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**Effects of the Norwegian oil
industry's emissions in the
North Sea on ozone exposure
levels and nitrogen deposition
in Southern Norway**

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Preface

This report is prepared for the Norwegian Oil Industry Association (OLF) by NILU as part of OLF's Sub-committee External Environment's work on NO_x-related matters.

The conclusions and results presented in this report will, together with other reports, be used by OLF in evaluation and analyses of the relationship between reduction of emissions and discharges from the petroleum industry and the associated benefits and costs.

NILU has performed the study based on data provided by the OLF member companies. SNOW a.s. has validated the input data and NILU has performed the analyses and drawn the conclusions presented in the report.

OLF has contributed with comments to the report which have been provided through a project workgroup having the following members:

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Summary and conclusions

On behalf of the Norwegian Oil Industry Association (OLF), the Norwegian Institute for Air Research (NILU) has carried out model calculations to investigate the effects of airborne emissions from offshore oil and gas production in the North Sea. Of particular interest in this connection are the emissions of nitrogen oxides, which may contribute to acidification in Southern Norway, and to photochemical ozone formation. Hydrocarbons emitted from offshore oil production may also contribute to the photochemical ozone production.

In the sunlit atmosphere, hydrocarbons and nitrogen oxides enter into numerous photochemical reactions which gradually convert the hydrocarbons to oxygenated compounds and eventually to carbon dioxide. The nitrogen oxides are not consumed in this process, but are only cycled between nitrogen monoxide (NO) and nitrogen dioxide (NO₂). Each cycle generates one ozone molecule. Thus, the amount of produced ozone depends on how many cycles the nitrogen oxides go through before they are ultimately lost through other processes. Usually the ozone production potential for each NO_x molecule is between 2 and 6. The dominant loss process for NO_x (NO+NO₂) is by reaction with free radicals which converts NO_x to gaseous nitric acid. Gaseous nitric acid may subsequently dissolve in water droplets or be converted to nitrate particles. The chemical reactions and the deposition mechanisms have been discussed in a previous report (Semb et al., 1993).

In order to simulate these reactions, and the dispersion and mixing of the North Sea emissions with the surrounding air, a new dispersion model with detailed photochemical reactions has been developed. The effects of the North Sea emissions with focus on Norwegian emissions, on the chemical composition of the air have been studied with this model through case studies for selected days and through a complete six-months calculation.

The share of airborne concentrations of nitrogen compounds and ozone stemming from emissions linked to oil exploitation in the North Sea have been calculated, and are compared with background concentrations, estimated with a regional model. The estimated concentrations have also been compared with measured concentrations in Southern Norway. Taking into account that the FOTOPLUME model did not at this stage include deposition losses of oxidized nitrogen compounds and ozone during the transport, the agreement between measured and observed values is reasonably good. The predicted ozone levels are generally within $\pm 20\%$ of the measured concentrations. Nitrogen dioxide concentration levels are also well accounted for, while the airborne concentrations of nitric acid and nitrate particles appear to be overpredicted. The measurements cannot be used to verify the model estimate contributions from the offshore oil and gas production, however.

Results from preliminary experiments show that the composition of the surrounding air is particularly important for the effect of the emissions on ozone formation. The case studies also indicate that, under the conditions prevailing in the North Sea during the six-month simulation period, it is the nitrogen oxides and not the hydrocarbons emitted from the oil platforms which are mainly controlling further ozone formation downwind of the oil installations. The contribution from the North Sea emissions to the concentration of ozone and acidifying nitrogen compounds is critically dependent on the long range transport, particularly of nitrogen oxides, ozone and VOC's from more distant sources, and thereby on the weather situation. The average contribution for 1992 (summer half year) has been estimated, but it is important to emphasize that this value will vary from year to year.

The calculations indicate that emissions in the North Sea caused an increase in the summertime ambient ozone concentration of 10-20 $\mu\text{g}/\text{m}^3$ above the concentrations which would have been present if these emissions had not occurred. Emissions in the Norwegian sector of the North Sea are responsible for between 40% and 50% of this concentration increase, and emissions in the British sector of the North Sea for 50% to 60% of the ozone concentration increase. The air quality guideline for hourly mean concentrations of ozone in Norway is 100 $\mu\text{g}/\text{m}^3$. This air quality guideline is exceeded at all sites where the ozone concentration is measured. In 1992, exceedance occurred on 30 to 80 days in Southern Norway, and 7-18 days in Northern Norway.

Because periods with elevated concentrations of ozone are particularly harmful to vegetation, the accumulated exposure above a threshold of 40 ppb, or 80 $\mu\text{g}/\text{m}^3$, has been adopted by UN-ECE as an indicator of possible harmful concentration levels (Fuhrer and Achermann, 1994). A critical load is generally defined as an exposure or deposition which is not expected to cause effects. For forest vegetation in general, it has been proposed to use an accumulated ozone exposure above 40 ppb (AOT40), of 10 000 ppb.hours as a provisional critical load. In 1992 the AOT40 values, based on measured concentrations, were around 15 000 ppb.hours at a number of sites in Southern Norway. Taking into account that the ozone concentrations calculated by the model are representative of the free troposphere, and therefore somewhat higher than the concentrations at ground level, the contribution from emissions in the North Sea to these AOT values may be estimated at between 700 and 1700 ppb.hours. The contribution from the emissions in the North Sea to the AOT40 values may be 5-10% of the total load. Oil and gas extraction activities in the Norwegian sector of the North Sea may be responsible for 30-50% of this contribution.

Similar calculations have been performed for the nitrogen compounds. Nitric oxide (NO), which is the main component in the emissions, is rapidly oxidized to nitrogen dioxide. In the presence of sunlight, further oxidation of nitrogen dioxide to nitric acid takes place within 4-6 hours. The typical time it takes for the emissions to reach the Norwegian coast is 8-20 hours. Nitric acid reacts with sea-salt aerosol particles to form nitrate-containing particles.

During nighttime, nitrogen dioxide is converted to nitric acid and to nitrate in particles by reaction with ozone. This reaction is slower than the reaction with hydroxyl radicals in sunlight. During summer, however, high concentrations of ozone and long periods of sunlight cause nitrogen oxides emitted from oil extraction activities to be converted to nitric acid and nitrates before the air reaches the Norwegian coast. These emissions therefore contribute little to the concentration level of nitrogen oxides at the Norwegian mainland.

The deposition of nitrogen oxide and nitrogen dioxide to the sea surface is negligible. Nitric acid is very water-soluble and is therefore readily absorbed by the sea surface. This deposition of nitric acid to the surface is incorporated in the model calculations of the background concentrations but not in the plume model. The deposition velocity varies with the wind velocity, but is typically of the order of 0.5 cm/s, corresponding to a loss in the airborne concentrations of about 2%/h. Typically, about 20% is deposited to the sea surface by this process. Further deposition occurs by precipitation scavenging, which is also an efficient removal process. The probability of rain within the time it takes the air to travel over the North Sea may be estimated at around 30%. Deposition rates of nitric acid and nitrate in particles are increased over land, mainly because of the increased surface aerodynamic roughness. Measured deposition rates for nitric acid to forested areas approach 8 cm/s.

Since these deposition processes were not included in the FOTOPLUME model calculations, dry deposition and precipitation scavenging en route from the emissions to the receptor points had to be estimated on the basis of deposition rates and precipitation frequencies, in order to estimate the contributions of the oil industry's emission in the North Sea to the airborne concentrations and the deposition of nitrogen at the sites.

The percentage contribution of the oil industry's emission in the Norwegian sector of the North Sea to the deposition of oxidized nitrogen was estimated at up to 20%, while the contribution to the total nitrogen deposition was a little more than 10%. These figures apply only to a relatively small coastal area in South-Western Norway, and only for the period of calculation, April-September 1992. During winter, the relative contribution from the emissions in the North Sea is expected to be less than indicated by the above figures, mainly because of slower conversion of NO_2 to nitric acid and nitrate particles.

In relation to acidification, it is the total deposition of sulphur and nitrogen which is of significance. However, because much of the nitrogen deposited is stored and accumulated in soil and biota, sulphate is still the dominating anion in acidified rivers and lakes. In some areas, however, nitrogen deposition may be responsible for up to 20-30% of the acidification. This implies that emissions of nitrogen oxides in the Norwegian Sector of the North Sea could be responsible for 2-3% of the acidifications in some areas.

Even if the calculations cover a full 6-month period, these results should be regarded mainly as indicative, mainly because meteorological conditions change quite considerably from one year to another. Ozone concentration levels are

generally high in Norway when there is a stable summer anticyclone over Central or Eastern Europe, which results in transport of air from areas with relatively high emissions of nitrogen oxides and volatile organic compounds which form ozone. 1992 was a year with relatively high ozone levels, particularly in May and June. The calculations also represent the first results from the use of a recently developed model, which does not adequately describe a situation where plumes from different sources mix and interact with each other. Further developments of this model should also include precipitation scavenging and more detailed description of the dry deposition processes.

Effects of the Norwegian oil industry's emissions in the North Sea on ozone exposure levels and nitrogen deposition in Southern Norway

1. Introduction

On behalf of the Norwegian Oil Producers' Association, the Norwegian Institute for Air Research has been contracted to evaluate the effects of the emissions of nitrogen oxides from the oil exploitation activity in the Norwegian sector of the North Sea. Nitrogen oxides enter into many reactions in the atmosphere, and are particularly important in connection with photochemical oxidant formation and production of ozone in the atmosphere. Ozone in ambient air is harmful both to vegetation and to human health, and efforts to limit the emissions causing photochemical oxidants formation, are being made on both national and international levels. Deposition of nitrogen compounds act as a fertilizer for both terrestrial plants and marine algae, and nitrogen deposition may also contribute to acidification of surface waters, causing fish kills and general deterioration of aquatic habitats.

Photochemical models describing the reactions between hydrocarbons and nitrogen oxides in the presence of sunlight have been developed for the description of ozone formation on both the urban scale and regional scales. Of particular relevance in this connection is the ongoing studies of photochemical oxidant formation in Europe, in connection with the European Monitoring and Evaluation Programme (EMEP), under the UN Economic Commission for Europe (ECE) (Simpson, 1993). The main emissions causing this photochemical oxidant formation are emissions of nitrogen oxides and volatile organic compounds from automobiles, but the chemical transformations and the dispersion of the products occur on a regional scale, causing elevated concentrations of ozone over the whole of Europe.

The emissions in the North Sea represent a special case, as both nitrogen oxides and hydrocarbons are emitted from point sources, and slowly diluted and mixed with the surrounding air which also contain important reacting species. Nitrogen oxides initially consume ozone in the surrounding air, then act as a catalyst in the formation of ozone from peroxy radicals, and is transformed to gaseous nitric acid and nitrate particles. The formation of ozone is critically dependent on the mixing ratio of nitrogen oxides to other reacting species, and it is therefore very important to describe the dispersion of the emissions correctly. This has necessitated the development of a new plume model, which combine the mixing of the emissions with the surrounding air, and the chemical reactions involving nitrogen oxides, volatile organic compounds and ozone. This report describes the results of model calculations with this model, and the effect of emissions in both the Norwegian and in the British sectors of the North Sea on airborne concentrations of ozone and oxidized nitrogen compounds in Norway. The significance of the results are discussed in relation to adverse effects of ozone on plants, air quality standards for ozone, and deposition of oxidized nitrogen and acidification of rivers and lakes.

2. Emissions

Both natural and anthropogenic sources emit nitrogen oxides and volatile organic compounds to the atmosphere. In Europe, however, the man-made emissions are dominating. Nitrogen oxides are mainly emitted from motor vehicles and from combustion of coal and oil in power plants and other large stationary sources. Volatile organic compounds are mainly emitted from the storage, transport and use of gasoline, and the evaporation of solvents. Natural emissions of volatile hydrocarbons include emissions of isoprene and terpenes from vegetation. Sulphur dioxide, which is the main precursor for acid precipitation, is also emitted from combustion of fossil fuels, and to a lesser extent from process industries.

According to information collected in connection with EMEP, emissions of sulphur dioxide have been reduced in Western Europe by about 50%, and in Eastern Europe by about 30%, in the period 1980-1993. During the same period, the emissions of nitrogen oxides have been reduced in some countries, but have increased in other countries (Tuovinen et al., 1994).

Emissions of ammonia, mainly from agriculture and animal husbandry, are also of importance in connection with nitrogen deposition and acidifications of surface waters. These emissions have also increased in Europe during the last 50-100 years, but have remained relatively constant during the last 15 years.

The annual deposition of sulphur in Norway has been estimated on the basis of model calculations and measurements to about 135 000 tonnes, while the total deposition of both oxidized and reduced nitrogen compounds is estimated to 112 000 tonnes annually, as nitrogen equivalents. These figures are averages for the period 1988-1992 (Tørseth and Pedersen, 1994).

Det Norske Veritas (DNV Industries) has collected information on emissions from North Sea oil and gas exploitation activities for 1992. Only emissions south of 62° N have been included. SNOW a.s. (1995) have used this information, in co-operation with NILU, to prepare a special emission data base suitable for the model calculations.

For the Norwegian sector of the North Sea, detailed information in the form of answered questionnaires was used to estimate emissions from the individual installations. For the British sector, emissions were available only as sums for the different fields. Figure 1 gives the location of some of the most important oil and gas fields in the North Sea.

The emission data are summarized in Table 1. It is seen that there are relatively large emissions of both nitrogen oxides (NO_x) and non-methane volatile organic compounds (NMVOCs) from oil and gas exploitation activities in the North Sea. The emissions of methane are relatively less important.



Figure 1: Location of the main oil and gas producing fields in the Norwegian and the British parts of the North Sea, as well as receptor points and measuring sites for which calculations of airborne concentrations have been performed.

Table 1: Emissions from offshore oil and gas exploitation on the Norwegian and the British sectors of the North Sea in 1992, in metric tonnes. Norwegian national emissions are given for comparison.

| | NO _x * | CH ₄ | NM VOC |
|--|-------------------|-----------------|---------|
| Total emissions, British and Norwegian sectors | 130 867 | 42 775 | 105 289 |
| British sector | 87 521 | 26 676 | 15 947 |
| Norwegian sector | 43 346 | 16 099 | 89 342 |
| Norway, national emissions | 217 000 | 280 000 | 283 000 |

* NO_x as NO₂.

Emissions of nonmethane volatile organic compounds (NMVOC) from oil and gas production in the Norwegian Sector are predominantly from loading of crude oil (95% in 1992). Gas turbines used at the platforms stand for the largest part of the emissions of nitrogen oxides, but the contribution from marine activities are also substantial. A more detailed sectorial breakdown of the emissions is given in Appendix A.

It is seen that the emissions of nitrogen oxides in the Norwegian sector is about 43 000 tonnes annually, and that the corresponding emissions in the British sector is about twice as high. Emissions of non-methane volatile organic compounds (NMVOC) are much smaller in the British sector than in the Norwegian sector. This is because there is less offshore loading of tankers in the British sector.

3. Model calculations

Nitrogen oxides interact with ozone and with the breakdown products of volatile organic compounds in the atmosphere. In this process, nitrogen oxides function as a catalyst in the formation of ozone, but is also oxidized further to nitric acid which is not active in these reactions. The photochemical reactions and deposition processes are described in a separate report (Semb et al., 1994).

Both nitrogen oxides and volatile organic compounds are necessary for the photochemical formation of ozone in the lower atmosphere. Usually, when nitrogen oxides and volatile organic compounds are emitted in the same area, the VOC concentrations are limiting the formation of ozone near the source, but nitrogen oxides are limiting at some distance from the sources.

The model developed by Eliassen et al. (1982) and Simpson (1993) describes the dispersion of volatile organic compounds and nitrogen oxides, and the subsequent formation of ozone and other reaction products in Europe along air mass trajectories, based on meteorological parameters and emission numbers given on 150 by 150 km grid cells. Altogether 70 trace species are included in the chemistry calculations based on about 150 chemical reactions. This model is operational at the Norwegian Meteorological Institute (DNMI), and is used in connection with EMEP. The EMEP model is also available at NILU and has been used in this work to provide information on the concentration of ozone and other reactive species in the air into which the emissions from the oil extraction activities are released. The EMEP model is also used to estimate the airborne concentrations of ozone and oxidized nitrogen compounds which would have occurred if there had been no emissions in the North Sea area. The EMEP model was run for the whole of the period April to September 1992. Emissions were taken from the EMEP emission database (Simpson, 1993; 1994), but with the emissions in the North Sea left out. Concentrations are calculated every six hours in individual EMEP grid squares.

