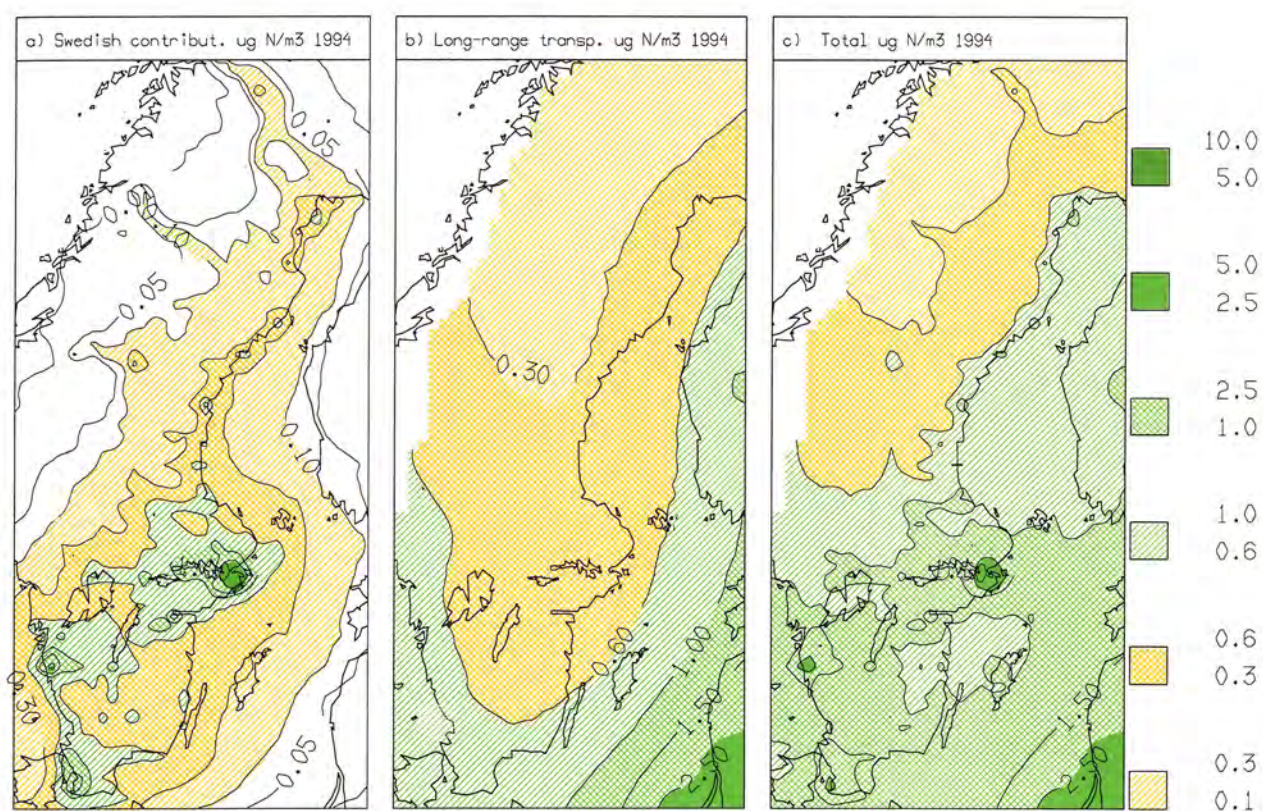


Air Pollution Assessment Study Using the MATCH Modelling System

Application to sulphur and nitrogen compounds over Sweden 1994



Joakim Langner, Christer Persson,
Lennart Robertson and Anders Ullerstig

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Cover:

Annual average air concentration of NO₂ (µg
N/m³) i n 1994 for a) Swedish contribution b)
long-range transport contribution c) total.

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Abstract

The MATCH (Mesoscale Atmospheric Transport and CHemistry) model has been developed as a tool for air pollution assessment studies on different geographical scales. The MATCH system is based on an Eulerian atmospheric transport model, including physical and chemical processes governing sources, atmospheric transport and sinks of oxidised sulphur and oxidised and reduced nitrogen. With the MATCH system, air pollution contributions from different source types like traffic, industry, shipping, farming etc. can be obtained. Using a combination of air and precipitation chemistry measurements and the MATCH dispersion model, the contribution of air pollution and deposition from long-range transport can be quantified in the model region. The calculations for the year 1994 show that the Swedish import was 5.5 times larger than the export for sulphur and 4.4 times larger for reduced nitrogen, while the Swedish import of oxidised nitrogen only exceeded the export by 10%.

Using the MATCH system we estimate the long-range transport in an independent way compared to EMEP. Comparison between the EMEP and MATCH estimates for 1994 indicate differences exceeding 20% for total deposition of oxidised and reduced nitrogen, with higher estimates derived from the MATCH system. Similar differences were found for 1991 but in that case the differences were largest for sulphur and reduced nitrogen. The EMEP estimates of Swedish contributions to deposition over Sweden are 55, 48 and 22% smaller for sulphur, oxidised and reduced nitrogen respectively. Part of these differences can be explained by different meteorological data, especially precipitation, and differences in dry deposition velocities.

The MATCH system has also been used to investigate how the design of the network of precipitation chemistry stations affects the estimated distributions of wet deposition of sulphur and nitrogen compounds. There is a clear indication that a substantial reduction of the number of Swedish precipitation chemistry stations only has a limited effect on the obtained annual and monthly wet deposition pattern over Sweden. This is however true only if the future station network selected for the Swedish environmental survey is run with high quality in sampling, chemical analyses and with representative sites and a good geographical distribution over Sweden.

1. INTRODUCTION

Deposition of acidifying pollutants in Sweden is a well known problem. Long-range transport was suggested as a major cause of increased acidification of air and precipitation in Sweden by Svante Odén in the late 1960's (Odén, 1976). Since then considerable efforts have been made on both national and European scales in order to quantify and understand the phenomenon. The work on the European scale has been co-ordinated within EMEP (Co-operative programme for monitoring and evaluation of the long range transmission of air pollutants in Europe, EMEP, 1980). Most European countries report air and precipitation chemistry data to EMEP from selected background locations as well as emission data. EMEP runs a model covering Europe which is capable of allocating the deposition on a 150x150 km horizontal grid to the emitting countries on an annual basis (Eliassen and Saltbones, 1983). The monitoring data submitted is used for model validation and development. Initially the EMEP work focused on sulphur compounds but now both oxidised and reduced nitrogen compounds are included as well. EMEP has provided key information in the negotiation of emission reduction protocols for sulphur in Europe.

In addition to EMEP most countries run national acidification programmes. Sweden has a long tradition of monitoring the chemical composition of precipitation, and the first network was established in the 1950's. Since then monitoring efforts on the chemical composition of both air and precipitation have been expanded and now include measurements of sulphur and nitrogen compounds at several background locations as well as a dense network of through-fall measurements in the southern part of Sweden. Modelling work aimed at utilising these data to provide additional information and generalisations have so far been limited in Sweden. To optimise efforts such as liming and national emission controls to limit the effects of acid deposition, information about deposition of acidifying pollutants with higher resolution than currently available from EMEP is desirable. In describing the effects of acidification on the ecosystem level, information should be available at least on the size of the ecosystems. The work presented here is an attempt to meet these requirements by combining model calculations for national emissions with careful analysis of observations linked with high resolution meteorological data.

Over the last five years SMHI has developed a system for regional dispersion modelling called MATCH (Mesoscale Atmospheric Transport and Chemistry model). The application of the MATCH system for the area of Sweden (Figure 1) is called MATCH-Sweden and has a horizontal resolution of 20 x 20 km. The first assessment study for sulphur and nitrogen compounds covering Sweden using MATCH-Sweden was carried out for the year 1991 (Persson et al., 1995; Langner et al., 1996). Prior to this similar studies had been carried out for smaller regions in Sweden (Figure 1). The development of MATCH-Sweden has been supported by the Swedish Environmental Protection Agency (NV) and the assessment studies is a part of the national environment monitoring program directed by NV. The intention is to continue to produce annual assessments of the type presented here. The chemical components included in this study are oxidised and reduced nitrogen compounds and oxidised sulphur compounds.

In addition to the assessment study the MATCH system has also been used to investigate how the design of the network of precipitation chemistry stations affects the estimated distributions of wet deposition of sulphur and nitrogen compounds.

