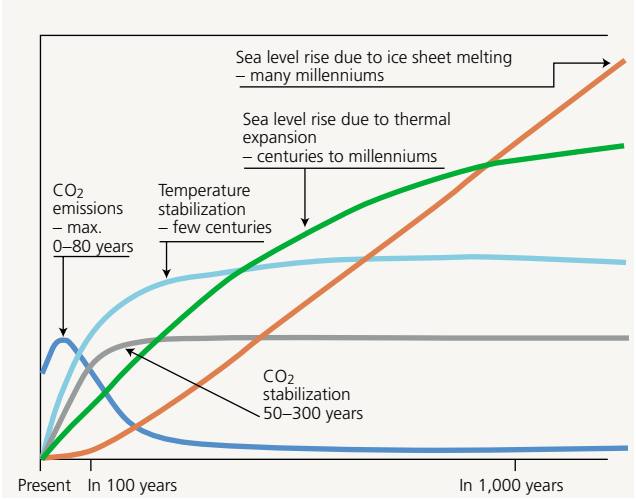


Figure 2.6.8
Time horizons for various aspects of the greenhouse problem. The figure is purely qualitative, but could indicate stabilization at twice the present CO_2 level and a global temperature increase of approx. 4°C. The final rise in sea level could be as much as several metres.
(Source: IPCC, 2001e).



A scenario for Denmark

The starting-point for assessing the effects in Denmark of anthropogenic climate change continues to be uncertain. The main reason is that the world can develop in many possible ways. Some assumptions must therefore be made (an emission scenario) that are realistic but that may never be realized. Further, however, the climate models still have numerous uncertainties, and their ability to project changes at a sufficiently fine resolution is at the borderline of what is required to examine the consquences for a small area such as Denmark.

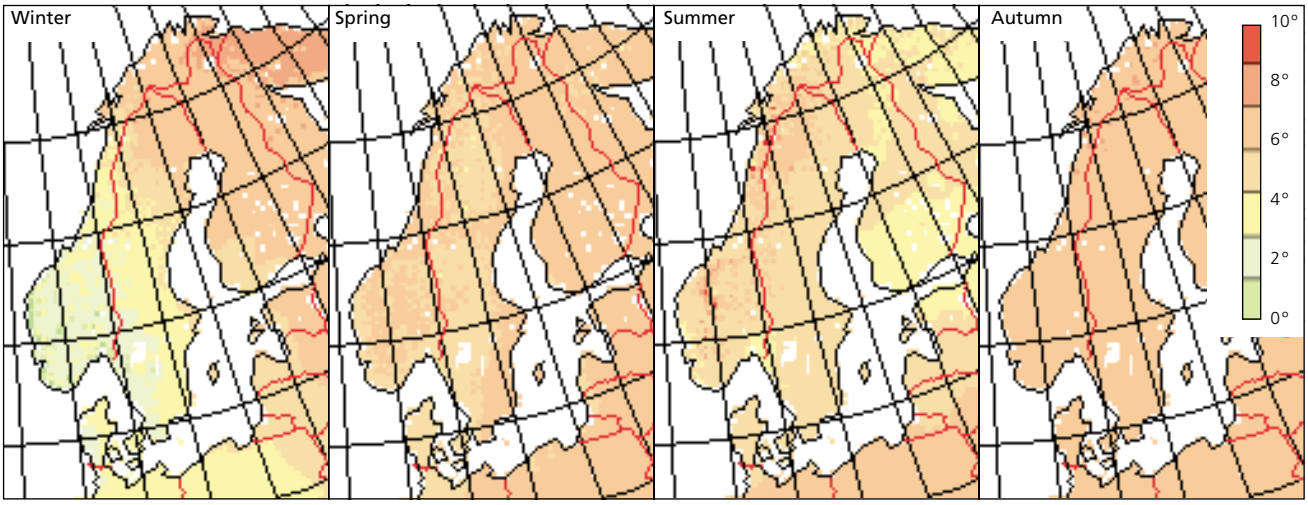
Global climate modelling has a resolution of only 300–500 km, but this can be improved by operating models with high resolution for a small area in which the conditions at the periphery continue to be determined by the results of the global model. Several Nordic climate centres have made this type of calculation for Scandinavia. One modelling simulation used the IPCC emission scenario IS92a ("business as usual"), which produces global warming of about 4°C by 2100 and compares the climate in about 1990 with the climate in about 2075 – trends over slightly less than a century (*Figure 2.6.9*). The model found a general warming of about 4°C for Scandinavia that is greater in the northernmost regions, during the winter and at night. This means that the diurnal and seasonal variation will decline.