A special model has been developed in this work to describe the dispersion of nitrogen oxides and volatile organic compounds emitted from oil extraction activities and the chemical reactions which occur when these emissions are

dispersed and mixed into the surrounding airmass. The model is hereafter called the FOTOPLUME model.

The model is a segmented plume model, with expanding concentric shells and turbulent mixing between the shells. Concentrations of reactive species are calculated in different timesteps, and are available every hour. The model can be used to calculate concentrations which arise downwind of the emission sources or, alternatively, concentrations at fixed receptor points over a period of time. When the work was started, it was also intended to describe the mixing of plumes which occur when sources are close to each other, or when the air trajectories from one emission source pass close to another. Unfortunately, this proved impossible to solve within the frame of the project.

Deposition processes were also not included in the model calculations. The deposition processes influence both the transmission to the Norwegian coastline from oil installations in the North Sea, and the subsequent deposition of the oxidized nitrogen compounds. These effects must therefore be considered when the results of the calculations are evaluated.

In addition to initial model runs, which were used to test the model and to obtain information on typical concentrations and reaction rates, the FOTOPLUME model was also run for the whole period April - September 1992, giving results every hour. Five receptor points were chosen along the Norwegian coast, in order to describe the influence of the emissions at representative locations. For some of these sites measurements of airborne concentrations of ozone and nitrogen compounds are also available for comparison with model results. Emissions were taken from the emission data base developed by SNOW a.s., as described in Chapter 2. With the FOTOPLUME model results for individual receptor sites are only obtained when the plume is arriving at the site. When this is not the case, concentrations are taken from calculations by the EMEP model. When plumes from different sources overlap at one of the receptor sites, the plume with the highest concentrations has been chosen. Four different emission scenarios have been chosen:

- No emissions in the North Sea (EMEP model).
- Emissions only in the Norwegian sector of the North Sea.
- Emissions only in the British sector of the North Sea.
- Emissions in both the British and the Norwegian sectors of the North Sea.

More detailed technical description of the models and the model calculations are described in Appendix B: *Description of the models and model calculations*.

4. Results of the model calculations

4.1 Initial model runs

To obtain some information of the typical concentrations down wind of the emitting sources, and to check the reaction rates and check the model performance, some initial model runs were made. Three different sources were

chosen, one representing large emissions of nitrogen oxides and medium VOC emissions. One with medium nitrogen oxides and large VOC emissions and one with low nitrogen oxides and large VOC emissions. Two situations were selected, and the development of the concentrations were followed in the respective shells along trajectories for 48 hours. The developments of the concentrations of nitrogen dioxide and ozone on 25 June are shown for the centre of the plumes as a function of the time from the release of the emissions in Figure 2. Quite different results were obtained on the two days chosen for this experiment.

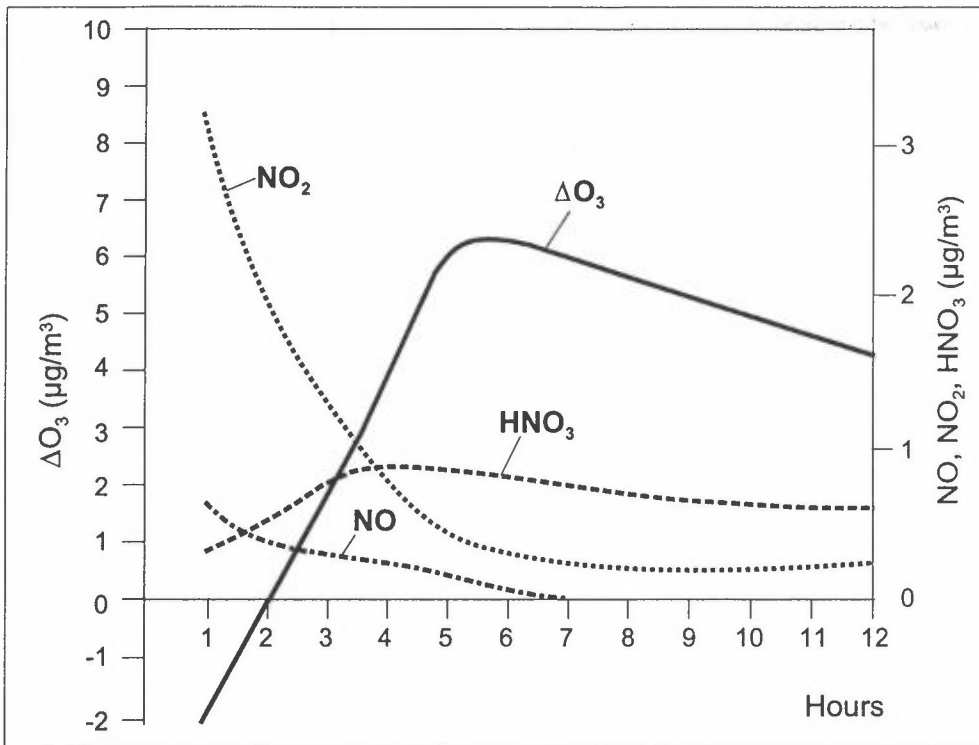


Figure 2: Calculated development of the concentrations of nitrogen oxides (NO_2 and NO), nitric acid (HNO_3), and ozone in the centre of the plume of a medium-size point source of nitrogen oxides in the North Sea, on 25 June 1992. For ozone only the absolute difference between the concentration in the plume centre and the background concentration is given.

On 22 May, rather high concentrations of ozone occurred over the North Sea, in connection with slow transport of polluted air masses from the south. The nitrogen oxides released from the sources were rather quickly diluted and transformed to nitric acid and nitrate. Very little ozone formation occurred, and the concentration of ozone in the centre of the plume became only 2-4 $\mu\text{g}/\text{m}^3$ higher than for the surrounding air, for the source representing very large emissions of nitrogen oxides.

In the other situation, 25 June 1992 (Figure 2), quite marked formation of ozone occurred within 4-6 hours. The increase was largest for the plume from the largest source, but significantly increased ozone formation also occurred downwind of the two other emission sources. In both cases, most of the chemical transformation took place within 4-6 hours from the initial release. Most of the oil installations are situated within 50 to 300 km from the Norwegian coast. The receptor points are situated along this coast, and the typical shortest distance from the oil installations to the receptor points is in the range 300-500 km. Since the average wind speed in the North Sea is 5-10 m/s, the time of travel from the emission sources to the receptor points will typically be 5-30 hours. Most of the ozone formation and the oxidation of nitrogen oxides to nitric acid and nitrates will be completed within this time range.

Another apparent conclusion from these initial model runs is that the emissions of NMVOCs did not seem to influence the ozone formation or the transformation of the nitrogen oxides to other species. This confirms that nitrogen oxides are limiting ozone formation in this part of the North Sea. This conclusion has also been drawn by DNMI (Simpson et al., 1995).

4.2 Calculations for April–September 1992

The marked difference between the two situations with respect to ozone formation demonstrates the importance of the concentrations of ozone and other reactive species in the air into which the emissions are released, in determining the effect of the emitted nitrogen oxides and other species on ozone formation. In order to generalize these effects, it is therefore necessary to carry out calculations for a longer, and more representative time period. These have been carried out for the period April–September 1992, as described in the previous section, and the concentrations of ozone and oxidized nitrogen compounds in air have been calculated for the following receptor points along the coastline of Southern Norway: Jeløya, Langesund, Birkenes, Stavanger, Voss and Kårvatn. Calculated monthly mean concentrations at these receptor sites are given in Appendix C. Figures 3 and 4 (p. 20–21) show the positions of the receptor points and the calculated mean concentrations of ozone and oxidized nitrogen compounds for the entire period. Since dry deposition and precipitation scavenging was not included in the FOTOPLUME model calculations, the effect of these processes must also be considered in the evaluation of the model results.

4.2.1 Estimation of dry deposition and precipitation scavenging

The removal by dry deposition and precipitation scavenging depends on the chemical and physical properties of the pollutant species.

Ozone has relatively low solubility in water, and the removal of ozone by precipitation is almost negligible. The dry deposition to the sea surface is also very small. Over land surfaces uptake of ozone by vegetation is an important process, resulting in a dry deposition velocity of 0.6-1 cm/s under daylight conditions, and less than 0.2cm/s during night. The calculated concentrations are therefore representative of the contributions from the oil installations in the Norwegian and in the British sectors to the air concentrations at the coast, provided that the

trajectories from the emission sources has not passed over land previous to the arrival at the receptor sites.

Precipitation scavenging and dry deposition at the sea surface is also negligible for nitrogen dioxide and PAN.

However, nitric acid is readily taken up by the sea surface and by vegetation, and is also efficiently removed by precipitation scavenging. Nitrate in sea-salt particles is also removed by dry and wet deposition processes. Since these removal processes were not incorporated in the FOTOPLUME model, and the calculated contributions from the Norwegian and the British oil installations to the estimated concentrations at the Norwegian coast are therefore too high. The background concentrations were calculated with the EMEP model, which includes parameterization of both dry and wet deposition based on surface characteristics and meteorological observations. In order to compare the calculated contributions from the oil installations in the Norwegian and the British sectors with the background concentrations, it is therefore necessary to estimate the removal by dry deposition and precipitation scavenging.

The uptake of nitric acid at the sea surface is generally limited only by the turbulent diffusion. The sea surface is relatively smooth, and the aerodynamic roughness length increases with the wind velocity. This relationship is described by Charnock's equation, and results in dry deposition rates of 0.3-0.6 cm/s for typical wind velocities of 5-10 m/s, as discussed by Joffre (1988) and Barrett (1994). For a transport distance of 300 km, this will reduce the airborne concentration with 17%, assuming a mixing height of 1 km.

Over land the aerodynamic roughness length increases, and the dry deposition velocities become much higher. This is particularly the case for forested areas, for which application of the aerodynamic resistance would lead to dry deposition velocities of several cm/s. Experimental studies by Meyers et al. (1989) and Meixner et al. (1988) indicated that this was indeed the case for both deciduous and coniferous forest, finding deposition velocities up to 8 cm/s. Dollard et al. (1987) found deposition velocities for nitric acid ranging from 1.7 to 3.6 cm/s for short grass.

Very little quantitative information is available concerning the deposition rates of nitrate particle. Since airborne nitrate is mainly associated with large aerosol particles, it is reasonable to assume that the deposition velocity is similar to the deposition velocity for nitric acid.

Precipitation only occur for part of the time, during which the deposition rate will be very high. In the EMEP model, which has a time resolution of 6 hours in the meteorological data, a scavenging ratio of 10^6 is used together with observed or estimated precipitation amounts to describe the wet deposition of nitrate and sulphate particles in 150×150 km² grids. The scavenging ratio is the ratio between the concentration in precipitation and the airborne concentration, in dimensionless units. A scavenging ratio of 1.4×10^6 is used for gaseous nitric acid, to account for the faster scavenging rate of this component. These scavenging ratios correspond

to 63% of the airborne concentrations by precipitation amounts of 1 and 0.7 mm, respectively. In order to assess the precipitation scavenging of nitrate and nitric acid during transport from the emission sources to the receptor sites, we need to know the probability of rainfall of this intensity and duration to occur. Observations over the sea are not generally available, and precipitation gauges at coastal sites give mainly precipitation amounts within fixed time intervals of 24 hours. Typical annual precipitation amounts at coastal sites are 500-1000 mm, so that the frequency of precipitation above 1 mm/h cannot exceed 10%. The amount and frequency of precipitation increases somewhat from south to north in the North Sea.

Over land, particularly at some distance from the coast in Western and Southwestern Norway, both precipitation intensities and the frequency of precipitation is considerably increased because of orographic lifting. Examination of the records from some of the meteorological stations in Southwestern Norway for the period April-September 1992 show that the occurrence of more than 1 mm of precipitation for a given 24-h was typically 40-50%.

Taking 10 hours as a typical time for transport from the emission sources, a probability of precipitation scavenging of 30% may be reasonable. Further transport over land areas will increase this probability to more than 50%. On the basis of this discussion, the airborne concentrations of nitric acid and nitrate calculated by the FOTOPLUME model can be corrected for dry deposition and precipitation scavenging by multiplication with a correction factor ϕ , which may be defined as follows:

$$j = e^{-1/h(v_{d,1} \cdot t_1 + v_{d,2} \cdot t_2)} (1 - p)$$

The mixing height h is taken to be 1000 m, $v_{d,1}$ is chosen to be 0.5 cm over sea surfaces and $v_{d,2}$ is taken to be 5 cm/s over vegetated land surfaces. t_1 and t_2 are the respective amounts of time spent during transport over these two types of surfaces, and have been deduced from the transport distances assuming a mean wind of 8 m/s over the sea and 5 m/s over land. The deposition velocity over the sea decreases with decreasing wind speed. p is the probability of precipitation scavenging during transport.

The distance from the emission sources to the receptor sites and the resulting correction factors are given in Table 2.

These transport distances have been subjectively estimated on the basis of the location of the oilfields which are closest to the receptor sites, taking into account also that the air trajectories are not necessarily straight lines. It is seen that the corrections are quite large, reflecting the high precipitation frequencies in the Norwegian coastal areas and the efficient dry deposition removal of nitric acid, particularly over land areas. The correction factors are relatively high for Voss and

Table 2: *Transport distances and correction factors to account for dry deposition and precipitation scavenging from the emission sources in the North Sea to the indicated receptor sites.*

| Receptor site | Transport distance | | Precipitation scavenging probability | Correction factor |
|---------------|--------------------|-----------|--------------------------------------|-------------------|
| | Over sea | Over land | | |
| Jeløya | 300 | 200 | 50 | 0.04 |
| Langesund | 300 | 100 | 50 | 0.13 |
| Birkenes | 300 | 50 | 40 | 0.27 |
| Stavanger | 300 | - | 30 | 0.53 |
| Voss | 200 | 70 | 50 | 0.20 |
| Kårvatn | 300 | 200 | 50 | 0.04 |

Kårvatn, which are both at some distance inland from the coast. Langesund and Jeløya are both coastal sites, but their locations make transport from the emission sources in the North Sea over land areas more likely.

These correction factors shall only be applied to the concentrations which are in excess of the background concentrations calculated by the EMEP model. These can be derived from the calculated results given in Appendix C, Table C3. Table 3 gives the both the corrected and the uncorrected values for the period April-September 1992.

Table 3: *Estimated concentrations of nitric acid and nitrate in aerosol, corrected for precipitation scavenging and dry deposition. Uncorrected values are given in parentheses. Unit: $\mu\text{g}/\text{m}^3$ as N.*

| | Background (No emissions in the North Sea) | Estimated contribution from the Norwegian Sector | Estimated contribution from the British Sector | Sum |
|-----------|--|--|--|------|
| Jeløya | 0.42 | 0.01 (0.23) | 0.02 (0.38) | 0.45 |
| Langesund | 0.42 | 0.03 (0.25) | 0.05 (0.40) | 0.50 |
| Birkenes | 0.39 | 0.08 (0.31) | 0.15 (0.56) | 0.62 |
| Stavanger | 0.26 | 0.14 (0.26) | 0.21 (0.39) | 0.61 |
| Voss | 0.39 | 0.05 (0.28) | 0.11 (0.54) | 0.55 |
| Kårvatn | 0.19 | 0.01 (0.17) | 0.01 (0.29) | 0.21 |

These corrected values have been incorporated in Figure 4.

4.2.2 Results for ozone

For ozone (Figure 3) the model calculations indicate, on average, an increase in the ozone concentrations due to emissions from oil and gas extraction in the Norwegian sector of the North Sea of between 4 and 6.7 $\mu\text{g}/\text{m}^3$ while the

corresponding increase due to the emissions in the British sector is between 6 and 12 $\mu\text{g}/\text{m}^3$. It has been noted that the difference between the ozone concentrations calculated with emissions in the Norwegian sector and the background ozone concentration level is larger than the difference between the calculated concentrations with emissions in the British sector and emissions in both sectors. This is apparently caused by the overlap effect, which in general causes an underestimate of the concentrations when all the emission sources are added in the computer runs.