MATCH Modelling Regions in Sweden

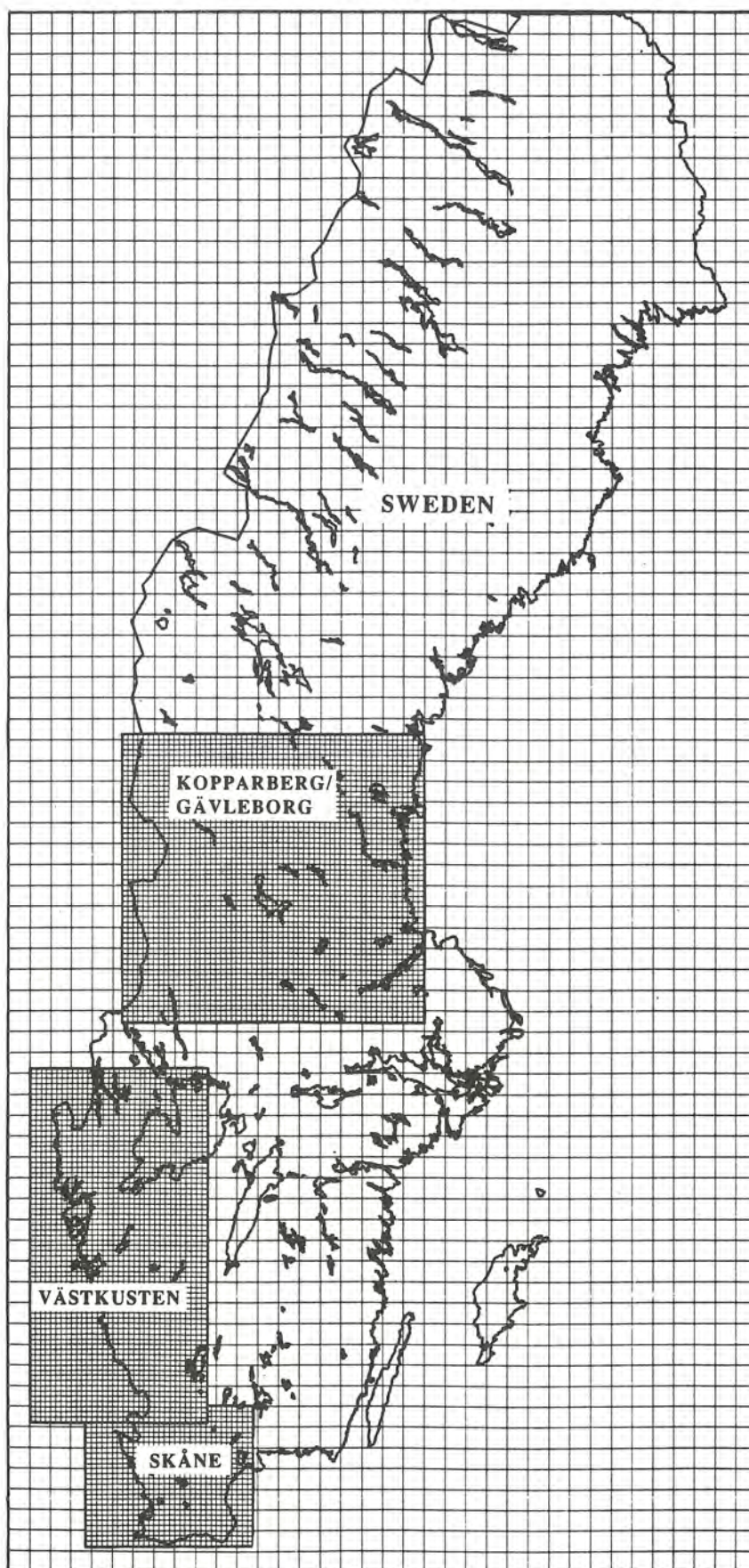


Figure. 1 MATCH modelling areas used in air pollution assessment studies in Sweden. The model version covering the whole of Sweden has a grid size of 20 x 20 km, for subregions a grid size of 5 x 5 km is used.

2. EMISSION DATA

Information on Swedish emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x) and ammonia (NH_3) has been mapped to the 20x20 km grid of MATCH-Sweden. The emission data used in the assessment for 1991 was prepared by The Swedish Environmental Research Institute (IVL) with some further modifications done at SMHI. This information has been updated at SMHI to reflect the emissions for 1993. The emission information includes contributions from all types of sources considered of importance. The emission data should be regarded as preliminary since the mapping of emissions from small sources and area sources, such as domestic heating, domestic animals and shipping is rather coarse. Furthermore, information about stack parameters such as stack heights, effluent temperature and speed is lacking for large point sources. Information about the temporal variation of the emissions over the diurnal and annual time scales is also missing. Emission data for road traffic has been obtained from The Swedish Road and Transport Research Institute (VTI). So far, gridded information for emissions from individual source categories (e.g. domestic heating, industry) is not available with the exception of road traffic and a rough mapping of the emissions ships calling Swedish harbours.

The MATCH system has been used recently in an assessment study for three counties on the Swedish west-coast; Halland, Gothenburg and Älvsborg (Persson et al, 1994a). Some information from this study regarding emissions have been used also in MATCH-Sweden. The study for the west-coast region was based on an emission data base including detailed information about both the geographical and temporal variations of emissions from different source categories. Detailed information about stack parameters for a large number of individual point sources was also available. This information has been used to derive statistics on emission heights, stack parameters and temporal variations that could be used in the MATCH-Sweden study. For example in the case of NO_x there is a large diurnal variation in the emission since traffic is a major source of NO_x . There are also variations over the days of the week and for different months which are taken into account. Emissions of ammonia are assumed to derive only from domestic animals and are assumed to take place mainly during summer as in the west-coast study. The total emissions used in the MATCH-Sweden calculations for 1994 are given in Table 1. The numbers for 1991 are also given for comparison.

Table 1. Emissions used in MATCH-Sweden for 1994 (tonnes S/year and tonnes N/year).

	Sulphur	NO_x	NH_x
Emission			
1991	70 000	118 400	44 500
1994	50 500	121 400	47 800

3. METEOROLOGICAL AND PHYSIOGRAPHICAL DATA

The dispersion model requires meteorological data to calculate transport, chemistry and deposition processes. For studies over Sweden an objective meteorological analysis system has been developed (Meuller et al., 1990). The system makes use of routine meteorological observations to derive a number of parameters including wind fields, temperature, precipitation, friction velocity, sensible heat flux, Monin-Obukovs length and mixing height required by the dispersion model. The analyses are performed at three hour intervals. Figure 2 illustrates the different types of data that are used as input to the analysis scheme.

The precipitation analysis is given special attention. About 800 stations measuring daily precipitation is combined with precipitation and weather information from synoptic stations to give precipitation fields with three hourly time resolution and high horizontal resolution. Corrections for sampling losses and topographic effects are also applied.

Some comments concerning the meteorological conditions during the year 1994 can be of interest in order to judge the representativity of the atmospheric chemistry results shown below. The annual mean temperature was above normal in the southern half of Sweden, while northern Sweden had a temperature somewhat below normal. The annual precipitation amount was larger than normal in most of southern Sweden, exceeding normal values by up to 30-40% at the most, while the annual precipitation was less than normal in the northern half of Sweden. The month of July was exceptional in southern and central Sweden, the weather was extremely warm and dry, while months like March, September and December were relatively wet in southern Sweden.

A high resolution data base for topography and land use has been mapped to the 20 x 20 km grid of MATCH-Sweden. The data base provides topography, surface roughness and land use (fraction of forest, field, water and urban areas). Land use is given in percent for each grid square in MATCH-Sweden. The data base is used both in the meteorological analysis system in the derivation of wind and turbulence fields, and in the transport model in the calculation of dry deposition. As an example the distribution of the fraction of forest is given in Figure 2.

4. AIR AND PRECIPITATION CHEMISTRY DATA

In the assessments presented in this study data from a number of background air and precipitation chemistry stations has been used. Most of the stations used belong either to the European EMEP network or the Swedish Precipitation Chemistry Network (PMK) run by NV. Compared to the study for 1991 (Persson et al., 1995) the number of foreign stations has increased from five to 11 through the addition of four Finnish stations, one Danish and one Lithuanian station. The locations of the stations are shown in Figure 3. A more detailed discussion of the sampling networks is given in Section 8.

4.1 Background stations with hourly or diurnal sampling

Table 2 lists (from north to south) the stations with diurnal or hourly sampling included in the assessment together with some of their characteristics. Data for the Swedish

MATCH - SWEDEN

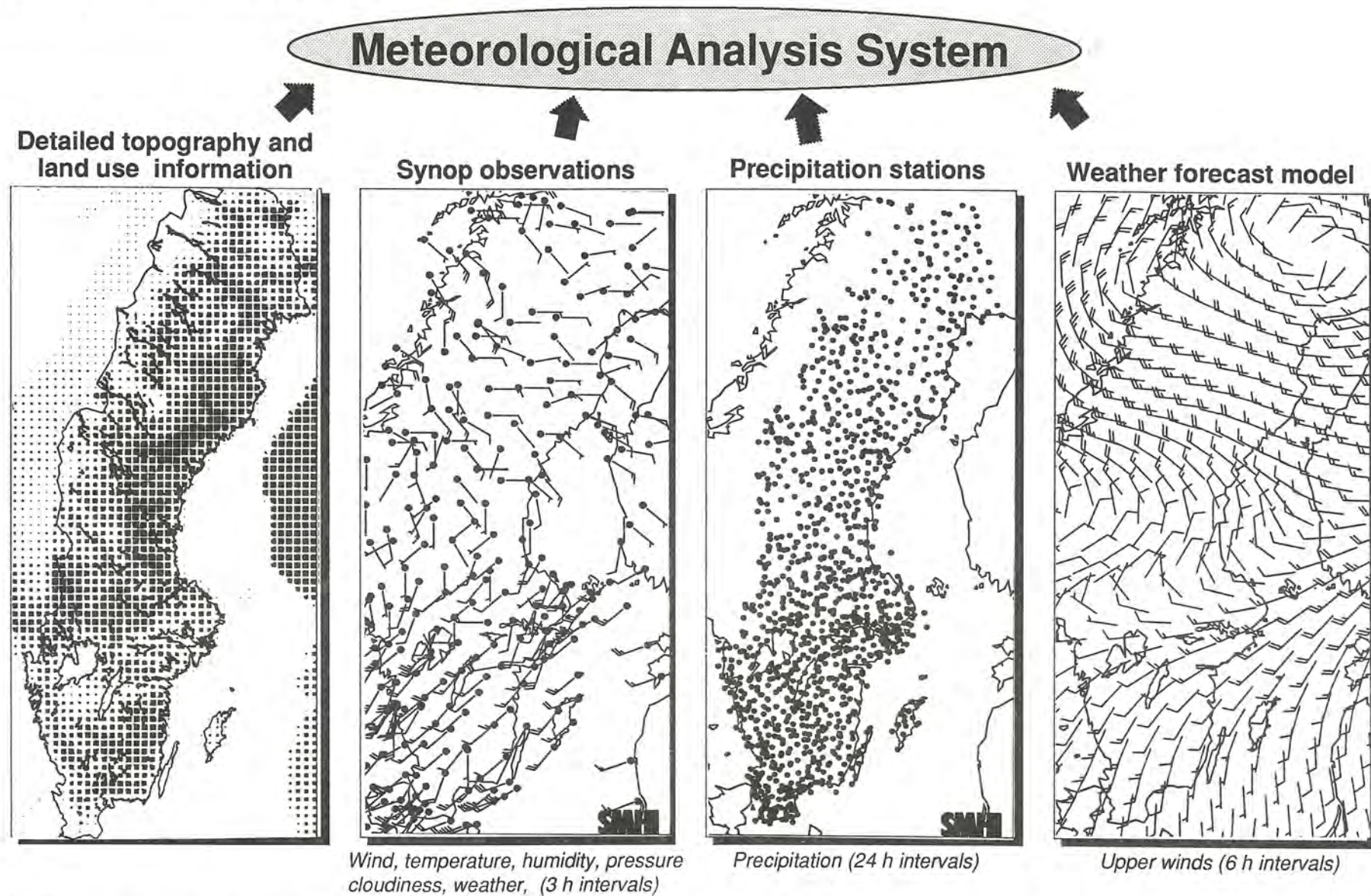


Figure 2. Schematic diagram of the meteorological analysis system used in MATCH-Sweden.