As mentioned previously, large direct changes in the great ocean currents are not likely. Model calculations made by the Danish Meteorological Institute show a weakening during the next century followed by regeneration. This will probably not produce net cooling in Denmark but merely slow the warming.

Analysis of the projected precipitation shows a tendency towards a wetter climate with more frequent heavy precipitation. The precipitation for Denmark is projected to increase by 5–10%, with the greatest increase in the winter and the possibility of a slight decline in the summer. Overall, it will not rain more frequently but will rain more heavily when it rains. For Denmark, the calculations show that the amount of precipitation falling in heavy episodes with a rate of more than 15 mm per day will increase by about 50%.

The total effect on runoff to watercourses in Denmark from December to April is expected to increase about a further 10%. Changes in the summer runoff continue to be very uncertain.

Figure 2.6.9
Differences in mean temperature in Scandinavia today and in 2075 (model predictions) shown for each season. The colours indicate for each season the difference between the climate today and the modelled climate around the year 2075.
(Source: Christensen, 2000).



Consequences of climate change

The expected climate change corresponds very roughly to moving the world's climate zones a few hundred kilometres towards the poles. In the mountains, this increase in temperature is equivalent to a change in height analogous to a change in climate zones. These changes may not sound very great, but over the span of a century it corresponds to more than the migration rate of many tree species. In marginal areas in particular, some ecosystems may therefore disappear and be replaced by others.

Nevertheless, it cannot be assumed, for many reasons, that a specific area in the long term will have vegetation like that present slightly closer to the equator. The diurnal and seasonal pattern of solar radiation will not change, and most plants have already adapted to the existing variable weather and climate. Solar radiation may change, however, because of changing cloud cover. Some plant species may have problems with briefer snow cover and a growth season that starts earlier, especially if the early spring lures flowers and buds forth before the risk of frost has passed. The cultural landscapes in the affluent countries located in the temperate zone are generally expected to be the most robust in relation to climate change. Similarly, the natural ecosystems in the marine part of the temperate zone are generally expected to be least exposed to harmful effects.

Increasing temperature is not necessarily the decisive factor when assessing the importance of climate change for vegetation. Interaction between vegetation, soil, temperature, wind and precipitation determines the resulting moistness of the soil via evaporation. The pattern of precipitation also has an effect. Heavy sporadic cloudbursts are less beneficial than steady rain, and agricultural crops preferably need rain during growth and not during harvesting.

An important aspect of climate change is its effects on agricultural production and thereby on the food available to the growing world population. The IPCC assesses that the global potential will probably not change substantially, but important shifts may occur resulting in international conflicts.

Denmark seems to be well placed because it is located well within the temperate forest area. As such, drastic changes are not expected, but climate change may allow cultivation of other crops currently grown further south. Thus, the potential yield may increase in combination with the increasing concentration of CO_2, since this will promote the growth of certain plants. The preconditions for agricultural activities can be expected to change in a short period of time.

Higher temperatures may increase the risk of pests (such as Colorado beetles) and plant diseases, and as a consequence, pesticide consumption may increase. Changes to the environmental legislation may be necessary to ensure cost-effective agriculture and to protect the environment under a changed future climate.

Despite extensive forest clearance in developing countries, the global terrestrial ecosystems seem currently to be a CO_2 sink. This can change rapidly if climate change reduces forest growth. The northeastern part of South America would especially be threatened.