The best estimate of the contribution of emissions from Norwegian oil extraction activities in the Norwegian sector of the North Sea to ozone concentration levels is therefore provided by the difference between the concentrations calculated with the EMEP model and the FOTOPLUME model when only emissions in the Norwegian sector is considered. The significance of this calculated contribution in relation to effects will be discussed in Chapter 6. Remembering that the emissions of nitrogen oxides from activities in the British sector are about twice as high as the emissions in the Norwegian sector, it is not surprising that the calculated effect of the emissions in the British sector on ozone concentration levels is higher than that of the emissions in the Norwegian sector. However, the transport distance from the emissions in the British sector is slightly larger, and the probability for trajectories from the sources to reach the selected receptor sites is correspondingly lower.

It is possible to compare the effect of the emissions in the North Sea on the airborne concentrations of ozone and on oxidized nitrogen species. Nitrogen oxides act as a catalyst for ozone formation, but is transformed to unreactive nitric acid and nitrate by the OH radicals which are also involved in the photochemical ozone formation. Generally, each molecule of NO_x released into the atmosphere will produce, on average, between 2 and 6 molecules of ozone. The results shown in Figure 3 indicates an ozone increase from Norwegian sector only of the order of 5 $\mu\text{g}/\text{m}^3$. The increase in the estimated concentrations of nitric acid and nitrate, without accounting for deposition losses, is between 0,25 and 0,3 $\mu\text{g}/\text{m}^3$ as nitrogen.

The molecular weight of ozone is 48, and the atomic weight of nitrogen is 14. The number of ozone molecules forward per each nitrogenoxide molecule emitted is consequently $(5/48) : (0,28/14) \approx 5$.

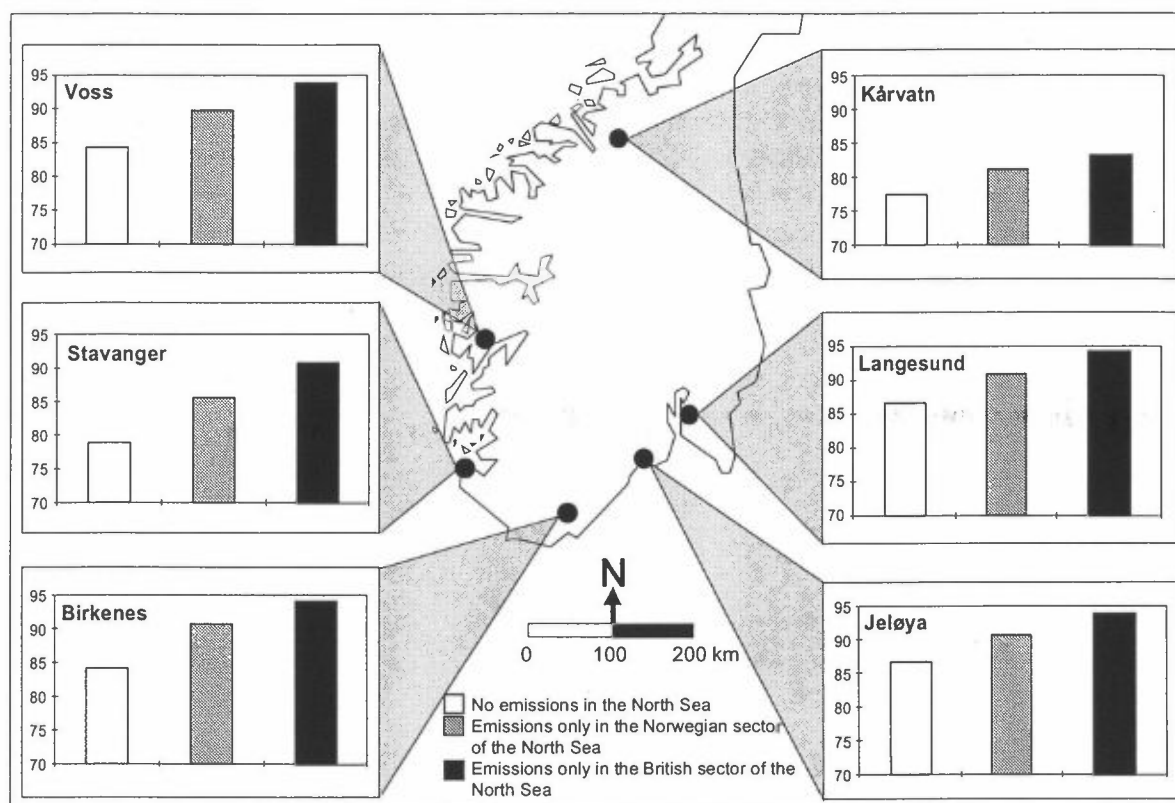


Figure 3: Estimated effect of the emissions in the North Sea on the concentrations of ozone at the indicated receptor points at the Norwegian coast. Open bars indicate the estimated concentrations in the North Sea area, light shaded bars indicate the concentrations when adding emissions from oil and gas extracting activities in the Norwegian sector, and dark shaded bars represent concentrations with emissions only in the British sector of the North Sea. Unit: $\mu\text{g}/\text{m}^3$.

4.2.3 Results for nitrogen compounds

Figure 4 shows the estimated airborne concentrations of oxidized nitrogen compounds for the three different emission scenarios. The concentrations of nitrogen dioxide and peroxyacetyl nitrate are only marginally increased by the emissions in the North Sea. Nitrogen dioxide concentration levels are least affected. Actually, nitrogen dioxide concentration levels appear to be decreased at some of the receptor sites. This is an artefact of the model calculations, and is caused by the different way in which the EMEP model and the FOTOPLUME model treats emissions located in the EMEP grid square in which the receptor site is located. Nitrogen dioxide and nitric oxide are quickly transformed to nitric acid and to nitrate particles, so a large part of the estimated nitrogen dioxide concentration levels at the receptor sites is due to emissions of nitrogen oxides in the $150 \text{ by } 150 \text{ km}^2$ grid square, in which the receptor site is located.

Peroxy-acetyl nitrate (PAN) is a minor component which, compared to the other oxidized nitrogen compounds, has a relatively long residence time in the atmosphere. Concentration levels at the receptor sites are therefore caused mainly

by transport from more distant sources, and is not so much influenced by the emissions in the North Sea.

It is seen that, in spite of the large corrections which have been made in order to account for the effects of dry deposition and precipitation scavenging, it is the estimated concentrations of nitric acid and nitrate which is most strongly affected by the emissions of nitrogen oxides from the oil installations in the North Sea.

Since nitric acid and nitrates are efficiently removed by dry deposition and precipitation scavenging, the largest contributions are estimated at the receptor points which are relatively closest to the emissions, and where direct transport over the sea surface is most likely. The largest effect of the oil installations' emissions on airborne concentrations and deposition of nitrogen compounds will therefore occur in the coastal areas of South-Western and Western Norway south of 62°N.

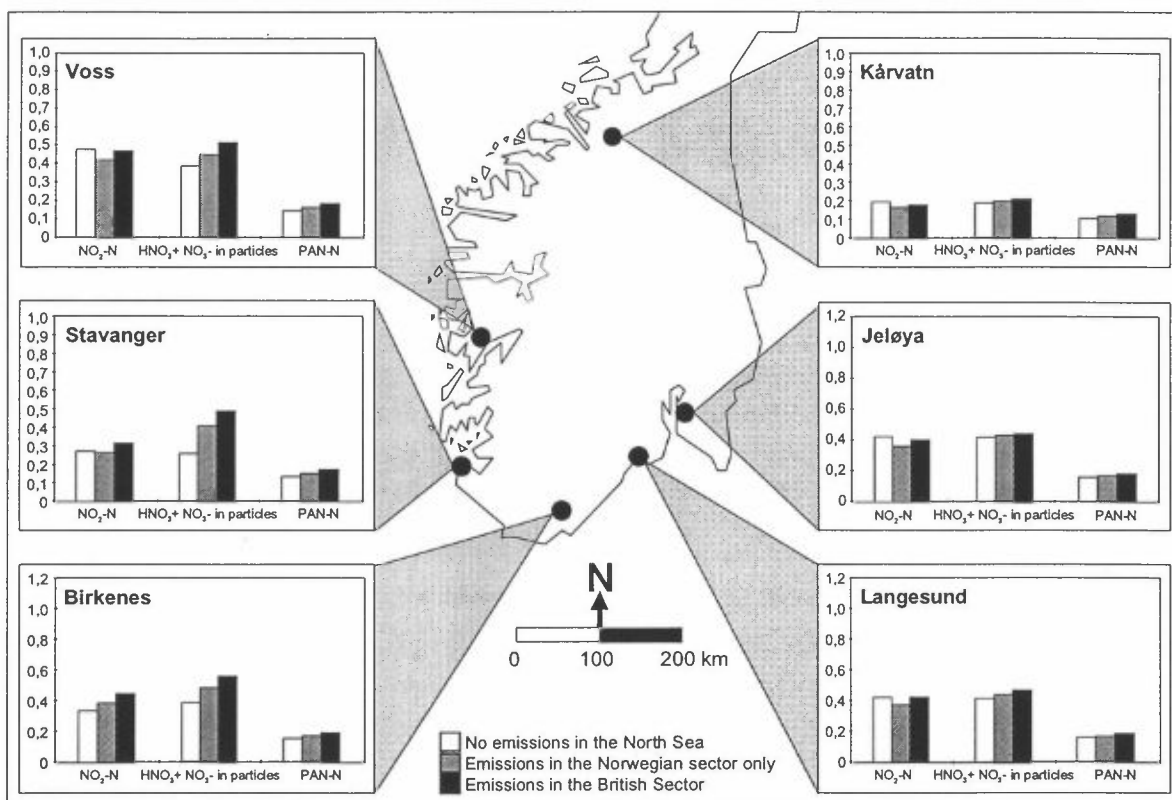


Figure 4: Estimated concentrations of nitrogen dioxide (NO_2), the sum of gaseous nitric acid and nitrate particles, and peroxyacetyl nitrate (PAN) at the indicated receptor points on the Norwegian coast. Open bars represent a situation with no emissions in the North Sea, light shaded bars represent a situation with emissions only in the Norwegian sector, dark shaded bars a situation with emissions only in the British sector. Unit: $\mu\text{g}/\text{m}^3$.

5. Comparison with measurements

Measurements of the concentrations of ozone and oxidized nitrogen compounds in air is measured by NILU on behalf of the Norwegian Pollution Control Authority (SFT, 1993), and may serve as a useful corrective for the model calculations. In the following, measured concentrations in ambient air have been compared with calculated concentrations for the period April-September 1992. The calculated concentrations in this section relates to the model runs with emission sources in both the Norwegian and the British sectors of the North Sea.

Figures 5 and 6 show a comparison of measured and estimated ozone concentrations at the sites Voss and Birkenes. It is seen that the measured concentrations of ozone are generally lower than the estimated concentrations, particularly during the night. Ozone is taken up by vegetation through the stomata, and may also react with other surfaces and with substances emitted from vegetation (e.g. terpenes). The concentrations at ground level are therefore lower than the mean concentration in the 300-1500 m thick layer for which the model estimates apply. This is particularly pronounced during night, because of the reduction of the vertical exchange of air after sunset. These relationships are relatively well known (e.g. Galbally, 1967; Garland and Derwent, 1979). Bearing this in mind, the estimated concentrations are generally in accordance with the measured values. It is important, however, to take into account the difference between the concentrations of the ozone near the surface and aloft when considering the effect of the estimated concentrations on vegetation. The difference between the estimated and the measured concentrations is smallest in the early afternoon, when the ozone concentration at ground level reaches its diurnal maximum value.

Table 2 gives a comparison of estimated monthly mean ozone concentrations, and the monthly mean of the daily maximum measured ozone concentration at the receptor sites.

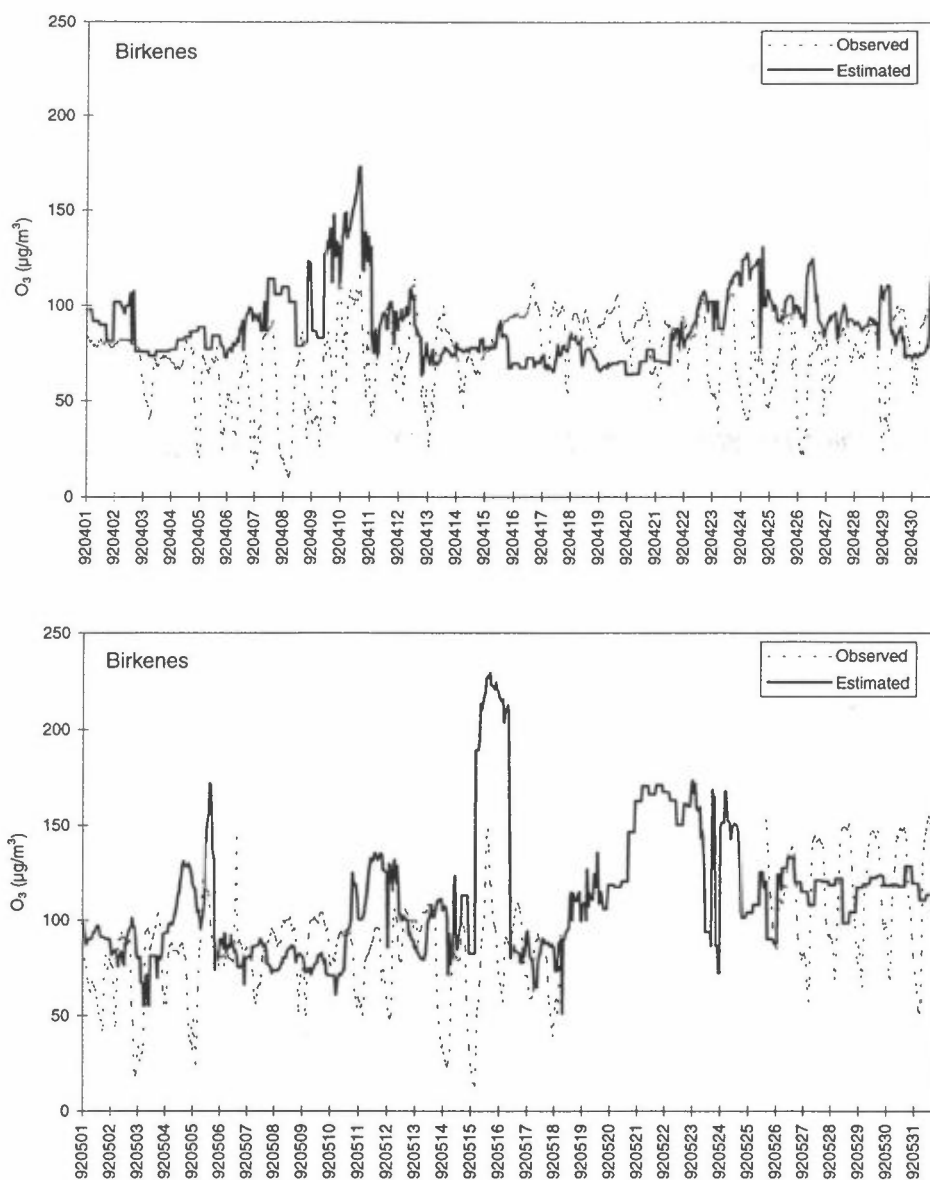


Figure 5: Measured and estimated concentrations of ozone at Birkenes. April and May 1992 ($\mu\text{g}/\text{m}^3$).