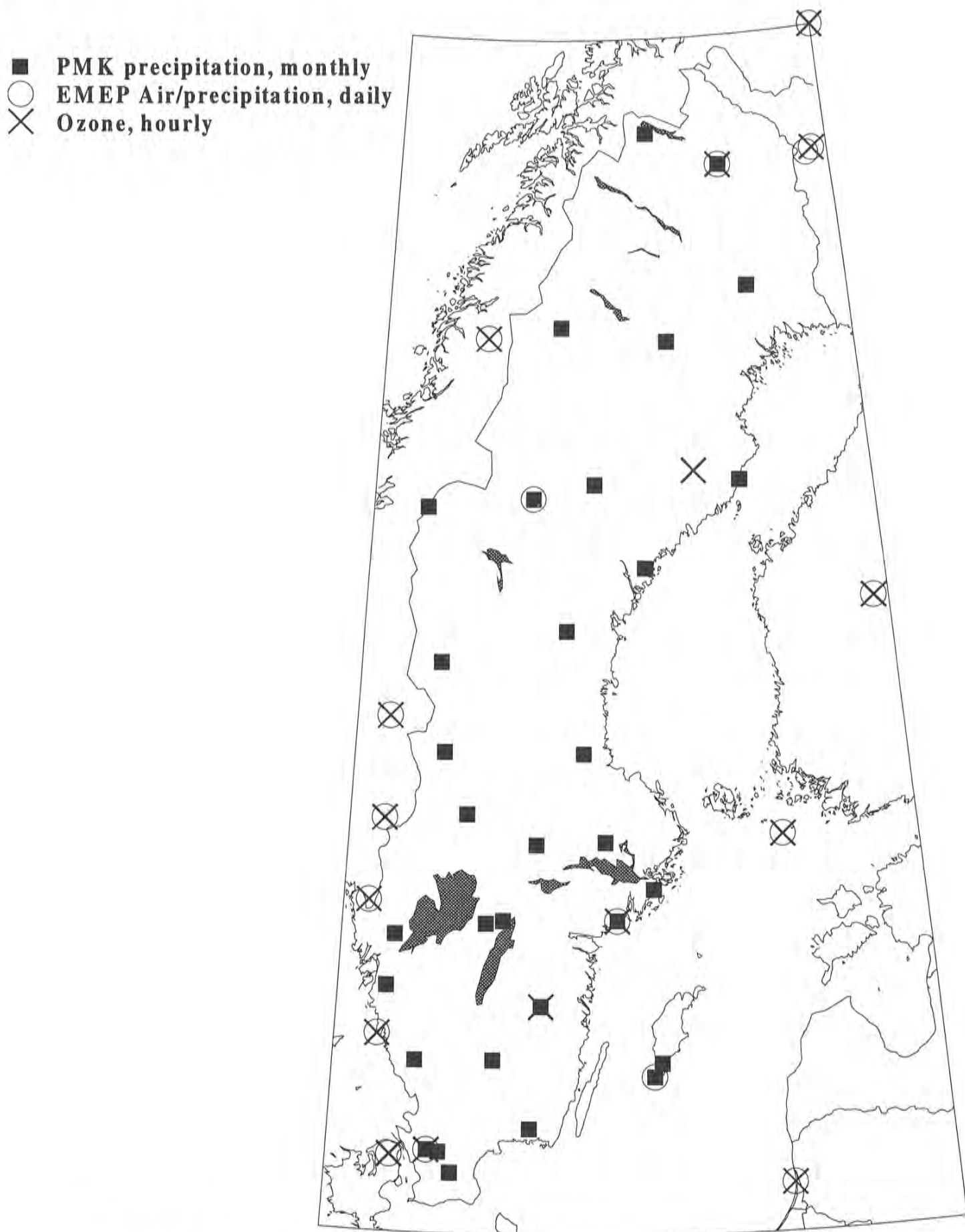


Figure 3. Background air and precipitation chemistry stations used in the air pollution assessment for 1994.

stations has been provided by IVL. For Norwegian stations data was obtained from The Chemical Co-ordinating Centre of EMEP (EMEP/CCC) at The Norwegian Institute for Air Research (NILU). Data for Finnish stations was obtained from the Air Quality Department of the Finnish Meteorological Institute (FMI).

Table 2. Background stations with diurnal and hourly sampling. Parameters used are for most stations as follows: (air) SO_2 , SO_4^{2-} , NO_2 , $NO_3^-+HNO_3$, $NH_3+NH_4^+$, (precipitation) SO_4^{2-} , NO_3^- , NH_4^+ , Na^+ .

Station name	Institute	Standard	Parameters		
			O ₃ (hourly)	air	precipitation
Jergul	NILU	EMEP	x	x	x
Sammaltunturi	FMI	-	x	x	-
Särkijärvi	FMI	-	-	-	x
Esrang	IVL	EMEP	x	x	-
Tustevatn	NILU	EMEP	x	x	x
Vindeln	IVL	-	x	-	-
Bredkälen	IVL	EMEP	-	x	x
Ähtäri	FMI	EMEP	x	x	x
Osen	NILU	EMEP	x	x	x
Nordmoen	NILU	EMEP-equivalent	x	x	-
Utö	FMI	EMEP	x	x	x
Prestebakke	NILU	EMEP-equivalent	x	x	x
Aspvreten	IVL	EMEP	x	x	x
Norra Kvill	IVL	-	x	-	-
Rörvik	IVL	EMEP	x	x	x
Vavihill	IVL	EMEP	x	x	x
Preila	ITM	EMEP-equivalent	x	x	x
Fredriksborg	DMU	EMEP	x	x	x

Danish data was obtained from The National Environmental Research Institute in Denmark (DMU) and data from the station in Lithuania was provided by The Institute of Applied Environmental Research at Stockholm University in Sweden (ITM).

4.2 Background stations with monthly sampling

Monthly precipitation chemistry data from the Swedish Precipitation Chemistry Network has also been used in the assessment. The parameters included are the same as for the EMEP network. Data from all stations (ca. 35 stations) in the network has been available, but data from some stations situated very close to EMEP stations have been excluded when information from the EMEP-station was available (c.f. section 8). Locations for all PMK stations are given in Figure 3.

5. THE MATCH MODELLING SYSTEM

The MATCH modelling system consists of three parts: A regional atmospheric transport model including modules for emission, chemistry and deposition of sulphur and nitrogen compounds. An objective analysis system for air and precipitation chemistry data, and an objective analysis system for meteorological data. The objective analysis scheme for meteorological data has been discussed in section 3. Here we give a description of the transport model and the analysis system for air and precipitation chemistry data.

5.1 Transport model

The MATCH (Mesoscale Atmospheric Transport and CHemistry) model (Persson and Robertson, 1991; Persson et al., 1994; Langner et al., 1995) is a three-dimensional Eulerian atmospheric transport model. The model is a so called "off-line" model, meaning that meteorological data from an external archive at regular time intervals (usually three or six hours) is required in order to calculate transport, chemistry and deposition. The model is designed to be flexible with regard to horizontal and vertical resolution and caters for the most commonly used horizontal and vertical grid systems. It is used for several different applications in atmospheric transport modelling at SMHI, with horizontal grid resolutions ranging from 5 to 100 km. Here a description is given of the model version, covering Sweden or subregions of Sweden, applied to air pollution assessment studies in Sweden. An important feature of the version of the model used here is a space and time variable vertical resolution. The model has three layers in the vertical. The first layer has a fixed thickness of 75 m. The top of the second layer is taken to be the same as the mixing height, and the top of the third, so called reservoir layer, is fixed at a certain level (~1.5 km in winter, ~2.5 km in summer). The thickness of the second and third layers in the model therefore varies both in space and time according to the variation of the mixing height. The mixing height has a decisive influence on the concentrations of pollutants in the lower part of the atmosphere. Provided that the mixing height can be determined, this type of model structure captures the most important processes determining the concentrations of pollutants in the lower part of the atmosphere with a minimum of model layers. It is possible to add additional layers if necessary, but for calculations over areas of the size of Sweden or smaller three layers was judged to be sufficient. The horizontal resolution for the calculations over

Sweden is 20x20 km while a 5x5 km resolution have been used for subregions in Sweden.

Horizontal advection is calculated using a fourth order flux correction scheme (Bott 1989a, 1989b). The scheme utilises polynomial fitting between neighbouring grid points of the concentration field in order to calculate the advective fluxes through the boundaries of adjacent grid boxes. It is a positive definite mass conserving scheme with low numerical diffusion. Vertical advection is calculated using an upstream scheme. Vertical diffusion between layers 1 and 2 is for the convective case described from a determination of the turn-over time for the boundary layer based on similarity theory, and for the neutral and stable case from a parametrisation based on a 40 layers 1-D eddy diffusivity model. Vertical transport is also induced by the spatial and temporal variations of the mixing height. For the numerical solution of the combined horizontal and vertical transport, chemistry and deposition an operator split time integration scheme is used.