Photo: CDanmark

Photo: NER/Peter Bondo Christensen

Denmark's forests are mostly highly managed production forests and operate with rotation times of about 100 years. They therefore require long-term planning. Converting from the dominant Norway spruce to more diverse forests, including beech, would make the forests more robust and resistant to the expected changes in climate.

There is considerable uncertainty about how climate change can affect water resources, which are mainly determined by the interaction of evaporation and precipitation with storage capacity and use. Some areas in Africa and some low-lying coastal areas already have severe problems with the quantity and quality of water, and these problems will probably worsen in the coming decades. In other (mountainous) areas, increasing precipitation in briefer and heavier episodes will increase runoff and the risk of flooding. Many countries already have a serious risk of dams breaching, and the management of water resources does not appear to be easier in the future given the expected changes in the pattern of precipitation.

More than 1 billion people already lack access to water of adequate quality. This problem is expected to worsen, although not inherently because of climate change, which can increase precipitation, but more because demand will increase in a warmer world with an increasing population.

The effects of climate change on the formation of groundwater in Denmark have not been systematically calculated, but groundwater may be sensitive to variation in climate, and this should be considered in determining the capacity of water-supply installations.

The quantity of water resources is affected by both the accessibility of water in nature and the use of water for various purposes. Given the projected drier and warmer summers in Denmark, the demand for water for many purposes may be expected to increase. Firstly, household consumption will increase because of garden watering unless restrictions are imposed. Secondly, agricultural demand for irrigation will increase substantially. Agriculture already seeks permission to increase irrigation in several areas in Denmark. Since irrigation greatly influences summer flow in watercourses, there will continue to be problems in achieving the flow targets related to watercourses. The current problems in the form of the conflicting interests of agriculture and environment may be expected to increase as the need for irrigation increases. Thirdly, nature's need for water to maintain such features as wetlands will be affected. The future trends in the aquatic balance of wetlands are difficult to project because they are influenced by many factors, and because each wetland location can be expected to react differently depending on such factors as local geological conditions.

Photo: NERI/Morten Strandberg

Rising sea level in areas near the coast may cause salt water to infuse the groundwater, adversely affecting its quality.

Groundwater is used to produce nearly all fresh water of drinking-water quality in Denmark. Occurrence of salt (NaCl) in the water is usually attributable to underground deposits. The infusion of salt water is only significant in a few areas such as small islands (such as Langeland and Samsø) and locations near low-lying coasts (such as near Køge Bay). A rising sea level will enhance saltwater infusion and will be expected to limit water abstraction in more places than are currently limited.

The rising sea level will become a serious problem for numerous coastal areas and small islands throughout the world. Without extra protection, a plausible rise of 40 cm would mean that the number of people affected by flooding would increase from more than 30 million annually to nearly 250 million annually.

Denmark's coastline has changed since the last Ice Age 10,000 years ago as a result of relative changes in the sea level. The coast is relatively long – 7,400 km compared with an area of about 42,000 km^2. Eighty per cent of Denmark's population lives in urban areas linked to the coasts. The vulnerable areas mostly comprise land-upheaval areas, marsh areas and drained areas that contain a total of 60,000 to 80,000 buildings. Not all these buildings are threatened by the expected global rise in sea level of about 33 to 46 cm during the next 100 years. The greatest threat to life and property is expected in southwestern Denmark, where changes in the prevailing direction, frequency and duration of the storms may contribute to increase the problem.

About 1,100 km of the coastline is protected by dikes and 700 km by permanent structures. Soft engineering solutions, especially coastal defences using sand and gravel dredged from the sea (beach nourishment), are increasingly used.

So far, direct planning based on a rise in sea level exceeding the present secular movements has been extremely modest. The same applies to the infrastructure near the coasts, for which the unofficial attitude has been "Wait and see!".

An important aspect is the effects on ecosystems near the coasts, especially marine foreland, salt marshes and dunes. Here the choice must be made between protecting these ecosystems at the expense of the natural ecosystems or a natural coastal development allowing the sea to encroach at the expense of protecting land but where some of the natural ecosystems will disappear in the long term.