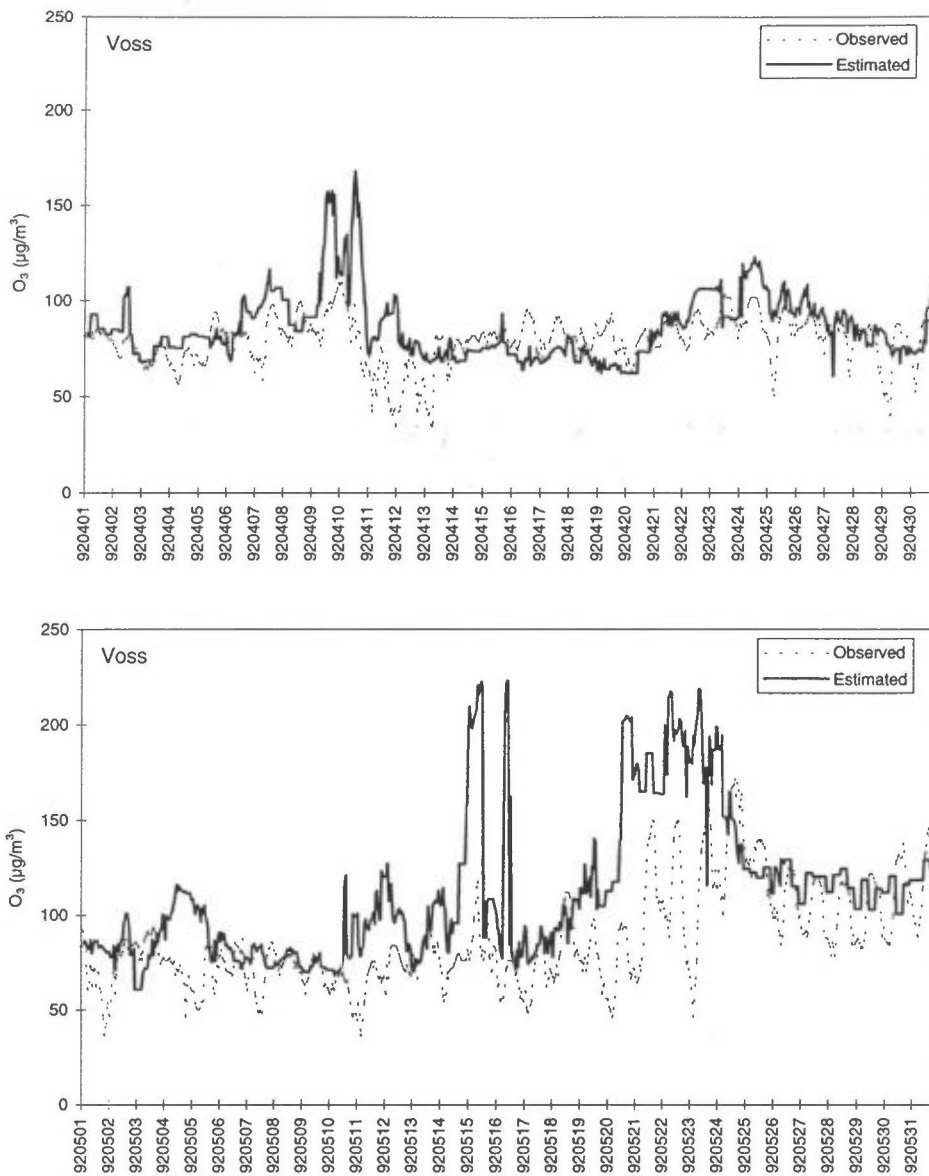


Figure 6: Measured and estimated concentrations of ozone at Voss, April and May 1992 ($\mu\text{g}/\text{m}^3$).

Table 4: Estimated and measured monthly mean daily maximum ozone concentrations in $\mu\text{g}/\text{m}^3$.

| | Jeløya | | Langesund | | Birkenes | |
|-----------|-----------|----------|-----------|----------|-----------|----------|
| | Estimated | Measured | Estimated | Measured | Estimated | Measured |
| April | 89 | 92 | 89 | 91 | 89 | 96 |
| May | 108 | - | 109 | 105 | 112 | 117 |
| June | 97 | - | 99 | 103 | 102 | 127 |
| July | 99 | - | 100 | 85 | 99 | 90 |
| August | 100 | - | 102 | 75 | 101 | 77 |
| September | 80 | 70 | 78 | 87 | 74 | 75 |
| | Stavanger | | Voss | | Kårvatn | |
| | Estimated | Measured | Estimated | Measured | Estimated | Measured |
| April | 84 | - | 86 | 91 | 79 | 100 |
| May | 111 | - | 112 | 107 | 100 | 131 |
| June | 95 | - | 102 | 93 | 84 | 91 |
| July | 94 | - | 99 | 70 | 86 | 64 |
| August | 95 | - | 101 | 61 | 84 | 60 |
| September | 78 | - | 74 | 61 | 74 | 60 |

It is seen again that the estimated concentration levels are, on average, quite close to the measured concentration levels. However, the comparison only shows that the calculated concentration levels are consistent with the observations. It is not possible to use the observations to verify the model's predictions with respect to the effect of the emissions in the Norwegian and the British sectors of the North Sea on the ambient ozone concentration levels, because the contributions are at the same level as the deviations between the model calculations and the measured concentrations.

Measurements of the concentrations of oxidized nitrogen compounds in air are carried out at Birkenes and at Kårvatn. Monthly mean concentrations have been obtained from the annual report issued by the Norwegian Pollution Control Authority (SFT, 1993), and compared with the monthly mean estimated values in Tables 5 and 6. For nitrogen dioxide the correspondence between the measured and the estimated concentration levels is surprisingly good. Due to the relatively rapid transformation of nitrogen dioxide to nitric acid and nitrates, a relatively large fraction of the summertime NO_2 concentrations originate from sources within Norway.

Table 5: Comparison of measured and estimated monthly mean concentrations of nitrogen dioxide (NO_2), in $\mu\text{g}/\text{m}^3$.

| | Birkenes | | Kårvatn | |
|-------------|-----------|----------|-----------|----------|
| | Estimated | Measured | Estimated | Measured |
| April | 1,87 | 2,43 | 0,62 | 0,16 |
| May | 1,38 | 0,99 | 0,69 | 0,39 |
| June | 0,56 | 2,14 | 0,38 | 0,72 |
| July | 0,93 | 1,31 | 0,33 | 0,72 |
| August | 1,35 | 1,22 | 0,33 | 0,52 |
| September | 3,58 | 2,69 | 1,19 | 0,82 |
| April-Sept. | 1.61 | 1.80 | 0.59 | 0.55 |

Table 6: Estimated and measured concentrations of the sum of gaseous nitric acid and nitrate in air ($\mu\text{g}/\text{m}^3$, as N). (Estimated concentrations are corrected for precipitation scavenging and dry deposition during transport from the emission sources in the North Sea, as in Table 3.)

| | Birkenes | | Kårvatn | |
|-----------|-----------|----------|-----------|----------|
| | Estimated | Measured | Estimated | Measured |
| April | 0.58 | 0.32 | 0.19 | 0.07 |
| May | 0.88 | 0.31 | 0.20 | 0.13 |
| June | 0.54 | 0.23 | 0.19 | 0.13 |
| July | 0.53 | 0.24 | 0.13 | 0.08 |
| August | 0.54 | 0.20 | 0.13 | 0.06 |
| September | 0.66 | 0.35 | 0.25 | 0.06 |

The estimated concentrations of nitric acid and nitrates are generally higher than the corresponding measured concentrations, even after applying corrections for dry deposition and precipitation scavenging. These measured concentrations are also generally lower than the concentrations estimated by the EMEP model.

These discrepancies are partly due to the rapid uptake and dry deposition of nitric acid and nitrate particles, which makes concentrations at ground level much lower than in the air mass above. The concentration profiles given by Meixner et al. (1988) and by Meyers et al. (1989) indicate that concentrations of nitric acid at 2 m, where the measurements are made, are typically about 50% lower than the concentrations 10-20 m above the canopy of the forests stands.

6. Discussion of the effects of the emissions from oil exploitation in the North Sea

6.1 Ozone

Ozone is both of concern in relation to human health, and as a phytotoxic agent. The World Health Organisation considers that ambient concentrations above 150-200 $\mu\text{g}/\text{m}^3$ may be damaging to human health, while European Community's

air quality standard is $110 \mu\text{g}/\text{m}^3$, averaged over 8 hours. Both these limits are currently exceeded every summer in almost every country in Europe, because of photochemical oxidant formation. The Commission of the European Communities' ozone directive further requires governments to inform the public when hourly mean ozone concentrations exceed $180 \mu\text{g}/\text{m}^3$, and to give warnings when the concentrations exceed $360 \mu\text{g}/\text{m}^3$ on a 1 h basis. The Norwegian Pollution Control Authority recommended that the ozone concentration should not exceed $100 \mu\text{g}/\text{m}^3$, on a 1-h basis. These guidelines are based on extensive epidemiological and experimental evidence on the effect of ozone on the human respiratory function.

In Norway, the hourly mean ozone concentration may also exceed $180 \mu\text{g}/\text{m}^3$, on average every second year (Schjoldager, 1995). The emissions in the North Sea may contribute to these exceedances, which are mainly caused by photochemical ozone production in polluted air masses transported from the more densely populated parts of Europe. In Table 7, the calculated contributions of the emissions in the North Sea is shown for those hours when the calculated concentrations exceed 100. It is seen that the emissions in the North Sea contribute significantly both to the concentration levels and the number of hours with estimated concentrations above $100 \mu\text{g}/\text{m}^3$.

The phytotoxic effects of ozone have been extensively studied. In certain sensitive species, ozone may cause direct damage in the form of necrotic spots. Tobacco (especially the sensitive cultivar Bel W3), spinach, beans, and clover are examples of plants that will show characteristic tissue damage symptoms if exposed to ozone concentrations above certain levels. Ozone also causes invisible damage, because it interferes with the photosynthetic assimilation of carbon dioxide in the stomata. This effect has also been systematically studied, both in the laboratory (e.g. Forberg et al., 1989) and in so-called open-top chambers, where plants can be grown and exposed to different concentration levels of ozone under field conditions (Heck et al., 1982). These latter experiments have shown that the crop yield losses due to ozone exposure are considerable in both Europe and in North America. Closer examination of these data have shown that the growth reductions are related to the accumulated exposure of ozone above a certain threshold concentration level. As a consequence, a special UN-ECE workshop has concluded that the damage caused by ozone is best described by the accumulated exposure above a threshold of 40 ppb (AOT40) (Fuhrer and Achermann, 1994). The workshop further recommended that the critical level for protection of agricultural crops and forests should be set at 5000 ppb.hours and 10 000 ppb.hours, respectively, the AOT40 values for crops to be calculated for a 3-month period during daylight hours only, and the AOT40 value for forests for a 6-month period.

In order to determine the contribution of the emissions in the North Sea to the AOT40 exposure levels, account has to be made of the relationship between the ground-level concentrations and the estimated concentrations from the model calculations. The daily maximum concentrations at ground level are, on average, 80% of the estimated concentrations. Also, the groundlevel concentrations show a strong diurnal variations, with low values during the night, whereas the estimated concentrations do not show such a strong diurnal variation.

Accordingly, the contribution of emissions in the North Sea to the AOT40 exposure index has been determined from the calculated increased ozone concentrations when estimated concentrations are above $100 \mu\text{g}/\text{m}^3$ (50 ppb), which corresponds to a ground-level concentration of 40 ppb. The number of hours when this concentration level is exceeded has been halved, in order to take into account the diurnal variations in the ground-level ozone concentrations. Table 8 shows how the contributions to the AOT40 levels during the six-month period April-September may be calculated. Also shown are the AOT40 levels calculated from measurements.

Table 7: Estimated increased ozone concentrations and number of hours when the estimated concentrations are above $100 \mu\text{g}/\text{m}^3$, for different emission scenarios. The reason why the numbers are not additive is explained in the text.

| | Emissions in both the Norwegian and the British sectors | | Emissions only in the Norwegian sector | | Emissions only in the British sector | |
|-----------|---|--------------------|--|--------------------|--------------------------------------|--------------------|
| | Number of hours | ΔO_3 | Number of hours | ΔO_3 | Number of hours | ΔO_3 |
| Jeløya | 238 | 18 | 182 | 8 | 224 | 15 |
| Langesund | 251 | 19 | 187 | 9 | 225 | 17 |
| Birkenes | 259 | 24 | 196 | 14 | 223 | 21 |
| Stavanger | 194 | 35 | 103 | 23 | 182 | 31 |
| Voss | 235 | 25 | 174 | 13 | 213 | 22 |
| Kårvatn | 123 | 23 | 74 | 15 | 108 | 21 |

Table 8: Measured AOT40 values and estimated contributions to the AOT values from emissions in the Norwegian and the British sectors of the North Sea. Numbers in brackets give the percentages of the AOT40 values based on measured values.

| | Emissions in both the Norwegian and the British sectors | | Emissions only in the Norwegian sector | | Emissions only in the British sector | | Measured AOT40 values |
|-----------|---|------|--|-----|--------------------------------------|-----|-----------------------|
| Jeløya | 1 071 | (10) | 364 | (3) | 840 | (8) | 10 643 |
| Langesund | 1 192 | | 420 | | 956 | | |
| Birkenes | 1 554 | (9) | 686 | (4) | 1 170 | (7) | 16 972 |
| Stavanger | 1 697 | | 592 | | 1 410 | | |
| Voss | 1 468 | (14) | 565 | (5) | 1 171 | (4) | 10 165 |
| Kårvatn | 707 | (5) | 277 | (2) | 567 | (4) | 15 184 |

These calculated contributions to the AOT40 values are extremely sensitive to background ozone concentrations, as it is the increased formation of ozone occurring when the ozone background concentrations are high which increases the AOT40 values. The meteorological conditions in the spring and summer of 1992 resulted in relatively high concentration levels of ozone at Norwegian background

stations, when compared to other years. Under such conditions, the contributions from emissions in the oil and gas extraction activities in the North Sea to the ozone exposure levels in Southern Norway may be significant. In other years, the contribution may be much smaller.

6.2 Deposition of nitrogen compounds in relation to acidification and eutrophication

Deposition of nitrogen is caused by deposition of oxidized and reduced nitrogen. Reduced nitrogen compounds are mainly caused by emissions from agricultural activities. Oxidized nitrogen compounds originates from emissions of nitrogen-oxides and the emissions in the North Sea will contribute to deposition of oxidized nitrogen and not to reduced nitrogen compounds. A little more than half the total deposition of nitrogen in Norway is in the form of oxidized nitrogen. Deposition of nitrogen compounds may cause eutrophication in aquatic and terrestrial ecosystems, and contribute to the acidification of rivers and lakes. It does not matter if the deposition is in the form of reduced or oxidized nitrogen.

The oil industry's contribution to the nitrogen deposition may be directly deduced from the results given in Chapter 4, assuming that both dry and wet deposition is proportional with the estimated airborne concentrations. Measurements at background stations (SFT,1993) provide data for the deposition by precipitation, and airborne concentrations which may be used to infer the dry deposition. In addition to the sites Birkenes and Kårvatn, there are also precipitation measurements at Voss. The EMEP site Skreådalen is located not so far from Stavanger, and Prestebakke is relatively close to Jeløya. Table 9 gives deposited amounts of sulphur and of reduced and oxidized nitrogen for the period April-September 1992. Appendix D 1 gives more details.

Table 9: Deposition of sulphur and of reduced and oxidized nitrogen at some background sites, April-September 1992. Unit: g/m² as S and N, respectively (SFT, 199?).

| | Precipitation | | | Dry deposition | | | Total | |
|-------------|---------------|--------|------|----------------|--------|------|-------|------|
| | S | Red. N | Ox.N | S | Red. N | Ox.N | S | N |
| Prestebakke | 0.35 | 0.18 | 0.23 | 0.07 | 0.02 | 0.21 | 0.42 | 0.64 |
| Birkenes | 0.54 | 0.31 | 0.37 | 0.08 | 0.02 | 0.21 | 0.62 | 0.91 |
| Skreådalen | 0.60 | 0.35 | 0.36 | 0.05 | 0.05 | 0.16 | 0.65 | 0.92 |
| Voss | 0.27 | 0.08 | 0.13 | 0.04 | 0.02 | 0.10 | 0.31 | 0.33 |
| Kårvatn | 0.09 | 0.06 | 0.07 | 0.03 | 0.02 | 0.07 | 0.12 | 0.22 |

The emissions from the oil industry contributes only to the deposition of oxidized nitrogen. The percentage contributions to this deposition may be deduced from Table 3 and the percentage contributions to the deposition of total nitrogen and to total potential acidity deduced from this and from Table 9.

The percentage contributions at the receiving sites to this deposition are assumed to be the same as the percentage contributions to the concentrations of airborne nitric acid and nitrate in aerosol, in Table 3.