5.1.1 Emissions

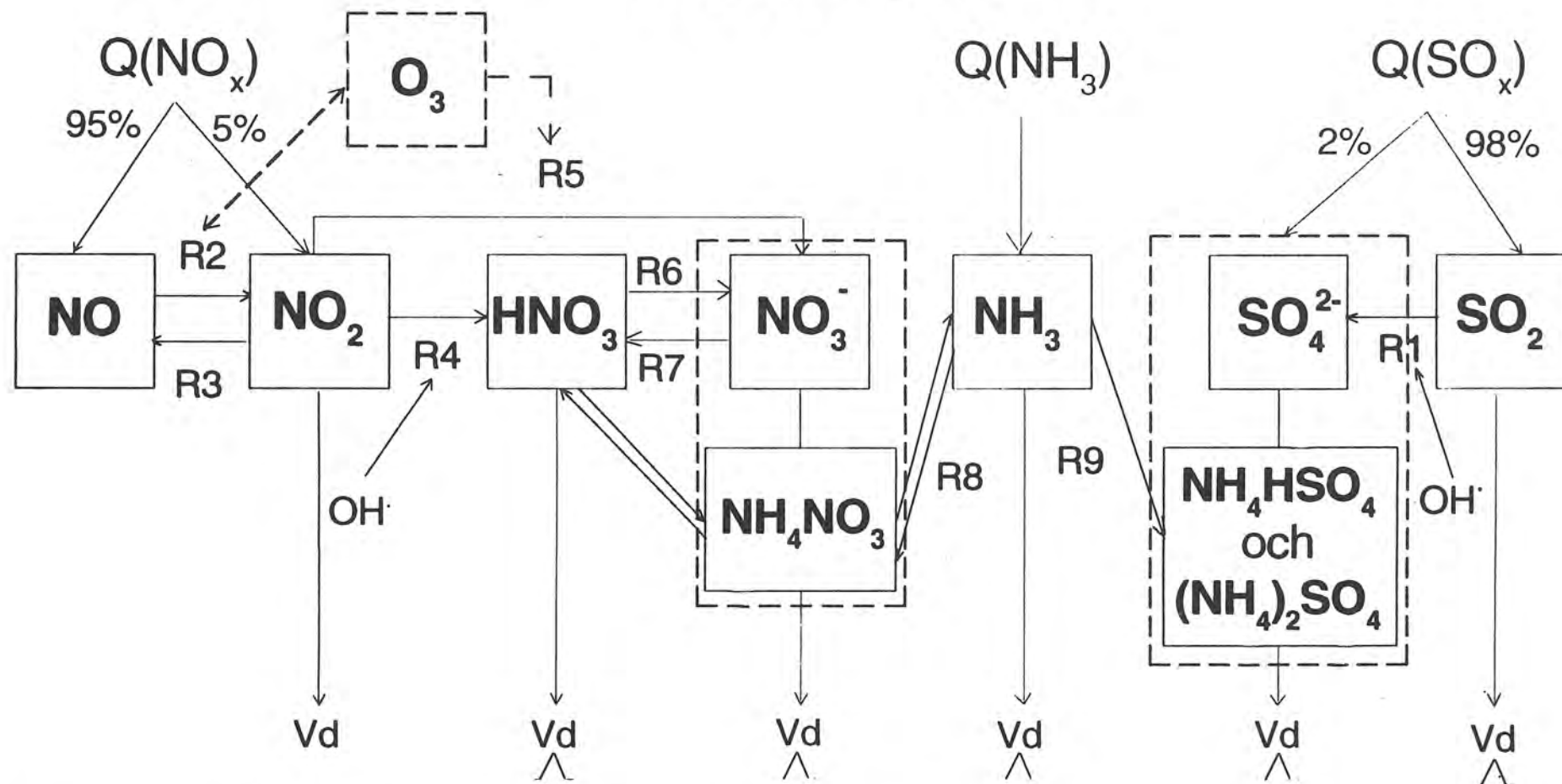
Emissions can be specified both as area and point sources. Surface area sources are introduced into the lowest layer of the model. The initial dispersion from point sources is described with a Gaussian puff model including plume rise calculations. A new puff is introduced every hour for each source. The puffs are then advected until they have reached the size of the horizontal grid when they are merged into the large scale concentration field.

In air pollution applications the number of point sources are often large (several hundred). To reduce the amount of computations usually only the 30 largest sources are treated as individual point sources. The remaining point sources are classified in three classes according to stack height. Emission weighted source characteristics (stack diameter, exhaust gas flux and temperature) are calculated for each class. The weighted source characteristics are then used to calculate the plume rise and partition the emissions from each class in the three levels of the Eulerian model. In the calculations over Sweden as a whole for 1994 all emissions were treated as area sources and partitioned between the different levels in the model based on statistics from subregions in Sweden (c.f. section 2)

5.1.2 Chemistry

The chemistry in the model deals with sulphur oxides and oxidised and reduced nitrogen and is almost identical to that used in the EMEP model (Iversen et al., 1989). The following compounds are included: sulphur dioxide (SO_2) ammonium sulphate ($(\text{NH}_4)_2\text{SO}_4$ and NH_4HSO_4), other sulphate particles (SO_4^{2-}), nitric oxide (NO), nitrogen dioxide (NO_2), ammonium nitrate (NH_4NO_3), other nitrate particles (NO_3^-), nitric acid (HNO_3) and ammonia (NH_3). The main difference compared with the EMEP model is in the specification of ozone (O_3) concentrations. Here analysed O_3 distributions with one hourly time resolution are generated from observations (c.f. section 5.3). A local adjustment of the O_3 concentration with regard to local NO- and NO_2 -concentration and solar radiation is also done. A schematic diagram of the chemical scheme included in the model is given in Figure 4.

CHEMISTRY



- O_3 - Observed background concentration + local chemical adjustment
 OH^\cdot - seasonal and diurnal variations
 Vd = f (compound, topography, landuse, time, weather)
 \triangle = f (compound, precipitation intensity)

Figure 4. Schematic diagram of the chemical scheme and deposition processes included in the model.

5.1.3 Deposition processes

Pollutants are removed from the atmosphere by wet and dry deposition processes. Wet scavenging of the different species is taken as proportional to the precipitation rate and a species specific scavenging coefficient. Dry deposition is proportional to the concentration and a species specific dry deposition velocity at 1 m height. Since the lowest model layer has a thickness of 75 m, the dry deposition flux calculation is transformed to the middle of that layer using standard similarity theory for the atmospheric surface layer. Dry deposition velocities are specified as a function of the surface characteristics (fraction forest, field etc.). Scavenging coefficients and deposition velocities have in most cases values close to those used in the EMEP calculations. For some compounds (mainly NO₂ and particles) the deposition velocities to forest have been somewhat larger than used by EMEP.

5.2 Analysis of air and precipitation chemistry data - assessment of long-range transport contribution

The transport model described above, combined with national emission estimates and meteorological data provides estimates of concentrations in air and precipitation as well as dry and wet deposition of the simulated sulphur and nitrogen compounds. These results refer to contributions from sources within the model area (in this case Sweden). To derive distributions of the contribution to these quantities from sources outside Sweden the following method is employed: Model calculated daily contributions from Swedish sources are deducted from observed daily values of concentration in air and precipitation at background locations on a point by point basis (c.f. Figure 3). The residual is termed long-range transport contribution. These residuals are analysed using an optimum interpolation method, where differences in observation quality can be accounted for, to give distributions of long-range transport contributions of concentrations in air and precipitation over the modelling domain. The basic idea behind this method is that the long-range transport contributions to the concentrations can be expected to vary more smoothly in space than the total concentrations which are affected to some extent by local sources, and should therefore be more suitable for interpolation. Considerable efforts have been spent on quality control of both input chemical observation data and resulting analysed concentration distributions. The objective analysis scheme is a very useful tool for identifying different kinds of errors in the observations. Given analysed long-range transport contributions to concentration in air and in precipitation long-range transport wet deposition is calculated by multiplying with the observed precipitation field (c.f. section 3). Long-range transport dry deposition is calculated by running the long-range transport air concentrations through the dry deposition module of the transport model. A similar method using total concentrations has been developed by Erisman et al. (1995). The difference here is the possibility to separate the national and long-range transport contributions.

When using the method described above for the year of 1994, as well as for 1991, we have encountered problems with the consistency of the daily precipitation values for some of the EMEP stations. It appears as if in some cases, two or several days of precipitation have been merged before analysis. To avoid this type of systematic errors in the estimates of the total wet deposition we have only used monthly values for concentration of the different chemical components in precipitation from the EMEP stations.

NO2 vid Femman 1991

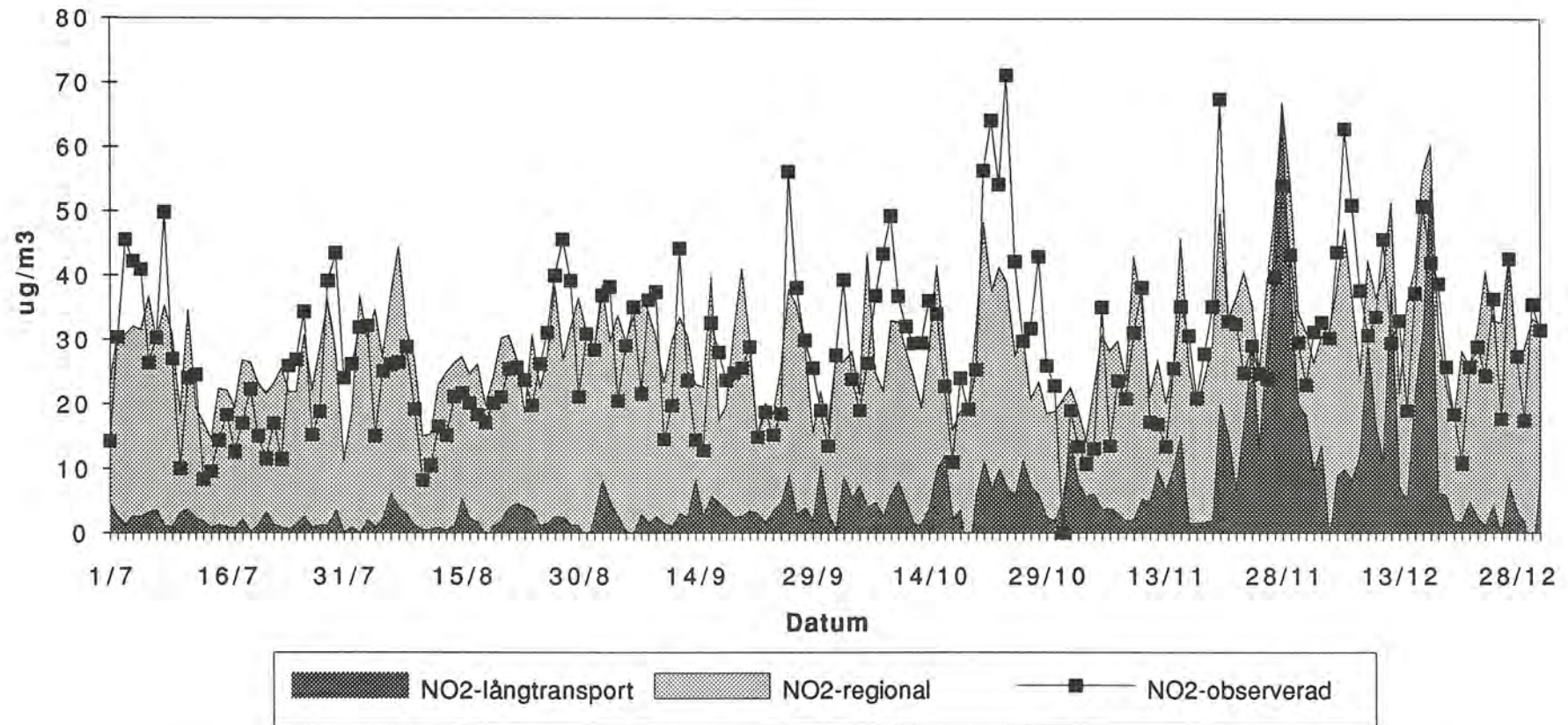


Figure 5. Comparison, for a measuring station in central Gothenburg, between long-range transport contribution (dark shaded) plus regional contribution (light shaded) from the Swedish west-coast area and observed (black squares) total NO₂ concentrations in air for the second half of 1991 ($\mu\text{g N}/\text{m}^3$).

5.3 Analysis of background ozone concentrations

The MATCH system includes an analysis of background ozone concentrations. The analysis is based on hourly values from the stations given in Table 2. The analysed concentrations are read into the transport model where a local adjustment due to photochemistry is performed. So far the resulting ozone concentrations are meant only for use in the chemical calculations. The intention is however to develop the methodology further to be able to provide a high quality mapping of surface ozone concentrations over Sweden.

5.4 Verification studies

The method outlined above, to separate national and long-range transport contributions, assumes that the model calculated national contribution is correct. This is not necessarily the case. It is often difficult to test meso-scale transport and chemistry models of the type used in MATCH-Sweden. For local scale models the best places for verification studies are close to large sources, e.g. in cities or close to large point sources. In this case the influence of long-range transport is small and local emissions dominate. The horizontal resolution of MATCH-Sweden (20 x 20 km) is however too coarse to resolve contributions from local sources or from the central parts of cities with any detail. The extent of the central parts of cities in Sweden is much smaller than the size of a grid square in the model. At the same time a test of MATCH-Sweden against data from some rural location is difficult since in this case the contribution from long-range transport, for sulphur and nitrogen compounds studied here, is relatively large compared to the contribution from Swedish sources. This is of course related to the fact that the residence times of these compounds in the atmosphere are long enough so that transport across the boundaries of the MATCH-Sweden area to a large extent affects the distribution of sulphur and nitrogen compounds over the whole area.

In order to justify the method we show some comparisons that have been made with independent air chemistry measurements for smaller modelling areas in Sweden. One such comparison taken from a study over the Swedish west-coast region (hereafter referred to as MATCH-W) using exactly the same method as described here is given in Figure 5. It shows a time series of the concentration of NO_2 in central Gothenburg for the second half of 1991. In this case the horizontal resolution used in MATCH-W is 5 x 5 km so it should be possible to resolve a city like Gothenburg to some extent. It should also be mentioned that the measurements are made at roof top level (at a height of about 35 m) and not down in a street canyon. As can be seen both the overall concentration level and episodes are captured favourably. Additional comparisons can be found in Persson et al. (1994a). In Figure 6 and 7 we have taken the comparison one step further and show comparisons of calculated annual average air concentrations of SO_2 , NO_2 and NH_x over the Swedish west-coast area using MATCH-Sweden and MATCH-W. Unfortunately somewhat different emission data has been used in the two versions of the model. Figure 6 shows the calculated contribution from emissions from the Swedish west-coast area calculated with MATCH-W, while the corresponding results for contributions from Swedish emissions calculated with MATCH-Sweden are shown in Figure 7. A reasonable comparison can only be made in the central parts of the area. Towards the boundaries the contribution from Swedish sources outside of the area becomes important, and these are only included in Figure 7. Although the contribution from the remaining part of Sweden is missing in MATCH-W the calculated

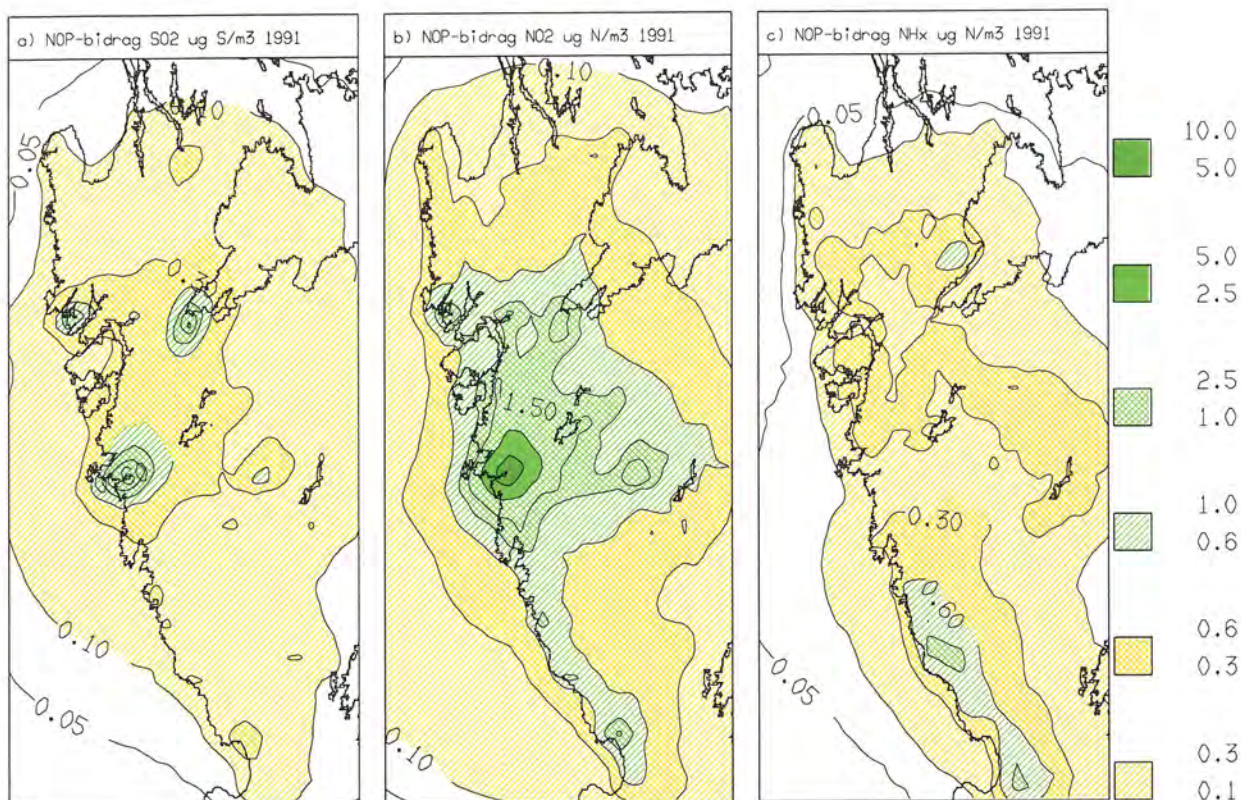


Figure 6. Calculated, using MATCH-W, contributions of annual average concentrations for 1991 from emissions in the Swedish West-coast area of a) SO_2 ($\mu\text{g S/m}^3$), b) NO_2 ($\mu\text{g N/m}^3$) and c) NH_x ($\mu\text{g N/m}^3$)