Table 10: Percentage contributions from the emissions in the Norwegian and the British Sectors of the North Sea to the deposition of oxidized nitrogen, total nitrogen and total potential acid at the receptor sites, April-September 1992.

| | Oxidized nitrogen | | Total nitrogen | | Total potential acid* | |
|-----------|-------------------|----------------|------------------|----------------|-----------------------|----------------|
| | Norwegian sector | British sector | Norwegian sector | British sector | Norwegian sector | British sector |
| Jeløya | 2% | 4% | 2% | 3% | 1% | 1% |
| Birkenes | 14% | 26% | 9% | 17% | 4% | 7% |
| Stavanger | 23% | 36% | 13% | 20% | 6% | 9% |
| Voss | 11% | 21% | 7% | 15% | 3% | 6% |
| Kårvatn | 5% | 9% | 3% | 6% | 1% | 3% |

* Potential acid refers to a situation in which all nitrogen deposited is leached as nitrate. The actual acidifying effect of the nitrogen deposition is typically about 1/3 of the quoted percentages.

Both sulphur and nitrogen deposition contributes to the acidification of soils and surface waters. The calculated "potential acidity" refers to a hypothetical situation in which all nitrogen ends up as nitrate in the soil and in runoff water, in which the acidification potential of sulphur and nitrogen is almost the same on a weight by weight basis.

However, mainly because accumulation of nitrogen in the soil and in the biomass, the actual runoff of nitrate is typically much lower. Special research programme, aimed at investigating the deposition and runoff of nitrogen compounds in Norway, has carried out extensive sampling and chemical analyses of lakes and rivers in the area of southwestern Norway where the atmospheric deposition is largest (Henriksen et al., 1993). It appears that the nitrate concentration in the runoff is typically in the range 10-20 micromoles/litre, corresponding to a runoff of 15-30 meq/m². The nitrogen retention in the watersheds is about 60-80%.

The actual contribution of the nitrogen deposition to the acidification, particularly the contributions of the oil industry's emissions in the North Sea, is therefore much less than the contributions to the deposition of "total potential acidity" given in Table 10.

It should also be remembered that the calculations cover only one summer half-year. Because of less photochemical activity and slower oxidation of the nitrogen oxides to nitric acid, the relative contributions from the oil industry's emissions in the North Sea to deposition in Norway may be less in winter than in summer.

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• $\frac{1}{2} \int_{-\infty}^{\infty} \delta(x) dx = \frac{1}{2}$

• $\int_{-\infty}^{\infty} \delta(x) dx = 1$



Appendix A

Emissions from different activities in connection with oil and gas extraction

THE UNIVERSITY OF CHICAGO

PH.D. THESIS

BY

IN THE DEPARTMENT OF _____

CHICAGO, ILLINOIS

Table A1: Emissions in the Norwegian sector of the North Sea (1992) broken down in activities. NO_x is given as weight equivalents of NO_2 .
Unit: tonnes/year.

| | NO_x | CH_4 | NMVOC |
|---|--------|--------|--------|
| Gas turbines | 20 463 | 2 195 | 580 |
| Supply ships | 3 975 | | 284 |
| Standby ships | 1 286 | | 92 |
| Shuttle tankers | 7 264 | | 519 |
| Loading buoys | | 3 470 | 82 499 |
| Well testing | 89 | 56 | 24 |
| Helicopters | 244 | | |
| Diffuse emissions | | 10 247 | 4 836 |
| Flares | 3 589 | 72 | 18 |
| Diesel engines | 6 396 | | 457 |
| Other sources | 40 | 59 | 32 |
| Total emissions in the Norwegian sector | 43 346 | 16 099 | 89 342 |

1. The first part of the document is a list of names and titles, including "The Hon. Mr. Justice" and "The Hon. Mr. Justice".

2.

3.

4.

Appendix B

Description of models and model calculations

B.1. The EMEP Photo-oxidant model

The EMEP model (Simpson, 1993) is a one-layer Lagrangian trajectory model which has been developed to describe regional formation and long-range transport of air pollutants in Europe.

Emissions and meteorological data are gridded in a special geographical grid with 150*150 km² squares (Figure B1). Annual emissions are reported by the Parties to the Convention on Long-Range Transboundary Air Pollution. These are given as national totals, but many countries also report emissions in 150*150 km² or 50*50 km² grids. The Norwegian Meteorological Institute maintains a database of European emission data, and carries out the necessary additional work in estimating annual and diurnal variations, distribution of national total emissions in grid squares, and estimation of missing values. The status of the emission data are described in a separate report by Berge et al. (1995).

In order to conform with the model formulation, total non-methane hydrocarbons (NMHC) emissions are speciated into equivalent emissions of ethane, ethene, propene, n-butane, o-xylene and isoprene. Natural emissions of volatile organic hydrocarbons are also included (Simpson, 1994).

The meteorological information is prepared from the international meteorological observational network with the help of the Norwegian Meteorological Institute's numerical forecasting model. Of particular importance is the wind force and direction, which is given in the 925 hPa pressure level, corresponding to about 700 m a.s.l.

The chemical scheme involves about 70 different compounds, and more than 150 chemical reactions. It has been tested against more comprehensive chemical reactions systems, and has been found to simulate adequately both the chemical breakdown of hydrocarbons and the formation of ozone. More recently, the model predictions have been tested against measured concentrations of hydrocarbons, and aldehydes and ketones at several measurement sites in Europe. Good agreement has been obtained, particularly for aldehydes (Solberg et al., 1995).

The EMEP model is used to determine the background concentrations, into which the nitrogen oxides and volatile organic hydrocarbons from the activities related to oil and gas extraction are injected. Concentrations are calculated to the center of each grid in the North Sea every 6 hours, following the 96 hours back trajectories arriving at these points. The initialisation procedure has been simplified somewhat in relation to the EMEP model, in that typical measured concentrations are taken as initial concentration values.

The EMEP model is also used to calculate the background concentration values of ozone and nitrogen oxides for the selected receptor points in Norway. Emissions in the North Sea were set to zero in all the EMEP model runs.

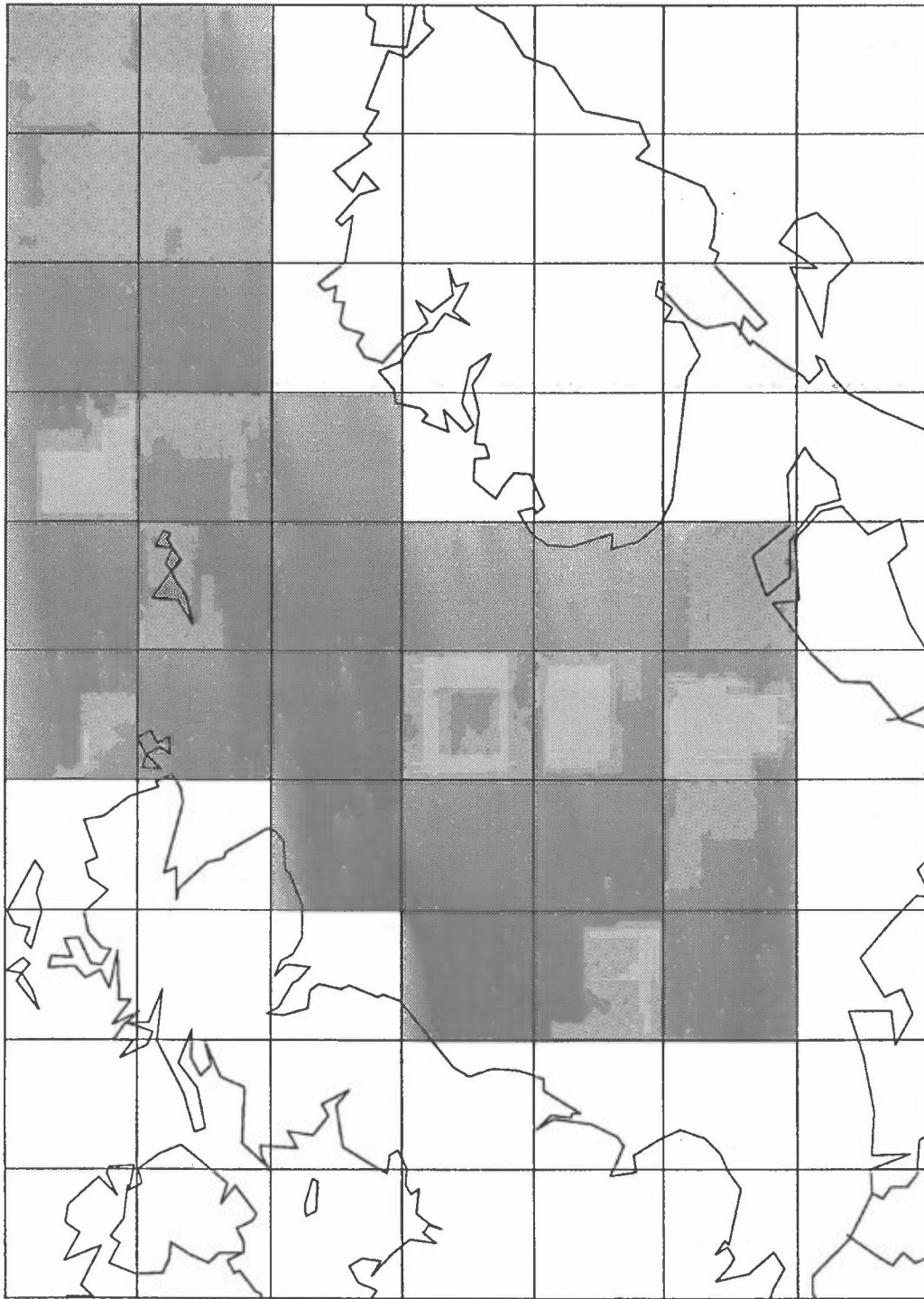


Figure B1: The EMEP grid and computational area. The North Sea grids which have been indicated with shading define the area where the emissions from the oil and gas extraction activities occur.

B.2. The photochemical plume model

A special model called FOTOPLUME has been used to simulate the dispersion and the chemical reactions downwind of emission sources in the North Sea. Both nitrogen oxides and VOCs are released in relatively high concentrations, e.g. in the exhaust gases from gas turbines, where the concentration of nitrogen oxides are several hundred parts per million. Subsequent dilution with the surrounding air is determined by the atmospheric turbulence, which causes the plume to increase its width and height, until it is more or less evenly dispersed within the mixing layer within a few hours. The lateral dimensions are also increased, within the same time frame, up to a few kilometres.

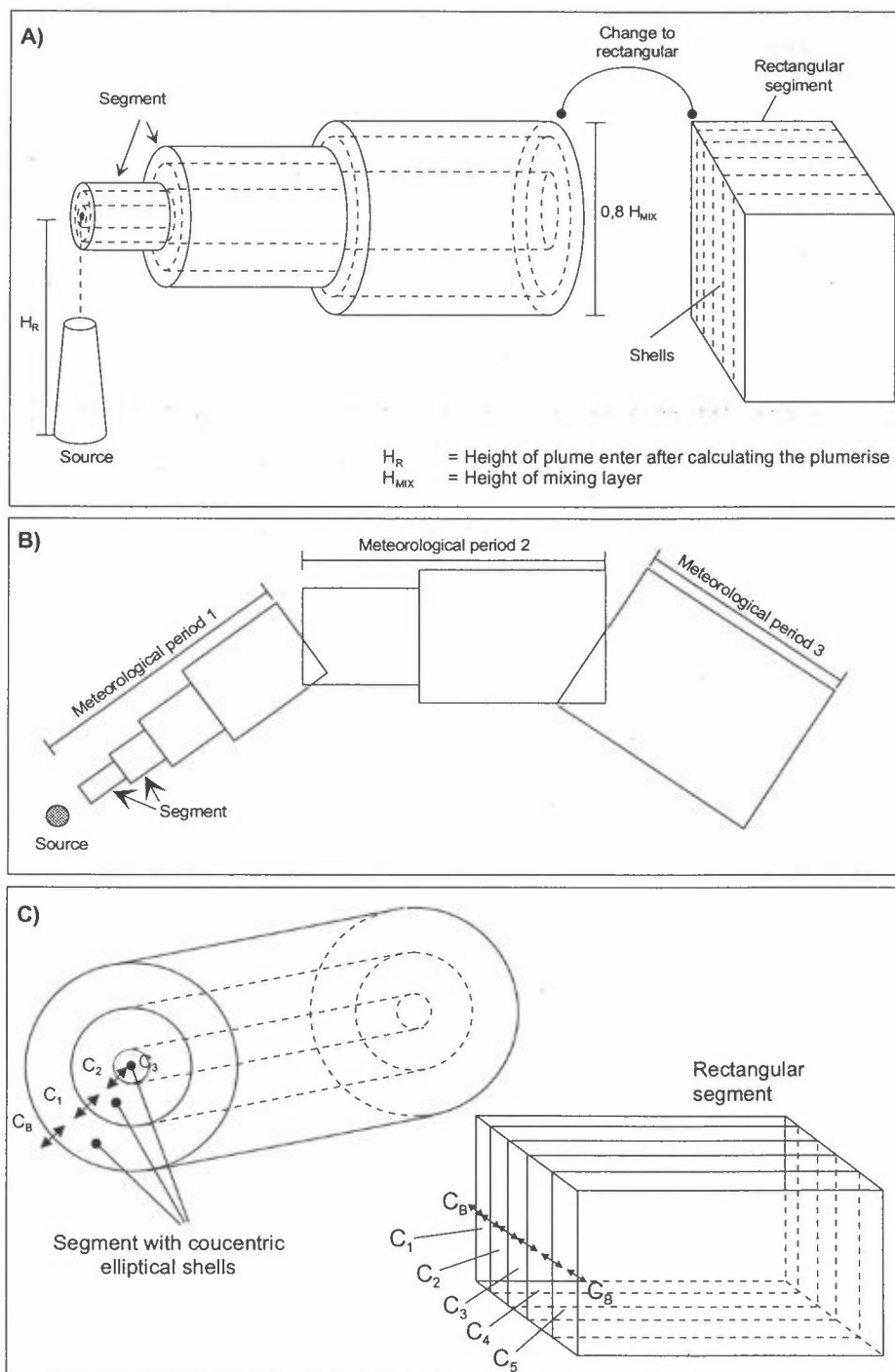
In order to describe the chemical reactions of the nitrogen oxides and the volatile organic compounds emitted from the platforms and other installations, it was considered important to describe this mixing with the external air as correctly as possible., because the formation of ozone by photochemical reactions depends critically on the concentrations of nitric oxide and nitrogen dioxide in relation to the concentrations of the other reacting species.

Figure B2 (a,b) shows how the dispersion from a point source is simulated by stepwise expanding segments. The plume is divided into segments along the mean advection axis. The length of this axis corresponds to the time resolution of the plume expansion, which is 15 minutes. The width and height of the elliptic cylinder segments are determined from plume dispersion parameters, which have been taken from the meteorological data. In order to simulate the concentration variations across the plume, each segment is divided into several shells. As the segments expand due to mixing with the air outside the plume, some simplifications and changes of the geometry are necessary. When the width of the plume equals the length of of the segment, that segment will be added to the segment which was emitted in the preceding timestep. Another rearrangement occurs when the vertical extent of the plume has increased to 80% of the height of the mixing layer. The concentric shells are then replaced by rectangular blocks, with a height corresponding to the mixing layer, as shown in Figure B2 (a and c). This is in accordance with the real situation, which results in relatively homogeneous vertical distribution, when the plume has been mixed down to the surface layer, and avoids rapid changes in the chemical composition within the individual cells, which would have caused computational difficulties.

Both the shells and the rectangular blocks expand in timesteps as a function of the dispersion parameters. In addition, there is also exchange of gases and particles by diffusion between the shells, and between the outer shell and the background air. Photochemical reactions are simulated for each segment and shell, with timesteps ~~which are chosen so that the computational solutions are stable.~~ The photochemical reaction scheme and the reaction rates are identical with the reaction scheme in the EMEP model.

The segments are advected with the wind taken from the EMEP model, which changes every 6 hours. Because the wind field changes with the location in the EMEP grid, the plumes will travel along curved trajectories. No interpolation of the wind strength or direction is made within the 6-h time intervals, however.