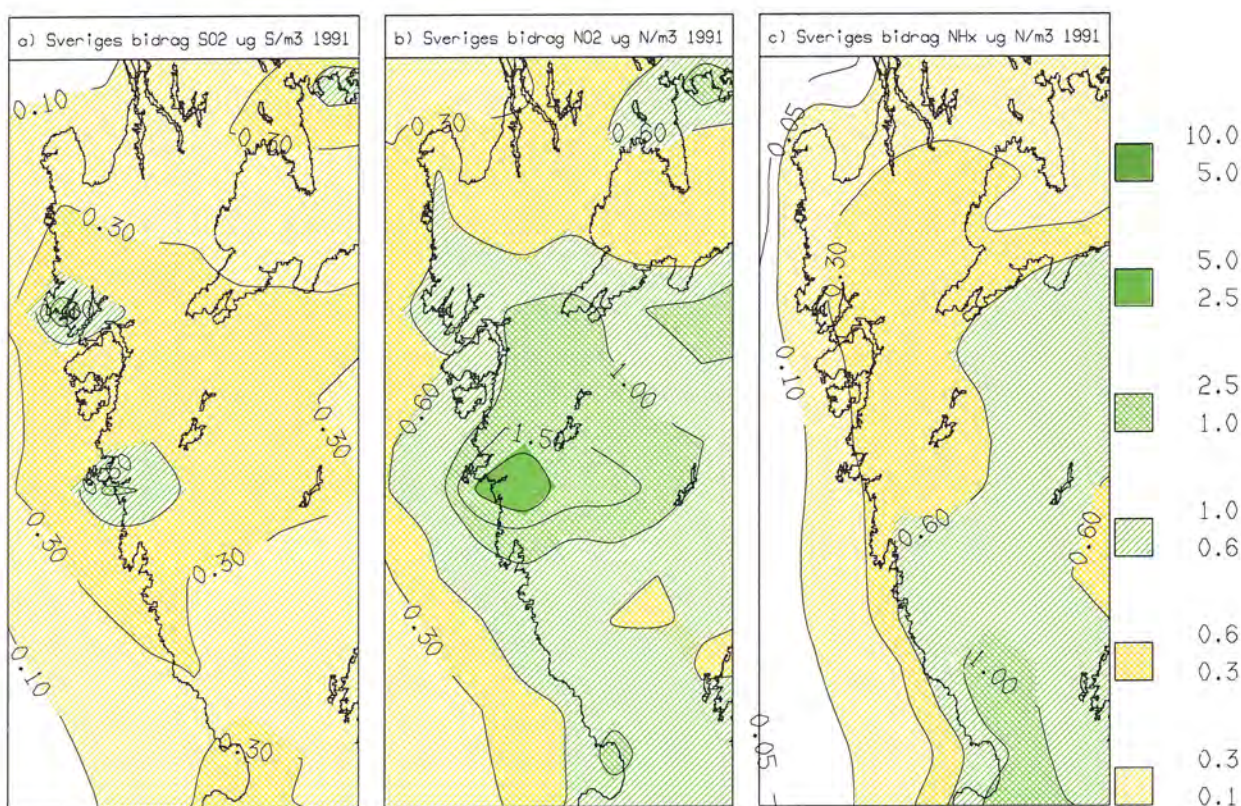


Figure 7. Calculated, using MATCH-Sweden, contributions to annual average concentrations for 1991 from emissions in Sweden of a) SO_2 ($\mu\text{g S/m}^3$), b) NO_2 ($\mu\text{g N/m}^3$) and c) NH_x ($\mu\text{g N/m}^3$). The results are presented for the same area as for MATCH-W.

concentrations of SO₂ and NO₂ in densely populated areas are somewhat larger in MATCH-W than in the calculations from MATCH-Sweden. This is of course related to the higher horizontal resolution used in MATCH-W. It can be noted that the maxima in the concentration of SO₂ in the southern part of lake Vänern (north-eastern part of the area) is missing in the MATCH-Sweden calculations. This is probably related to inaccuracies in the preliminary emission data used in the MATCH-Sweden calculations. In the northern part of lake Vänern the situation is reversed, with higher concentrations of both SO₂ and NO₂ in the MATCH-Sweden calculations. This is correct however, since emissions from this area were not included in the MATCH-W study. The calculated concentrations are otherwise comparable in the central parts of the area. Towards the boundaries MATCH-Sweden gives higher values since in that case the model includes contributions from all of Sweden. For NH_x MATCH-Sweden gives higher concentrations in the southern part of the area. This is due to large emissions of ammonia in southern Sweden. In the northern part of the area the agreement between the two model versions is good.

These indirect comparisons against independent data indicate that MATCH-Sweden can reasonably well describe the contribution from Swedish sources. Since MATCH-W and MATCH-Sweden is basically the same model, applied for different areas and using different resolutions, a successful verification of one version of the model gives also some support for the other.

6. ASSESSMENT FOR SWEDEN FOR 1994 BASED ON MODEL CALCULATIONS AND AIR AND PRECIPITATION CHEMISTRY DATA

Using the MATCH-Sweden system and air and precipitation chemistry data from EMEP and PMK stations we have carried out calculations of both the Swedish contribution and the long-range transport contribution to concentrations in air and precipitation as well as to deposition over Sweden. The components treated are concentrations in air of SO₂, SO₄²⁻ (SO₄²⁻ + NH₄HSO₄), NO, NO₂, HNO₃, NO₃⁻ (NO₃⁻ + NH₄NO₃), NH₃ and NH₄⁺ (NH₄HSO₄ + NH₄NO₃) and concentration in precipitation and deposition of SO₄²⁻, NO₃⁻ and NH₄⁺. Calculations have been carried out for the whole of 1994 and data is stored as daily values, but has also been aggregated to monthly and annual values. In addition to this a schematic mapping of hourly O₃ concentrations at the surface has been made for the whole period. This mapping is still under development and the results are only used internally in the chemical calculations in the MATCH model (c.f. section 5.3).

6.1 Availability of data

In addition to the presentation of results given below, the annually aggregated results from MATCH-Sweden will be available in digital format (ARC/INFO and ASCII) as a part of the environmental monitoring program. The available parameters are:

- Concentrations in air of: SO₂, SO₄²⁻, NO₂, (NO₃⁻ + HNO₃), NH₃ + NH₄⁺
- Deposition (wet + dry) of: SO₄²⁻, NO₃⁻ and NH₄⁺
- All parameters above are separated into Swedish, long-range transport and total contributions.

6.2 Discussion of results

It is of great interest to compare the contributions from Swedish sources to air pollution and deposition to the contribution from long-range transport which is caused by sources outside Sweden. In the presentation below we have focused on annual values and show comparisons of the different contributions to the total concentrations or deposition of the different components.

When discussing the results from MATCH-Sweden one should be cautious when interpreting the results in some parts of the modelling area outside Sweden, where air and precipitation chemistry data are lacking (e.g. western Norway) and where limited precipitation data has been available. In the plots presented below we have therefore blanked out areas where we consider the results less reliable.

6.2.1 Comparison of annual Swedish and long-range transport contributions to total air concentrations for 1994

Calculations of the Swedish and long-range transport contributions as well as total annual average concentrations for 1994 are given in Figures 8-12. Results are given for SO_2 , SO_4^{2-} , NO_2 , $(\text{NO}_3^- + \text{HNO}_3)$, $(\text{NH}_3 + \text{NH}_4^+)$. We have chosen to present the sums $(\text{NH}_3 + \text{NH}_4^+)$ and $(\text{NO}_3^- + \text{HNO}_3)$, since this is what is measured at the air chemistry station. Concentrations of NO are calculated in the model but are not presented since high NO concentrations occur mainly in the vicinity of sources and are of limited interest on the horizontal scale of MATCH-Sweden. The chemical conversion of NO to NO_2 has to a large extent already taken place when the nitrogen oxides are transported outside the main source areas.

The calculated contributions from Swedish sources are presented in the left (a) panel of each figure. The Swedish contribution includes both land-based emissions and emissions from shipping. The highest concentrations caused by Swedish sources are calculated for the primary (emitted) pollutants as SO_2 and NO_2 , while secondary (chemically produced) components as SO_4^{2-} and $(\text{NO}_3^- + \text{HNO}_3)$ show lower concentrations. Also NH_4^+ show lower concentrations than NH_3 , although this can not be seen since the figure only shows the sum of the two components. More densely populated areas and larger industries can be delineated in the distributions of SO_2 and NO_2 . The distribution of NH_x is determined by emissions from domestic animals, mainly in the agricultural areas in southern Sweden. The distributions of the secondary components are more smooth since the chemical production takes some time. The primary pollutants can therefore be transported over some distance before the conversion takes place.

The long-range transport contribution, which has been calculated as described in section 5.2, is presented in the middle (b) panel of each figure. The right (c) panel shows the sum of the Swedish and long-range transport contributions, i.e. the total concentration. For the primary pollutants NO_2 and NH_3 (Figures 9-10) the Swedish and long-range transport contributions are of the same order of magnitude in the southern part of Sweden. In the northern part of Sweden long-range transport dominates. The contributions to SO_2 and to the secondary components are dominated by long-range transport everywhere in the model domain.

6.2.2 Comparison of annual Swedish and long-range transport contributions to total deposition for 1994

The figures showing results for annual deposition 1994 have been divided into Swedish contribution, long-range transport contribution and total in a similar way as for the annual concentrations. Figures 13-15 show results for oxidised sulphur, Figures 16-18 show oxidised nitrogen and Figures 19-21 shows reduced nitrogen. For dry deposition (Figures 13, 16 and 19) the relative contributions from Swedish sources and long-range transport are similar to those for air concentrations with about equal contributions for oxidised and reduced nitrogen in southern Sweden and dominating long-range transport contributions in the northern part of Sweden. This is related to fact that the dry deposition is taken to be proportional to the air concentrations which, for the primary components, showed similar contributions from Swedish sources and long-range transport in southern Sweden. It is interesting to note the systematic differences in the dry deposition between land and water surfaces. This is due to differences in deposition velocities for water and land surfaces. The difference is most clearly seen for oxidised and reduced nitrogen.

For wet deposition (Figures 14, 17 and 20) the picture is different. In this case long-range transport dominates. This is due to the fact that precipitation scavenge pollutants from higher levels in the atmosphere were the long-range transport contribution dominates and that also secondary components are scavenged effectively. The relative contribution from long-range transport to wet deposition is largest for oxidised sulphur and smallest for reduced nitrogen. The wet deposition is largest in the south-western part of Sweden for all components. This is where the largest precipitation amounts are observed and where the concentrations of pollutants in precipitation are largest. The wet deposition decreases towards east and north, and the lowest values are found in the inland parts of northern Sweden and over the Gulf of Bothnia.

Figures 15, 18 and 21 show the sum of wet and dry deposition, the total deposition for 1994. Since the total deposition is dominated by wet deposition the distributions for total deposition are similar to those for wet deposition. As in the case of wet deposition the relative contribution from long-range transport is largest for oxidised sulphur and smallest for reduced nitrogen. The Swedish emissions of reduced nitrogen are to a large extent deposited close to the source areas since the primary emitted ammonia is removed efficiently by both dry and wet deposition processes. Calculated maximum total deposition values for sulphur, oxidised and reduced nitrogen for 1994 are ca. 1200 mg S/m², 1000 mg N/m² and 1100 mg N/m² respectively and are found in the south-western part of Sweden.

6.2.3 Budget calculations

Here we present budgets for 1994 for oxidised sulphur and oxidised and reduced nitrogen over the area of Sweden. The budgets are based on the results that we have presented above and are summarised in Table 3. The results for 1991 (Persson et al., 1995) are also included for comparison. As can be seen the import for 1994 is 5,5 times larger than the export for oxidised sulphur and 4.4 times larger for reduced nitrogen. For oxidised nitrogen the picture is markedly different. The import is only about 10% larger than the export. We arrive at these numbers when emissions from both land based sources and shipping are included in the Swedish emissions while deposition is summed only for the land and lake surfaces of Sweden.

The imported deposition is dominated by wet deposition for all three types of components considered. When looking at deposition from Swedish sources, dry and wet deposition are of about equal magnitude for reduced nitrogen, while wet deposition dominates for oxidised sulphur and dry deposition dominates for oxidised nitrogen.

The total deposition of sulphur to Sweden for 1994 Sweden is about 3.5 times larger than the emission from Swedish sources, for reduced nitrogen the corresponding number is about 2.3 times larger, while for oxidised nitrogen the total deposition is only about 10% larger than the emission from Swedish sources.

The fraction of Swedish emissions exported is also of some interest. There are large differences between e.g. oxidised nitrogen with the largest fraction exported (80%), and reduced nitrogen, with a substantially smaller export (38%). The reason for these differences are of course that the deposition processes for primary reduced nitrogen compounds are more efficient than for oxidised nitrogen compounds, which have to be transformed chemically to secondary components in order to be deposited effectively. This is especially true for wet deposition of oxidised nitrogen.

Some interesting differences between the results for 1991 and 1994 can be noted. The emissions have changed, especially for sulphur. If we normalise the results with regard to the Swedish emission we find that 30% more of the Swedish sulphur emission is deposited over Sweden in 1994 compared to 1991. The corresponding number for oxidised nitrogen is 10% while there is almost no difference for reduced nitrogen. The different changes result to a large extent from differences in the amounts and distribution of the precipitation over the year between 1991 and 1994. 1991 was a rather normal year with about equal amounts of precipitation in summer (April- September) and winter over Sweden, while in 1994 the summer was drier than the winter. The total precipitation in 1994 was also greater than for 1991 in the southern part of Sweden. These differences in precipitation in combination with the assumed seasonal variations in emissions for sulphur (maximum in winter) and reduced nitrogen (maximum in summer) explains most of the differences between the results for 1991 and 1994 for sulphur and oxidised nitrogen and also the different behaviour of reduced nitrogen. The larger fraction of Swedish sulphur emissions deposited in Sweden show up also as a smaller export for 1994. The Swedish contribution to the total deposition over Sweden is larger for all components in 1994. This is also related to the larger precipitation amounts in 1994.

Table 3. *Air pollution budget for Sweden for 1991 and 1994, calculated using MATCH-Sweden for sulphur, oxidised and reduced nitrogen (100 tonnes S/year and 100 tonnes N/year).*

	Sulphur		NO _x		NH _x	
	1991	1994	1991	1994	1991	1994
Emission	700	505	1184	1214	444	478
Deposition from Swedish sources to Swedish land areas						
dry deposition	101	95	119	148	138	155
wet deposition	142	131	88	94	138	140
dry + wet deposition	243	226	207	242	276	295
Imported long-range transport deposition to Swedish land areas						
dry deposition	513	370	240	271	161	199
wet deposition	1542	1166	848	807	822	599
dry + wet deposition	2050	1536	1088	1078	983	798
Export from Sweden	457	279	977	972	168	183
Fraction of emission (%)	(65%)	(55%)	(83%)	(80%)	(38%)	(38%)
Total deposition to Sweden						
Sum	2300	1760	1300	1320	1260	1090
Swedish contribution (%)	(11%)	(13%)	(16%)	(18%)	(22%)	(27%)

7. COMPARISON BETWEEN MATCH-SWEDEN AND EMEP DEPOSITION ESTIMATES

It is interesting to make some comparisons between the results obtained with MATCH-Sweden and those made using the EMEP model. Provisional estimates from the EMEP model for 1994 was taken from Barrett et al., (1995). The EMEP model has a much coarser horizontal resolution (150 x 150 km) compared to MATCH-Sweden (20 x 20 km). This means that MATCH-Sweden has about 56 grid squares for each EMEP grid

Table 4. Comparison between EMEP and MATCH estimates of the Swedish and total contribution to deposition of oxidised sulphur and oxidised and reduced nitrogen over Sweden for 1991 and 1994 (100 tonnes S/year and 100 tonnes N/year). The assumed Swedish emissions in the different models are also given.

	Sulphur		NO _x -nitrogen		NH _x -nitrogen	
	1991	1994	1991	1994	1991	1994
Swedish Emissions:						
EMEP3(Sandnes et al., 1993)	850		1220		440	
EMEP2(Touvinen et al., 1994)	530		1180		420	
EMEP1(Barrett et al., 1995)	565	505	1210	1214	600	478
MATCH	700	505	986	1214	440	478
Swedish deposition over Sweden:						
EMEP3(Sandnes et al., 1993)	234		151		233	
EMEP2(Touvinen et al., 1994)	152		148		220	
EMEP1(Barrett et al., 1995)	117	100	144	126	330	231
MATCH	243	226	207	242	276	295
Total deposition over Sweden:						
EMEP3(Sandnes et al., 1993)	1858		1193		824	
EMEP2(Touvinen et al., 1994)	1743		1199		721	
EMEP1(Barrett et al., 1995)	1725	1515	1145	981	784	614
MATCH	2300	1763	1300	1320	1260	1093

square, which of course should mean that MATCH-Sweden can resolve geographical variation with much better detail. Using the MATCH system, we also estimate the long-range transport in an independent way compared to EMEP. This should also affect the results. The EMEP model is improved continuously. Also the emission estimates used in the EMEP work change as better information become available. After major changes the EMEP model has been rerun for several years so that estimates based on different model versions (and different emission estimates) are available for recent years. These improvements have led to substantial changes in the EMEP estimates for the Swedish area, especially for sulphur. Table 4 shows a comparison of EMEP and MATCH estimates of deposition to Sweden for 1991 and 1994. For 1991 three different EMEP estimates are available; EMEP1 (Barrett et al., 1995), EMEP2 (Touvinen et al., 1994) and EMEP3 (Sandnes et al., 1993). If we account for the different emission estimates used we find that the estimated Swedish deposition over Sweden is almost unchanged for oxidised and reduced nitrogen, while the estimated sulphur deposition has decreased with each new revision of the EMEP estimates. In EMEP2 (Touvinen et al., 1994) a revised calculation of dry deposition was introduced which explains the differences between EMEP3 and EMEP2. The reason for the large change between EMEP2 and EMEP1 (Barrett et al. 1995) for sulphur is unclear. The MATCH estimates are higher for all components in both 1991 and 1994. The difference is larger than a factor of two for sulphur in both 1991 and

1994 if we compare with the most recent EMEP estimates (Barrett et al., 1995). The difference for 1991 is substantially smaller if we compare with the earlier EMEP estimates (EMEP2 and EMEP3). For oxidised nitrogen the EMEP1 estimates are 43% lower in 1991 and 48% lower in 1994 than the MATCH estimates. The corresponding numbers for reduced nitrogen are 12% for 1991 and 22% for 1994 if we account for differences in the emission estimates for 1991. A priori one would expect somewhat larger MATCH estimates since several corrections are applied in the precipitation analysis which result in larger analysed precipitation amounts. Somewhat higher dry deposition velocities has also been applied for particles and NO₂ in the MATCH system. Taken together these differences, and differences due to model resolution and meteorological input data, can probably account for a large fraction of the differences found for oxidised and reduced nitrogen. The reason for the larger differences for sulphur is unclear. It should be noted though that the results for 1994 given by Barrett et al. (1995) represent provisional estimates.

8. MODEL EXPERIMENTS BASED ON DIFFERENT PRECIPITATION CHEMISTRY NETWORKS

In a situation with limited economic resources for national and regional environmental monitoring, there is a pressure to optimise existing station networks in order to get resources to include new important problems and new compounds in the future activities. Other authors have investigated the design of precipitation chemistry networks. E.g. Oehlert (1996) has, by means of statistical methods, studied this problem for the precipitation chemistry network in USA

For the purpose of evaluating the Swedish network we have tried to make some experiments using the MATCH-Sweden system. The long-range transport analysis part of the system (c.f. section 5.2) has in this context been re-run for several cases, where the calculations were based on different assumed precipitation chemistry station networks. This was done in order to test the sensitivity of the estimated wet deposition of sulphur and nitrogen to the design of the station network. Only a brief discussion of this work is given here. A more detailed account will be published in the near future.