The results may be listed in files for the respective shells as a function of time. This procedure has been used in the case studies, where the course of reactions and the concentration patterns were of particular interest. For the model runs covering the entire period April-September 1992, results have been listed in special files for the defined receptor points, in such a way that if one of the plumes were located at the receptor point, the concentrations in the relevant shell and the time was stored. This procedure was necessary in order to reduce the output of data from the model calculations.

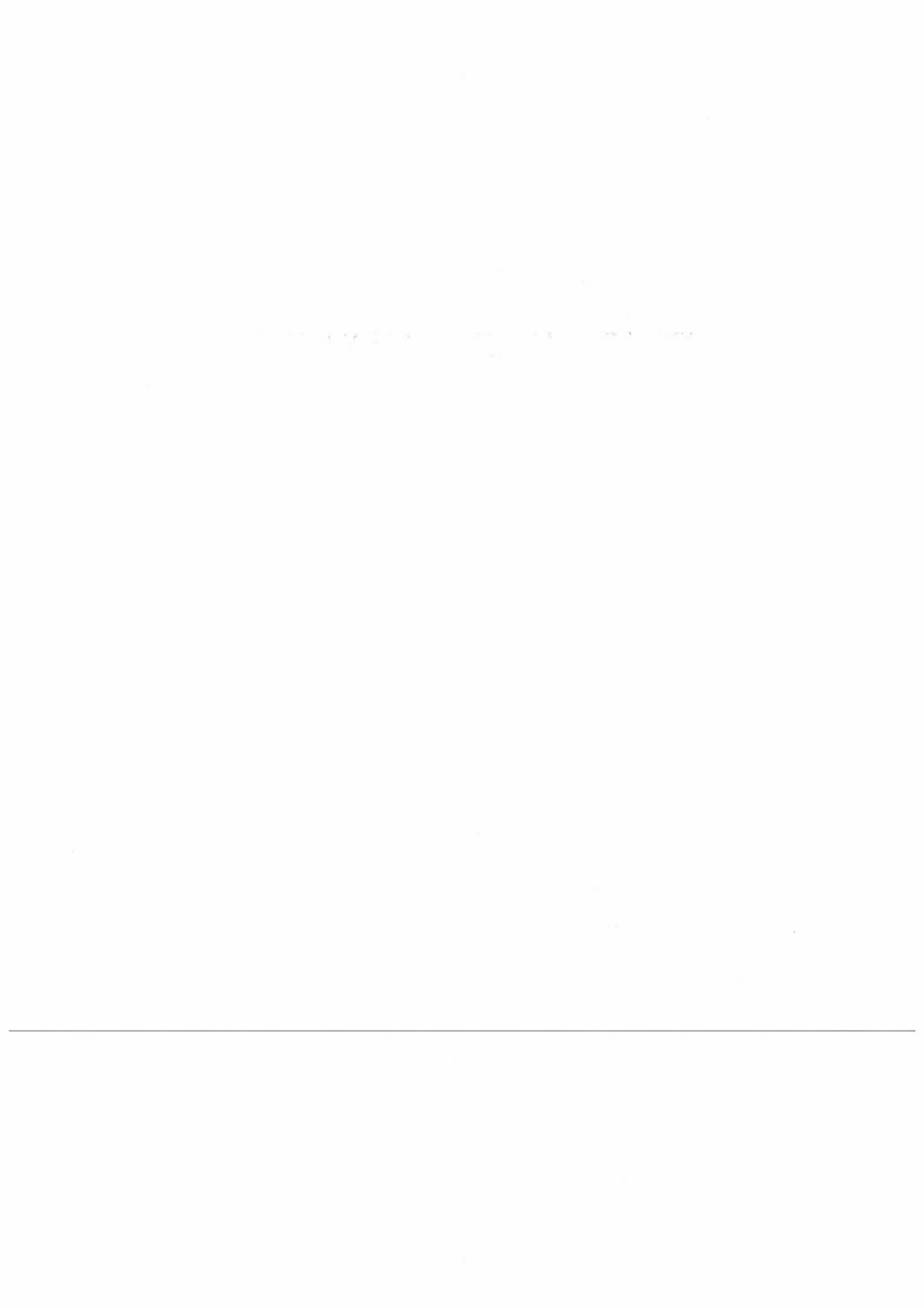


Figur B2: Graphical representation of the dispersion model.

A) The plume segments in perspective

B) The plume seen from above

C) One segment with shells.



Appendix C

Results from model runs, April-September 1992

1. $\frac{1}{2} \times \frac{1}{3} = \frac{1}{6}$

2. $\frac{1}{4} \times \frac{1}{5} = \frac{1}{20}$

3. $\frac{1}{6} \times \frac{1}{7} = \frac{1}{42}$

4.

5.

6.

7.

Table C1: Estimated monthly ozone concentration levels, April-September 1992.
Unit: $\mu\text{g}/\text{m}^3$.

| | Emissions only in the Norwegian sector | | Emissions only in the British sector | | Emissions in both the British and the Norwegian sectors | | No emissions in the North Sea | |
|-----------|--|------|--------------------------------------|------|---|------|-------------------------------|------|
| | Mean | Max. | Mean | Max. | Mean | Max. | Mean | Max. |
| Jeløya | | | | | | | | |
| April | 84 | 141 | 87 | 186 | 89 | 186 | 81 | 133 |
| May | 103 | 230 | 106 | 225 | 108 | 230 | 100 | 207 |
| June | 95 | 156 | 96 | 168 | 97 | 173 | 92 | 124 |
| July | 92 | 217 | 98 | 196 | 99 | 196 | 90 | 217 |
| August | 94 | 238 | 96 | 212 | 100 | 238 | 86 | 225 |
| September | 76 | 139 | 78 | 129 | 80 | 129 | 71 | 139 |
| Total | 91 | 238 | 94 | 225 | 96 | 238 | 87 | 225 |
| Langesund | | | | | | | | |
| April | 84 | 147 | 87 | 167 | 89 | 167 | 81 | 133 |
| May | 104 | 231 | 106 | 224 | 109 | 231 | 100 | 207 |
| June | 95 | 157 | 98 | 168 | 99 | 173 | 92 | 124 |
| July | 94 | 217 | 100 | 217 | 101 | 217 | 90 | 217 |
| August | 93 | 244 | 97 | 218 | 102 | 244 | 86 | 225 |
| September | 75 | 139 | 77 | 129 | 78 | 129 | 71 | 139 |
| Total | 91 | 244 | 94 | 224 | 96 | 244 | 87 | 225 |
| Stavanger | | | | | | | | |
| April | 79 | 142 | 83 | 153 | 84 | 153 | 75 | 104 |
| May | 102 | 225 | 107 | 223 | 111 | 225 | 91 | 222 |
| June | 88 | 159 | 92 | 181 | 95 | 178 | 84 | 129 |
| July | 86 | 189 | 93 | 180 | 94 | 189 | 80 | 174 |
| August | 87 | 288 | 92 | 234 | 95 | 288 | 78 | 206 |
| September | 71 | 126 | 77 | 131 | 78 | 131 | 64 | 118 |
| Total | 86 | 288 | 91 | 234 | 93 | 288 | 79 | 222 |
| Voss | | | | | | | | |
| April | 83 | 158 | 84 | 169 | 86 | 169 | 79 | 119 |
| May | 107 | 220 | 111 | 223 | 112 | 223 | 101 | 214 |
| June | 95 | 161 | 100 | 245 | 102 | 245 | 92 | 150 |
| July | 91 | 190 | 97 | 191 | 99 | 191 | 85 | 156 |
| August | 92 | 306 | 98 | 267 | 101 | 306 | 83 | 212 |
| September | 69 | 123 | 73 | 134 | 74 | 134 | 66 | 117 |
| Total | 90 | 306 | 94 | 267 | 96 | 306 | 84 | 214 |
| Birkenes | | | | | | | | |
| April | 86 | 159 | 88 | 173 | 89 | 173 | 82 | 137 |
| May | 107 | 229 | 109 | 226 | 112 | 229 | 100 | 200 |
| June | 97 | 203 | 98 | 169 | 102 | 203 | 90 | 144 |
| July | 91 | 212 | 98 | 179 | 99 | 212 | 84 | 152 |
| August | 92 | 239 | 98 | 223 | 102 | 239 | 82 | 159 |
| September | 70 | 123 | 73 | 134 | 75 | 134 | 66 | 117 |
| Total | 91 | 239 | 94 | 226 | 97 | 239 | 84 | 200 |
| Kaarvatn | | | | | | | | |
| April | 76 | 131 | 78 | 132 | 79 | 132 | 73 | 110 |
| May | 93 | 222 | 100 | 230 | 100 | 230 | 90 | 192 |
| June | 85 | 135 | 84 | 128 | 85 | 137 | 84 | 128 |
| July | 82 | 152 | 85 | 163 | 86 | 163 | 78 | 146 |
| August | 80 | 159 | 82 | 193 | 84 | 193 | 76 | 159 |
| September | 71 | 118 | 70 | 119 | 74 | 119 | 63 | 105 |
| Total | 81 | 222 | 83 | 230 | 85 | 230 | 77 | 192 |

Table C2: *Estimated monthly mean nitrogen dioxide concentrations.*
Unit: $\mu\text{g}/\text{m}^3$.

| | Emissions only in the Norwegian sector | Emissions only in the British sector | Emissions in both the British and the Norwegian sectors | No emissions in the North Sea |
|------------------|--|--|---|----------------------------------|
| | Mean | Mean | Mean | Mean |
| Jeløya | | | | |
| April | 1,20 | 1,70 | 1,64 | 1,45 |
| May | 1,11 | 1,31 | 1,32 | 1,27 |
| June | 0,97 | 0,94 | 0,87 | 1,15 |
| July | 0,86 | 0,82 | 0,87 | 0,94 |
| August | 1,04 | 1,07 | 1,17 | 1,12 |
| September | 1,96 | 2,14 | 2,12 | 2,49 |
| Total | 1,19 | 1,33 | 1,33 | 1,40 |
| Langesund | | | | |
| April | 1,42 | 1,97 | 1,96 | 1,45 |
| May | 1,04 | 1,27 | 1,27 | 1,27 |
| June | 0,98 | 0,81 | 0,78 | 1,15 |
| July | 0,90 | 0,84 | 0,95 | 0,94 |
| August | 1,02 | 1,20 | 1,27 | 1,12 |
| September | 2,12 | 2,32 | 2,27 | 2,49 |
| Total | 1,24 | 1,40 | 1,41 | 1,40 |
| Stavanger | | | | |
| April | 1,04 | 1,68 | 1,75 | 1,15 |
| May | 0,66 | 0,84 | 0,87 | 0,69 |
| June | 0,51 | 0,47 | 0,47 | 0,59 |
| July | 0,44 | 0,56 | 0,57 | 0,54 |
| August | 0,57 | 0,67 | 0,74 | 0,59 |
| September | 2,04 | 2,03 | 2,24 | 1,90 |
| Total | 0,87 | 1,04 | 1,10 | 0,90 |
| Voss | | | | |
| April | 1,23 | 2,05 | 1,93 | 1,87 |
| May | 1,00 | 1,11 | 1,09 | 1,44 |
| June | 0,71 | 0,66 | 0,62 | 0,89 |
| July | 0,78 | 0,76 | 0,73 | 0,97 |
| August | 0,88 | 0,92 | 1,12 | 0,80 |
| September | 3,74 | 3,78 | 3,99 | 3,50 |
| Total | 1,38 | 1,54 | 1,57 | 1,57 |
| Birkenes | | | | |
| April | 1,20 | 1,78 | 1,87 | 0,92 |
| May | 0,97 | 1,20 | 1,38 | 0,70 |
| June | 0,60 | 0,59 | 0,56 | 0,71 |
| July | 0,81 | 0,78 | 0,93 | 0,67 |
| August | 0,93 | 1,25 | 1,35 | 0,74 |
| September | 3,15 | 3,34 | 3,58 | 2,97 |
| Total | 1,27 | 1,48 | 1,61 | 1,11 |
| Kaarvatn | | | | |
| April | 0,49 | 0,58 | 0,62 | 0,50 |
| May | 0,71 | 0,67 | 0,69 | 0,68 |
| June | 0,38 | 0,40 | 0,38 | 0,42 |
| July | 0,34 | 0,31 | 0,33 | 0,38 |
| August | 0,32 | 0,33 | 0,33 | 0,39 |
| September | 1,06 | 1,27 | 1,19 | 1,55 |
| Total | 0,55 | 0,59 | 0,59 | 0,65 |

Table C3: Estimated monthly means of the sum of nitric acid and nitrates in air.
Unit: $\mu\text{g}/\text{m}^3$ as nitrogen. Data not corrected for deposition processes.

| | Emissions only in the Norwegian sector | Emissions only in the British sector | Emissions in both the British and Norwegian sectors | No emissemisions in the North Sea |
|-----------|--|--|---|---|
| | Mean | Mean | Mean | Mean |
| Jeløya | | | | |
| April | 0,52 | 0,77 | 0,87 | 0,32 |
| May | 0,80 | 1,00 | 1,08 | 0,62 |
| June | 0,44 | 0,54 | 0,58 | 0,36 |
| July | 0,56 | 1,04 | 1,08 | 0,35 |
| August | 0,72 | 0,97 | 1,14 | 0,25 |
| September | 0,87 | 1,05 | 1,19 | 0,63 |
| Total | 0,65 | 0,90 | 0,99 | 0,42 |
| Langesund | | | | |
| April | 0,56 | 0,84 | 0,94 | 0,32 |
| May | 0,81 | 0,98 | 1,06 | 0,62 |
| June | 0,45 | 0,60 | 0,65 | 0,36 |
| July | 0,66 | 1,03 | 1,11 | 0,35 |
| August | 0,69 | 1,04 | 1,20 | 0,25 |
| September | 0,84 | 1,01 | 1,13 | 0,63 |
| Total | 0,67 | 0,92 | 1,01 | 0,42 |
| Stavanger | | | | |
| April | 0,37 | 0,73 | 0,76 | 0,25 |
| May | 0,90 | 1,19 | 1,36 | 0,44 |
| June | 0,37 | 0,48 | 0,58 | 0,28 |
| July | 0,44 | 0,82 | 0,88 | 0,16 |
| August | 0,46 | 0,77 | 0,91 | 0,12 |
| September | 0,72 | 1,12 | 1,22 | 0,30 |
| Total | 0,54 | 0,85 | 0,95 | 0,26 |
| Voss | | | | |
| April | 0,48 | 0,67 | 0,75 | 0,30 |
| May | 0,96 | 1,13 | 1,23 | 0,71 |
| June | 0,46 | 0,65 | 0,76 | 0,34 |
| July | 0,57 | 0,89 | 0,99 | 0,23 |
| August | 0,63 | 1,03 | 1,17 | 0,16 |
| September | 0,68 | 0,96 | 1,05 | 0,36 |
| Total | 0,63 | 0,89 | 0,99 | 0,35 |
| Birkenes | | | | |
| April | 0,61 | 0,90 | 0,95 | 0,38 |
| May | 0,98 | 1,14 | 1,24 | 0,68 |
| June | 0,55 | 0,68 | 0,83 | 0,38 |
| July | 0,66 | 0,98 | 1,08 | 0,24 |
| August | 0,65 | 1,08 | 1,23 | 0,18 |
| September | 0,72 | 0,90 | 1,02 | 0,46 |
| Total | 0,70 | 0,95 | 1,06 | 0,39 |
| Kaarvatn | | | | |
| April | 0,32 | 0,42 | 0,48 | 0,17 |
| May | 0,51 | 0,75 | 0,80 | 0,35 |
| June | 0,22 | 0,22 | 0,23 | 0,19 |
| July | 0,22 | 0,41 | 0,43 | 0,11 |
| August | 0,24 | 0,42 | 0,47 | 0,11 |
| September | 0,62 | 0,68 | 0,94 | 0,21 |
| Total | 0,36 | 0,48 | 0,56 | 0,19 |

Table C4: Estimated monthly mean concentrations of peroxyacetyl nitrate (PAN). Unit: $\mu\text{g}/\text{m}^3$.

| | Emissions only in the Norwegian sector | Emissions only in the British sector | Emissions in both the British and Norwegian sectors | No emissions in the North Sea |
|-----------|--|--|---|-------------------------------------|
| | Mean | Mean | Mean | Mean |
| Jeløya | | | | |
| April | 2,11 | 2,47 | 2,57 | 1,98 |
| May | 2,04 | 2,15 | 2,24 | 1,85 |
| June | 1,26 | 1,24 | 1,26 | 1,29 |
| July | 1,08 | 1,23 | 1,25 | 1,12 |
| August | 1,23 | 1,29 | 1,41 | 1,17 |
| September | 1,16 | 1,20 | 1,26 | 1,14 |
| Total | 1,48 | 1,60 | 1,66 | 1,42 |
| Langesund | | | | |
| April | 2,16 | 2,53 | 2,64 | 1,98 |
| May | 2,07 | 2,20 | 2,30 | 1,85 |
| June | 1,26 | 1,24 | 1,25 | 1,29 |
| July | 1,12 | 1,23 | 1,27 | 1,12 |
| August | 1,23 | 1,41 | 1,50 | 1,17 |
| September | 1,15 | 1,18 | 1,24 | 1,14 |
| Total | 1,50 | 1,63 | 1,70 | 1,42 |
| Stavanger | | | | |
| April | 1,71 | 2,11 | 2,17 | 1,51 |
| May | 2,16 | 2,09 | 2,28 | 1,92 |
| June | 1,22 | 1,30 | 1,31 | 1,25 |
| July | 0,96 | 1,16 | 1,20 | 0,97 |
| August | 0,97 | 1,15 | 1,27 | 0,74 |
| September | 0,98 | 1,15 | 1,24 | 0,69 |
| Total | 1,33 | 1,50 | 1,58 | 1,18 |
| Voss | | | | |
| April | 2,06 | 2,23 | 2,36 | 1,86 |
| May | 2,18 | 2,45 | 2,52 | 2,00 |
| June | 1,14 | 1,29 | 1,31 | 1,21 |
| July | 1,12 | 1,24 | 1,29 | 1,04 |
| August | 1,14 | 1,37 | 1,50 | 0,86 |
| September | 0,93 | 1,09 | 1,15 | 0,77 |
| Total | 1,43 | 1,61 | 1,69 | 1,29 |
| Birkenes | | | | |
| April | 2,39 | 2,69 | 2,74 | 2,19 |
| May | 2,22 | 2,55 | 2,57 | 2,01 |
| June | 1,15 | 1,16 | 1,20 | 1,19 |
| July | 1,16 | 1,29 | 1,36 | 1,05 |
| August | 1,16 | 1,37 | 1,50 | 0,96 |
| September | 0,91 | 1,03 | 1,09 | 0,79 |
| Total | 1,50 | 1,68 | 1,74 | 1,36 |
| Kaarvatn | | | | |
| April | 1,51 | 1,65 | 1,69 | 1,36 |
| May | 1,51 | 1,71 | 1,74 | 1,35 |
| June | 0,84 | 0,85 | 0,85 | 0,86 |
| July | 0,85 | 0,88 | 0,92 | 0,81 |
| August | 0,70 | 0,78 | 0,79 | 0,67 |
| September | 0,85 | 0,93 | 1,07 | 0,59 |
| Total | 1,04 | 1,13 | 1,18 | 0,94 |

Table C5: Estimated number of hours with concentrations of ozone above $60 \mu\text{g}/\text{m}^3$, and mean difference between the ozone concentrations calculated with the FOTOPLUME model under different emission scenarios, and with no emissions in the North Sea (O_3 -background).

Mean difference between O_3 and O_3 background when O_3 -concentrations are $60 \mu\text{g}/\text{m}^3$ or higher (Emissions in both the British and the Norwegian sectors)

| | Jeløya | | Langesund | | Stavanger | | Voss | | Birkenes | | Kaarvath | |
|-----------|--------|-------|-----------|-------|-----------|-------|--------|-------|----------|-------|----------|-------|
| | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean |
| April | 119 | 8,48 | 119 | 8,48 | 119 | 9,22 | 120 | 7,48 | 120 | 7,11 | 120 | 6,09 |
| May | 124 | 8,83 | 124 | 9,28 | 124 | 19,90 | 124 | 11,68 | 124 | 12,41 | 124 | 10,06 |
| June | 120 | 5,92 | 120 | 7,55 | 118 | 10,83 | 120 | 10,24 | 120 | 11,92 | 120 | 1,20 |
| July | 124 | 8,90 | 124 | 10,55 | 124 | 14,23 | 124 | 14,25 | 123 | 15,34 | 124 | 7,73 |
| August | 123 | 14,20 | 123 | 15,43 | 124 | 17,55 | 124 | 18,07 | 124 | 19,89 | 124 | 8,49 |
| September | 108 | 9,94 | 104 | 8,60 | 108 | 14,71 | 101 | 9,56 | 100 | 9,48 | 105 | 12,16 |
| Total | 718 | 9,39 | 714 | 10,04 | 717 | 14,47 | 713 | 11,99 | 711 | 12,83 | 717 | 7,54 |

Mean difference between O_3 and O_3 background when O_3 -concentrations are $60 \mu\text{g}/\text{m}^3$ or higher (Emissions only in the Norwegian sector of the North Sea)

| | Jeløya | | Langesund | | Stavanger | | Voss | | Birkenes | | Kaarvath | |
|-----------|--------|------|-----------|------|-----------|-------|--------|------|----------|-------|----------|------|
| | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean |
| April | 119 | 3,24 | 119 | 3,45 | 119 | 3,52 | 120 | 4,35 | 120 | 3,32 | 120 | 3,22 |
| May | 124 | 3,40 | 123 | 4,21 | 124 | 10,68 | 124 | 5,89 | 124 | 7,54 | 124 | 3,40 |
| June | 120 | 3,10 | 118 | 3,21 | 118 | 4,37 | 120 | 3,43 | 119 | 6,83 | 120 | 0,86 |
| July | 124 | 2,30 | 124 | 3,68 | 124 | 5,88 | 123 | 6,67 | 123 | 7,63 | 124 | 3,56 |
| August | 123 | 7,41 | 123 | 6,99 | 124 | 9,07 | 124 | 9,07 | 124 | 10,20 | 124 | 4,08 |
| September | 107 | 5,53 | 101 | 4,36 | 99 | 7,92 | 96 | 3,86 | 96 | 4,94 | 104 | 8,73 |
| Total | 717 | 4,14 | 708 | 4,33 | 708 | 6,92 | 707 | 5,63 | 706 | 6,83 | 716 | 3,86 |

Mean difference between O_3 and O_3 background when O_3 -concentrations are $60 \mu\text{g}/\text{m}^3$ or higher (Emissions only in the British sector of the North Sea)

| | Jeløya | | Langesund | | Stavanger | | Voss | | Birkenes | | Kaarvath | |
|-----------|--------|-------|-----------|-------|-----------|-------|--------|-------|----------|-------|----------|------|
| | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean |
| April | 118 | 6,70 | 119 | 6,42 | 119 | 8,29 | 120 | 5,33 | 120 | 5,96 | 120 | 5,00 |
| May | 124 | 6,92 | 124 | 6,88 | 124 | 15,93 | 124 | 9,87 | 122 | 9,62 | 123 | 9,58 |
| June | 118 | 4,62 | 120 | 6,56 | 118 | 8,04 | 120 | 7,80 | 119 | 7,62 | 120 | 0,32 |
| July | 124 | 8,33 | 124 | 9,57 | 123 | 13,07 | 124 | 12,26 | 122 | 14,06 | 124 | 6,82 |
| August | 123 | 10,11 | 123 | 11,20 | 124 | 14,26 | 124 | 15,07 | 124 | 15,87 | 124 | 6,84 |
| September | 103 | 8,11 | 101 | 6,89 | 106 | 13,65 | 100 | 8,41 | 98 | 8,11 | 99 | 8,20 |
| Total | 710 | 7,47 | 711 | 7,97 | 714 | 12,23 | 712 | 9,87 | 705 | 10,32 | 710 | 6,09 |

Table C6: Estimated number of hours with concentrations of ozone above 80 µg/m³, and mean difference between the ozone concentrations calculated with the FOTOPLUME model under different emission scenarios, and with no emissions in the North Sea (O₃-background).

Mean difference between O3 and O3 background when O3-concentrations are 80 µg/m³ or higher (Emissions in both the British and the Norwegian sectors)

| | Jeløya | | Langesund | | Stavanger | | Voss | | Birkenes | | Kaarvatin | |
|-----------|--------|-------|-----------|-------|-----------|-------|--------|-------|----------|-------|-----------|-------|
| | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean |
| April | 73 | 12,69 | 74 | 12,33 | 54 | 17,72 | 71 | 11,43 | 73 | 10,41 | 38 | 16,62 |
| May | 106 | 10,00 | 108 | 10,31 | 92 | 26,57 | 103 | 13,87 | 110 | 13,55 | 80 | 15,30 |
| June | 107 | 6,24 | 106 | 8,25 | 87 | 14,20 | 92 | 12,54 | 101 | 13,33 | 72 | 2,01 |
| July | 100 | 11,10 | 101 | 12,71 | 71 | 23,69 | 95 | 18,39 | 95 | 19,29 | 56 | 16,86 |
| August | 102 | 16,52 | 102 | 18,16 | 91 | 23,06 | 103 | 21,41 | 105 | 22,95 | 67 | 14,36 |
| September | 65 | 13,11 | 58 | 11,86 | 53 | 21,50 | 40 | 16,25 | 49 | 14,06 | 39 | 22,86 |
| Total | 553 | 11,39 | 549 | 12,25 | 448 | 21,33 | 504 | 15,87 | 533 | 16,00 | 352 | 13,63 |

Mean difference between O3 and O3 background when O3-concentrations are 80 µg/m³ or higher (Emissions only in the Norwegian sector of the North Sea)

| | Jeløya | | Langesund | | Stavanger | | Voss | | Birkenes | | Kaarvatin | |
|-----------|--------|------|-----------|------|-----------|-------|--------|-------|----------|-------|-----------|-------|
| | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean |
| April | 63 | 4,90 | 65 | 5,32 | 42 | 7,13 | 65 | 6,88 | 67 | 5,21 | 27 | 10,57 |
| May | 95 | 4,10 | 99 | 4,67 | 85 | 15,45 | 97 | 7,44 | 104 | 8,74 | 80 | 5,02 |
| June | 102 | 2,78 | 101 | 3,25 | 81 | 5,70 | 86 | 4,22 | 98 | 7,70 | 73 | 1,39 |
| July | 96 | 2,89 | 95 | 4,66 | 63 | 10,45 | 85 | 9,42 | 77 | 11,23 | 54 | 7,90 |
| August | 91 | 9,37 | 92 | 9,49 | 70 | 14,23 | 90 | 12,02 | 90 | 13,53 | 49 | 8,57 |
| September | 42 | 6,45 | 41 | 5,99 | 26 | 16,49 | 25 | 6,53 | 30 | 7,20 | 28 | 22,97 |
| Total | 489 | 4,87 | 493 | 5,47 | 367 | 11,33 | 448 | 7,99 | 466 | 9,25 | 311 | 7,32 |

Mean difference between O3 and O3 background when O3-concentrations are 80 µg/m³ or higher (Emissions only in the British sector of the North Sea)

| | Jeløya | | Langesund | | Stavanger | | Voss | | Birkenes | | Kaarvatin | |
|-----------|--------|-------|-----------|-------|-----------|-------|--------|-------|----------|-------|-----------|-------|
| | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean |
| April | 69 | 10,96 | 71 | 10,31 | 52 | 17,34 | 65 | 9,00 | 71 | 9,32 | 35 | 14,93 |
| May | 104 | 8,07 | 105 | 7,90 | 91 | 21,56 | 103 | 11,80 | 107 | 10,69 | 80 | 14,68 |
| June | 104 | 4,75 | 106 | 6,85 | 84 | 11,18 | 91 | 9,63 | 95 | 8,55 | 70 | 0,43 |
| July | 98 | 10,67 | 102 | 11,40 | 69 | 22,59 | 92 | 16,11 | 92 | 18,30 | 54 | 15,28 |
| August | 97 | 12,35 | 93 | 14,65 | 86 | 19,72 | 98 | 18,68 | 100 | 19,15 | 57 | 13,15 |
| September | 58 | 11,94 | 51 | 10,36 | 48 | 21,56 | 38 | 15,38 | 42 | 12,51 | 29 | 17,30 |
| Total | 530 | 9,48 | 528 | 10,12 | 430 | 18,82 | 487 | 13,50 | 507 | 13,30 | 325 | 11,70 |

Table C7: Estimated number of hours with concentrations of ozone above 100 µg/m³, and mean difference between the ozone concentrations calculated with the FOTOPLUME model under different emission scenarios, and with no emissions in the North Sea (O₃-background).

Mean difference between O₃ and O₃ background when O₃-concentrations are 100 µg/m³ or higher (Emissions in both the British and the Norwegian sectors)

| | Jeløya | | Langesund | | Stavanger | | Voss | | Birkenes | | Kaarvatn | |
|-----------|--------|-------|-----------|-------|-----------|-------|--------|-------|----------|-------|----------|-------|
| | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean |
| April | 24 | 25,43 | 23 | 26,20 | 19 | 34,70 | 21 | 24,28 | 29 | 16,08 | 12 | 20,54 |
| May | 67 | 12,93 | 74 | 13,05 | 63 | 35,61 | 71 | 16,79 | 75 | 16,57 | 52 | 22,44 |
| June | 41 | 14,21 | 47 | 17,54 | 39 | 27,41 | 57 | 18,46 | 49 | 22,25 | 15 | 4,82 |
| July | 48 | 21,02 | 56 | 20,12 | 37 | 36,47 | 41 | 34,91 | 54 | 28,31 | 21 | 32,02 |
| August | 51 | 24,04 | 44 | 29,05 | 33 | 42,92 | 39 | 39,89 | 48 | 35,36 | 14 | 28,91 |
| September | 7 | 0,64 | 7 | 1,27 | 3 | 24,85 | 6 | 27,00 | 4 | 19,12 | 9 | 33,12 |
| Total | 238 | 18,06 | 251 | 19,15 | 194 | 35,11 | 235 | 25,12 | 259 | 23,56 | 123 | 23,26 |

Mean difference between O₃ and O₃ background when O₃-concentrations are 100 µg/m³ or higher (Emissions only in the Norwegian sector of the North Sea)

| | Jeløya | | Langesund | | Stavanger | | Voss | | Birkenes | | Kaarvatn | |
|-----------|--------|-------|-----------|-------|-----------|-------|--------|-------|----------|-------|----------|-------|
| | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean |
| April | 14 | 11,20 | 11 | 12,63 | 3 | 15,31 | 14 | 16,82 | 20 | 7,83 | 6 | 19,46 |
| May | 60 | 5,48 | 63 | 6,10 | 45 | 26,37 | 62 | 9,31 | 63 | 10,08 | 32 | 10,58 |
| June | 38 | 7,62 | 37 | 9,23 | 22 | 13,55 | 44 | 6,29 | 45 | 14,03 | 13 | 2,27 |
| July | 34 | 5,69 | 41 | 8,10 | 18 | 20,18 | 31 | 19,13 | 39 | 16,64 | 11 | 25,22 |
| August | 30 | 17,61 | 29 | 18,52 | 13 | 30,63 | 21 | 27,07 | 28 | 22,14 | 6 | 15,28 |
| September | 6 | -4,61 | 6 | -3,73 | 2 | 22,31 | 2 | 6,11 | 1 | -1,70 | 6 | 38,72 |
| Total | 182 | 8,07 | 187 | 9,15 | 103 | 22,69 | 174 | 13,01 | 196 | 13,73 | 74 | 14,68 |

Mean difference between O₃ and O₃ background when O₃-concentrations are 100 µg/m³ or higher (Emissions only in the British sector of the North Sea)

| | Jeløya | | Langesund | | Stavanger | | Voss | | Birkenes | | Kaarvatn | |
|-----------|--------|-------|-----------|-------|-----------|-------|--------|-------|----------|-------|----------|-------|
| | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean |
| April | 21 | 23,91 | 21 | 23,47 | 19 | 34,21 | 18 | 20,81 | 25 | 15,80 | 10 | 18,37 |
| May | 66 | 10,91 | 69 | 10,31 | 61 | 29,34 | 68 | 14,31 | 71 | 13,33 | 52 | 21,50 |
| June | 40 | 10,97 | 39 | 16,58 | 34 | 22,86 | 53 | 14,02 | 39 | 16,02 | 13 | 0,53 |
| July | 48 | 20,28 | 50 | 19,81 | 38 | 34,91 | 38 | 33,05 | 50 | 27,58 | 19 | 30,87 |
| August | 42 | 19,24 | 39 | 23,29 | 27 | 38,57 | 31 | 40,08 | 35 | 34,32 | 11 | 26,56 |
| September | 7 | 0,19 | 7 | 1,27 | 3 | 24,76 | 5 | 29,99 | 3 | 15,51 | 3 | 20,44 |
| Total | 224 | 15,37 | 225 | 16,71 | 182 | 31,09 | 213 | 22,25 | 223 | 20,60 | 108 | 20,82 |

Table C7: Estimated number of hours with concentrations of ozone above 120 µg/m³, and mean difference between the ozone concentrations calculated with the FOTOPLUME model under different emission scenarios, and with no emissions in the North Sea (O₃-background).

Mean difference between O₃ and O₃ background when O₃-concentrations are 120 µg/m³ or higher (Emissions in both the British and the Norwegian sectors)

| | Jeløya | | Langesund | | Stavanger | | Voss | | Birkenes | | Kaarvatn | |
|-----------|--------|-------|-----------|-------|-----------|-------|--------|-------|----------|-------|----------|-------|
| | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean |
| April | 8 | 34,44 | 8 | 33,13 | 6 | 58,60 | 4 | 64,79 | 8 | 25,00 | 1 | 37,24 |
| May | 37 | 18,45 | 38 | 17,73 | 32 | 58,60 | 36 | 25,01 | 36 | 23,33 | 23 | 34,32 |
| June | 14 | 26,73 | 15 | 29,27 | 19 | 37,55 | 25 | 30,84 | 25 | 33,28 | 4 | 10,21 |
| July | 22 | 30,91 | 23 | 33,43 | 19 | 48,86 | 22 | 47,07 | 25 | 41,70 | 9 | 45,57 |
| August | 21 | 35,96 | 20 | 40,78 | 14 | 58,54 | 19 | 56,18 | 21 | 44,67 | 2 | 32,76 |
| September | 1 | -2,36 | 1 | -0,66 | 1 | 4,99 | 1 | 12,97 | | | | |
| Total | 103 | 26,85 | 105 | 28,21 | 91 | 51,57 | 107 | 37,82 | 115 | 33,50 | 39 | 34,44 |

Mean difference between O₃ and O₃ background when O₃-concentrations are 120 µg/m³ or higher (Emissions only in the Norwegian sector of the North Sea)

| | Jeløya | | Langesund | | Stavanger | | Voss | | Birkenes | | Kaarvatn | |
|-----------|--------|-------|-----------|-------|-----------|-------|--------|-------|----------|-------|----------|-------|
| | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean |
| April | 4 | 16,68 | 3 | 30,24 | 1 | 23,34 | 2 | 84,99 | 4 | 27,25 | | |
| May | 28 | 8,23 | 28 | 8,10 | 22 | 44,27 | 32 | 15,21 | 31 | 15,17 | 14 | 18,38 |
| June | 7 | 20,79 | 7 | 20,15 | 5 | 22,55 | 13 | 14,33 | 14 | 21,35 | 4 | 9,82 |
| July | 7 | 12,89 | 8 | 19,73 | 6 | 20,15 | 8 | 36,50 | 9 | 19,69 | 2 | 16,72 |
| August | 11 | 30,84 | 9 | 40,37 | 7 | 35,19 | 6 | 41,42 | 8 | 28,45 | 2 | 0,00 |
| September | 1 | 0,00 | 1 | 0,00 | | | | | | | | |
| Total | 58 | 15,04 | 56 | 17,49 | 41 | 36,03 | 61 | 22,68 | 66 | 19,44 | 22 | 15,00 |

Mean difference between O₃ and O₃ background when O₃-concentrations are 120 µg/m³ or higher (Emissions only in the British sector of the North Sea)

| | Jeløya | | Langesund | | Stavanger | | Voss | | Birkenes | | Kaarvatn | |
|-----------|--------|-------|-----------|-------|-----------|-------|--------|-------|----------|-------|----------|-------|
| | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean | n.obs. | Mean |
| April | 7 | 31,04 | 6 | 29,70 | 6 | 58,53 | 2 | 40,16 | 8 | 24,32 | 1 | 34,84 |
| May | 34 | 15,27 | 37 | 13,19 | 29 | 50,87 | 35 | 22,12 | 33 | 18,61 | 22 | 33,80 |
| June | 9 | 26,67 | 14 | 29,00 | 14 | 29,15 | 22 | 24,09 | 18 | 25,60 | 3 | 0,00 |
| July | 22 | 30,31 | 23 | 33,01 | 19 | 47,68 | 20 | 45,72 | 24 | 40,46 | 7 | 53,52 |
| August | 19 | 27,76 | 18 | 31,92 | 11 | 52,70 | 17 | 54,17 | 19 | 42,26 | 1 | 12,27 |
| September | 1 | -2,36 | 1 | -0,66 | 1 | 4,99 | 1 | 12,97 | | | | |
| Total | 92 | 23,57 | 99 | 24,30 | 80 | 46,56 | 97 | 33,33 | 102 | 29,84 | 34 | 34,28 |

Appendix D

Measured wet deposition and airborne concentrations at Norwegian monitoring sites at or close to the selected FOTOPLUME receptor points(Data from SFT, 1993).

Estimated dry deposition amounts and estimated relative contributions to the deposition from emissions in the British and the Norwegian sectors of the North Sea.

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Table D1: Wet deposition from analysed precipitation samples, mg/m².

| | | SO ₄ -S | NO ₃ -N | NH ₄ -N |
|-------------|--------------|--------------------|--------------------|--------------------|
| Prestebakke | April | 79 | 63 | 51 |
| | May | 27 | 22 | 15 |
| | June | 37 | 18 | 23 |
| | July | 86 | 50 | 44 |
| | August | 76 | 50 | 23 |
| | September | 42 | 27 | 19 |
| | April- Sept | 347 | 230 | 175 |
| | Jan.-Dec. | 687 | 497 | 392 |
| Birkenes | April | 85 | 66 | 67 |
| | May | 22 | 14 | 7 |
| | June | 15 | 5 | 8 |
| | July | 159 | 98 | 74 |
| | August | 143 | 92 | 75 |
| | September | 113 | 94 | 77 |
| | April- Sept. | 537 | 369 | 308 |
| | Jan.-Dec. | 991 | 703 | 589 |
| Skreådalen | April | 56 | 35 | 43 |
| | May | 46 | 21 | 20 |
| | June | 49 | 25 | 18 |
| | July | 146 | 75 | 72 |
| | August | 127 | 81 | 70 |
| | September | 180 | 119 | 127 |
| | April-Sept. | 604 | 356 | 350 |
| | Jan.-Dec. | 1017 | 647 | 627 |
| Voss | April | 25 | 15 | 7 |
| | May | 12 | 7 | 3 |
| | June | 10 | 3 | 5 |
| | July | 108 | 61 | 46 |
| | August | 29 | 12 | 1 |
| | September | 90 | 35 | 15 |
| | April-Sept. | 274 | 133 | 77 |
| | Jan.-Dec. | 436 | 255 | 110 |
| Kårvatn | April | 14 | 5 | 8 |
| | May | 13 | 9 | 4 |
| | June | 18 | 6 | 6 |
| | July | 31 | 15 | 19 |
| | August | 10 | 11 | 14 |
| | September | 8 | 20 | 5 |
| | April-Sept. | 94 | 66 | 56 |
| | Jan.-Dec. | 159 | 113 | 94 |

Table D2: Measured average airborne concentrations in microgrammes/m³.

| | | SO ₂ -S | SO ₄ -S | NO ₂ -N | NH ₄ -N |
|-------------|-------------|--------------------|--------------------|--------------------|--------------------|
| Prestebakke | April | 0.43 | 0.98 | 0.47 | 0.77 |
| | May | 0.71 | 1.12 | 0.64 | 0.95 |
| | June | 0.36 | 0.94 | 0.65 | 0.82 |
| | July | 0.37 | 0.89 | 0.86 | 0.66 |
| | August | 0.22 | 0.66 | 0.37 | 0.51 |
| | September | 0.42 | 0.23 | 0.76 | 0.81 |
| | April-Sept. | 0.42 | 0.80 | 0.63 | 0.75 |
| | Jan.-Dec. | 0.48 | 0.70 | 1.02 | 0.65 |
| Birkenes | April | 0.64 | 0.85 | 0.74 | 0.61 |
| | May | 0.71 | 1.24 | 0.30 | 1.08 |
| | June | 0.45 | 0.83 | 0.65 | 0.82 |
| | July | 0.36 | 0.72 | 0.40 | 0.60 |
| | August | 0.25 | 0.62 | 0.37 | 0.56 |
| | September | 0.44 | 0.73 | 0.82 | 0.68 |
| | April-Sept. | 0.48 | 0.83 | 0.55 | 0.73 |
| | Jan.-Dec. | 0.40 | 0.65 | 0.69 | 0.53 |
| Skreådalen | April | 0.43 | 0.71 | 0.27 | 1.35 |
| | May | 0.47 | 1.15 | 0.31 | 3.13 |
| | June | 0.25 | 0.75 | 0.39 | 2.27 |
| | July | 0.25 | 0.61 | 0.33 | 1.38 |
| | August | 0.12 | 0.47 | 0.24 | 0.61 |
| | September | 0.56 | 0.68 | 0.33 | 0.78 |
| | April-Sept. | 0.35 | 0.73 | 0.31 | 1.59 |
| | Jan.-Dec. | 0.32 | 0.56 | 0.41 | 1.26 |
| Nausta | April | 0.23 | 0.42 | | |
| | May | 0.25 | 1.00 | | |
| | June | 0.20 | 0.62 | | |
| | July | 0.06 | 0.36 | | |
| | August | 0.12 | 0.32 | | |
| | September | 0.16 | 0.47 | | |
| | April-Sept. | 0.17 | 0.53 | | |
| | Jan.-Dec. | 0.17 | 0.39 | | |
| Kårvatn | April | 0.13 | 0.34 | 0.05 | 0.26 |
| | May | 0.19 | 0.88 | 0.12 | 0.68 |
| | June | 0.16 | 0.57 | 0.21 | 1.11 |
| | July | 0.04 | 0.22 | 0.22 | 0.46 |
| | August | 0.04 | 0.16 | 0.16 | 0.41 |
| | September | 0.13 | 0.37 | 0.25 | 0.57 |
| | April-Sept. | 0.12 | 0.42 | 0.17 | 0.58 |
| | Jan.-Dec. | 0.12 | 0.30 | 0.19 | 0.37 |

Table D3: Estimated dry deposition

| | | S | NO ₂ -N | NH ₄ -N | NO ₃ -N |
|-------------|-------------|-------|--------------------|--------------------|--------------------|
| Prestebakke | April | 11.77 | 4.87 | 3.99 | 44.06 |
| | May | 16.85 | 6.64 | 4.92 | 44.06 |
| | June | 10.47 | 6.74 | 4.25 | 29.81 |
| | July | 10.37 | 8.92 | 3.42 | 38.88 |
| | August | 6.84 | 3.84 | 2.64 | 32.40 |
| | September | 7.72 | 7.88 | 4.20 | 23.33 |
| | April-Sept. | 64.02 | 38.88 | 23.43 | 212.54 |
| Birkenes | April | 14.36 | 7.67 | 3.16 | 41.47 |
| | May | 17.47 | 3.11 | 5.60 | 40.18 |
| | June | 11.30 | 6.74 | 4.25 | 29.81 |
| | July | 9.33 | 4.15 | 3.11 | 31.10 |
| | August | 7.10 | 3.84 | 2.90 | 25.92 |
| | September | 10.63 | 8.50 | 3.53 | 45.36 |
| | April-Sept. | 70.19 | 34.01 | 22.55 | 213.84 |
| Skreådalen | April | 10.37 | 2.80 | 7.00 | 31.10 |
| | May | 13.27 | 3.21 | 16.23 | 34.99 |
| | June | 7.78 | 4.04 | 11.77 | 25.92 |
| | July | 7.05 | 3.42 | 7.15 | 24.62 |
| | August | 4.30 | 2.49 | 3.16 | 19.44 |
| | September | 12.23 | 3.42 | 4.04 | 32.40 |
| | April-Sept. | 55.00 | 19.39 | 49.35 | 168.48 |
| Voss | April | 5.75 | 0.00 | 0.00 | 15.55 |
| | May | 9.07 | 0.00 | 0.00 | 24.62 |
| | June | 6.32 | 0.00 | 0.00 | 20.74 |
| | July | 2.80 | 0.00 | 0.00 | 12.96 |
| | August | 3.53 | 0.00 | 0.00 | 11.66 |
| | September | 4.92 | 0.00 | 0.00 | 12.96 |
| | April-Sept. | 32.40 | 0.00 | 0.00 | 98.50 |
| Kårvatn | April | 3.78 | 0.52 | 1.35 | 9.07 |
| | May | 7.52 | 1.24 | 3.53 | 16.85 |
| | June | 5.44 | 2.18 | 5.75 | 16.85 |
| | July | 1.76 | 2.28 | 2.38 | 10.37 |
| | August | 1.45 | 1.66 | 2.13 | 7.78 |
| | September | 3.94 | 2.59 | 2.95 | 7.78 |
| | April-Sept. | 23.90 | 10.47 | 18.09 | 68.69 |

Dry deposition velocities applied: SO₄-S; NH₄-N: 0.2 cm/s; NO₂: 0.4 cm/s; SO₂: 0.8 cm/s, HNO₃ + nitrate particles: 5 cm/s.

Wet deposition:

| | Ox. N mg/m ² | Red. N mg/m ² | Tot. N mg/m ² | S mg/m ² |
|-------------|----------------------------|-----------------------------|-----------------------------|------------------------|
| Prestebakke | 230 | 175 | 405 | 347 |
| Birkenes | 369 | 308 | 677 | 537 |
| Skreådalen | 356 | 350 | 706 | 604 |
| Voss | 255 | 77 | 332 | 274 |
| Kårvatn | 113 | 56 | 169 | 94 |

Dry deposition

| | Ox. N mg/m ² | Red. N mg/m ² | Tot. N mg/m ² | S mg/m ² |
|-------------|----------------------------|-----------------------------|-----------------------------|------------------------|
| Prestebakke | 251 | 23 | 274 | 64 |
| Birkenes | 248 | 22 | 270 | 70 |
| Skreådalen | 188 | 49 | 237 | 55 |
| Voss | 114 | 30 | 144 | 32 |
| Kårvatn | 79 | 18 | 97 | 24 |

Total deposition:

| | Ox. N mg/m ² | Red. N mg/m ² | Tot. N mg/m ² | S mg/m ² | Potential acidity: millieq./m ² | Pot. acidity from ox. N millieq./m ² |
|-------------|----------------------------|-----------------------------|-----------------------------|------------------------|--|---|
| Prestebakke | 481 | 198 | 679 | 411 | 74 | 34 |
| Birkenes | 617 | 330 | 947 | 607 | 106 | 44 |
| Skreådalen | 544 | 399 | 943 | 659 | 109 | 39 |
| Voss | 369 | 107 | 476 | 306 | 53 | 26 |
| Kårvatn | 192 | 74 | 266 | 118 | 26 | 14 |

Estimated percentage contributions:

| | from Norwegian sector: | | | from British sector: | | |
|-------------|------------------------|-------------|----------|----------------------|-------------|----------|
| | Ox. N dep | Tot. N dep. | Pot.acid | Ox. N dep | Tot. N dep. | Pot.acid |
| Prestebakke | 2 | 2 | 1 | 4 | 3 | 2 |
| Birkenes | 14 | 9 | 6 | 26 | 17 | 11 |
| Skreådalen | 23 | 14 | 8 | 36 | 21 | 13 |
| Voss | 11 | 8 | 5 | 21 | 16 | 10 |
| Kårvatn | 5 | 3 | 2 | 9 | 7 | 5 |