8.1 Estimated wet deposition over Sweden based on different station networks

Wet deposition calculations were based on the following assumed station networks:

Case 1. All stations (EMEP + PMK, about 50 stations)

- " 2. EMEP (14 stations)
- " 3. PMK (about 35 stations)
- " 4. Swedish EMEP (4 stations)
- " 5. 10 EMEP stations outside Sweden
- " 6. 3 EMEP stations outside Sweden

” 7. Suggested new Swedish network (Swedish EMEP + New Precipitation Chemistry Network, about 25 stations).

A number of other station selection rules could of course have been used, the cases above were only chosen as examples. Maps showing the obtained results of wet deposition of sulphur for these cases are presented in Figure 22 and Figure 26 (the corresponding figures for oxidised and reduced nitrogen are not shown for brevity).

The obtained deposition values depend on the precipitation amounts as well as on the concentrations in precipitation. The precipitation amounts used in the different MATCH-estimates are always the same and are based on a detailed mapping of the precipitation, with a 3-h time resolution. This means that a comparison between wet deposition amounts from different MATCH-estimates automatically have a higher correlation compared to a comparison of concentrations in precipitation. In many cases it is therefore better to compare concentrations in precipitation rather than wet deposition. In Figure 23 the calculated annual mean values for concentration in precipitation of sulphur, oxidised nitrogen and reduced nitrogen are illustrated for case 1. The highest values are in the south-eastern parts of the model area for all three compounds and the lowest values in the north-western parts. The concentration gradients are rather uniform over Sweden.

The calculations in case 1 are based on measured chemistry data from all stations, both EMEP and PMK, which means that we have no independent measurements available for a comparison with the MATCH-estimates. If we use the dependent measurements (EMEP and PMK) in comparisons, we obtain scatter plots of the type shown in Figures 24 and 25 for monthly concentrations in precipitation. About 140 data points per diagram are included for the EMEP comparisons and about 400 data points for PMK. The MATCH system obviously includes the measurements in a detailed way, especially for sulphur, and the obtained correlations are high. The larger deviations are mainly caused by differences between stations localised close together. The indicated R^2 -values in the diagrams show the explained variance. Annual mean values show even stronger correlations between measurements and MATCH-estimates. In Table 5 we have included all the obtained correlation coefficients between the dependent monthly measurements and the monthly MATCH-estimates. The correlation coefficients for precipitation amounts are lower than for the chemical concentrations, however partly due to that independent data are used in that case.

Table 5. *Correlations between EMEP or PMK precipitation chemistry measurements and MATCH estimates (based on all EMEP+PMK stations). The correlation coefficients, based on monthly data for 1994, are given. All concentration measurements are dependent data.*

Measurements	Precipitation	SO ₄ -conc	NO ₃ -conc	NH ₄ -conc
EMEP (dependent data)	0.81	0.98	0.95	0.95
PMK (dependent data)	0.88	0.94	0.89	0.84

When using the EMEP-network over the model area, with 4 stations within Sweden and 10 EMEP stations in the neighbouring countries, we obtain general patterns in the depositions, which are very similar with the results for case 1, based on all available stations. However, the deposition values, based on EMEP, are for all three components a little higher over the whole of Sweden. Also the calculations based on about 35 PMK stations in Sweden show results over Sweden which are very similar to the results obtained for case 1. Outside Sweden, especially in the vicinity of the Baltic states, the differences are on the other hand rather large. This is of course due to the fact that no stations outside Sweden were included in the PMK-case.

A hypothetical station network, consisting of only 4 Swedish EMEP stations, show, over southern Sweden, results which are similar to what was obtained for case 2, EMEP network, while rather large differences are apparent over northern Sweden, especially for the mountain areas in north-west. This is not surprising since three of the Swedish EMEP-stations are localised in southern Sweden and only one station further north.

We have included also another two hypothetical cases, just as illustrations, where no stations within Sweden are used. It can of course be argued that it is unrealistic to expect the rest of the Nordic network to remain at full strength during a drastic reduction of the Swedish network. However, in these cases the MATCH-estimates have been based on some well situated stations of high quality in our neighbouring countries. The calculated wet deposition values, based on 10 Nordic EMEP stations, show somewhat surprising that the wet deposition pattern obtained without Swedish stations agree quite well with what is obtained in case 1, based on all stations. The reason for this good agreement obviously must be the regular annual mean gradient over Sweden (c.f. Figure 25) for all three components, which can be described also with a rather limited number of stations outside Sweden, as long as those stations are of high quality and situated along the Swedish borders.

Case 7 in the MATCH estimates is based on an assumed reduced Swedish station network of about 25 stations (EMEP+PMK). This case show deposition maps which are very similar to what was obtained in case 1, all stations. Obviously this rather modest reduction has only a very small influence on the obtained wet deposition of sulphur and nitrogen in the MATCH-system.

9. CONCLUSIONS

A modelling system capable of providing high resolution estimates of national and long-range transport contributions to concentrations in air and to dry and wet deposition of sulphur and nitrogen compounds over Sweden has been developed and applied using data for 1994.

A combination of a network of air and precipitation chemistry stations and a system like MATCH, including detailed meteorological information, gives the best possibilities for a correct and detailed mapping of the deposition over Sweden. The combination of measurements and model give a more detailed geographical mapping together with a critical quality control of the precipitation chemistry measurements.

Comparison between the EMEP and MATCH estimates for 1994 indicate differences exceeding 20% for total deposition of oxidised and reduced nitrogen, with higher estimates derived from the MATCH system. Similar differences were found for 1991 but in that case the differences were largest for sulphur and reduced nitrogen. The EMEP estimates of Swedish contributions to deposition over Sweden are 55, 48 and 22% smaller for sulphur, oxidised and reduced nitrogen respectively. Part of these differences can be explained by different meteorological data, especially precipitation, and differences in dry deposition velocities.

Using the MATCH system it has been possible to evaluate different hypothetical precipitation chemistry networks for sulphur and nitrogen over Sweden. There is a clear indication that a future reduction of the number of Swedish precipitation chemistry stations from about 50, which was used in the operative study for 1994, down to about 25 stations only has a limited effect on the obtained annual and monthly wet deposition pattern over Sweden. This is true only if the future station network selected for the Swedish environmental survey is run with high quality in sampling, chemical analyses and with representative sites and a proper geographical distribution over Sweden. Also time variations over periods of months and years can be followed by this less dense station network.

Acknowledgement

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References

- Barrett, K., Ø. Seland, A. Foss, S. Mylona, H. Sandnes, H. Styve, and L. Tarrasón: 1995, *European transboundary acidifying air pollution: Ten years calculated fields and budgets to the end of the first sulphur protocol*, EMEP/MSC-W Report 1/95, DNMI, Oslo, Norway.
- Bott, A.: 1989a, A positive definite advection scheme obtained by nonlinear renormalization of the advective fluxes, *Mon. Wea. Rev.* **117**, 1006 - 1015.
- Bott, A.: 1989b, Reply. Notes and correspondence, *Mon. Wea. Rev.* **117**, 2633 - 2626.
- Eliassen, A. and Saltbones, J.: 1983, *Atmos. Environ.* **17**, 1457-1473.
- Erisman, J. W., C. Potma, G. Draaijers, E. van Leeuwen and A. van Pul: 1995, A generalised description of the deposition of acidifying pollutants on a small scale in Europe, *Water Air and Soil Poll.* **85**, 2001-2006.
- EMEP: 1980, Summary report of the Western Meteorological Synthesising Centre for the first phase of EMEP, EMEP/MSC-W, Norwegian Meteorological Institute, Oslo, Norway.
- Iversen, T., Saltbones, J., Sandnes, H., Eliassen, A. and Hov Ø.: 1989, *Airborne Transboundary Transport of Sulphur and Nitrogen over Europe - Model Description and Calculations*, EMEP/MSC-W Report 2/89, DNMI, Oslo, Norway.
- Meuller, L., L. Robertson, E. Andersson, and N. Gustafsson: 1990, Meso- γ scale objective analysis of near surface temperature, humidity, and wind and its application in air pollution modelling, Swedish Meteorological and Hydrological Institute, Report RMK 61.
- Langner, J., C. Persson, and L. Robertson: 1995, Concentration and deposition of acidifying air pollutants over Sweden: Estimates for 1991 based on the MATCH model and observations. *Water Air and Soil Poll.* **85**, 2021-2026.
- Odén, S.: 1976, *Water, Air, and Soil Pollut.* **6**, 137-166.
- Oehlert, G. W.: 1996, Shrinking a wet deposition network. *Atmos. Environ.* **30**, 1347-1357.
- Persson, C. and Robertson, L.: 1991, In H. van Dop and D. G. Steyn (eds.), *Air Pollution Modelling and Its Application VIII*, Plenum Press, New York, pp 649-650.
- Persson, C., J. Langner, and L. Robertson: 1994a, A mesoscale air pollution dispersion model for the Swedish west-coast region - Air pollution assessment for the year 1991. Swedish Meteorological and Hydrological Institute RMK-65.
- Persson, C., Langner, J. and Robertson, L.: 1994b, In S-E. Gryning and M. M. Millán (eds.), *Air Pollution Modelling and Its Application X*, Plenum Press, New York, pp 9-18.

- Persson, C., J. Langner, and L. Robertson: 1995, Swedish Environmental Protection Agency Report 4386, (in Swedish).
- Sandnes, H.: 1993, Calculated budgets for airborne acidifying components in Europe: Calculated fields and budgets 1985-93, EMEP/MSC-W Report 1/93, DNMI, Oslo, Norway.
- Touvinen, J-H., Barrett, K. and Styve, H.: 1994, *Transboundary acidifying pollution in Europe: Calculated fields and budgets 1985-93*, EMEP/MSC-W Report 1/94, DNMI, Oslo, Norway.

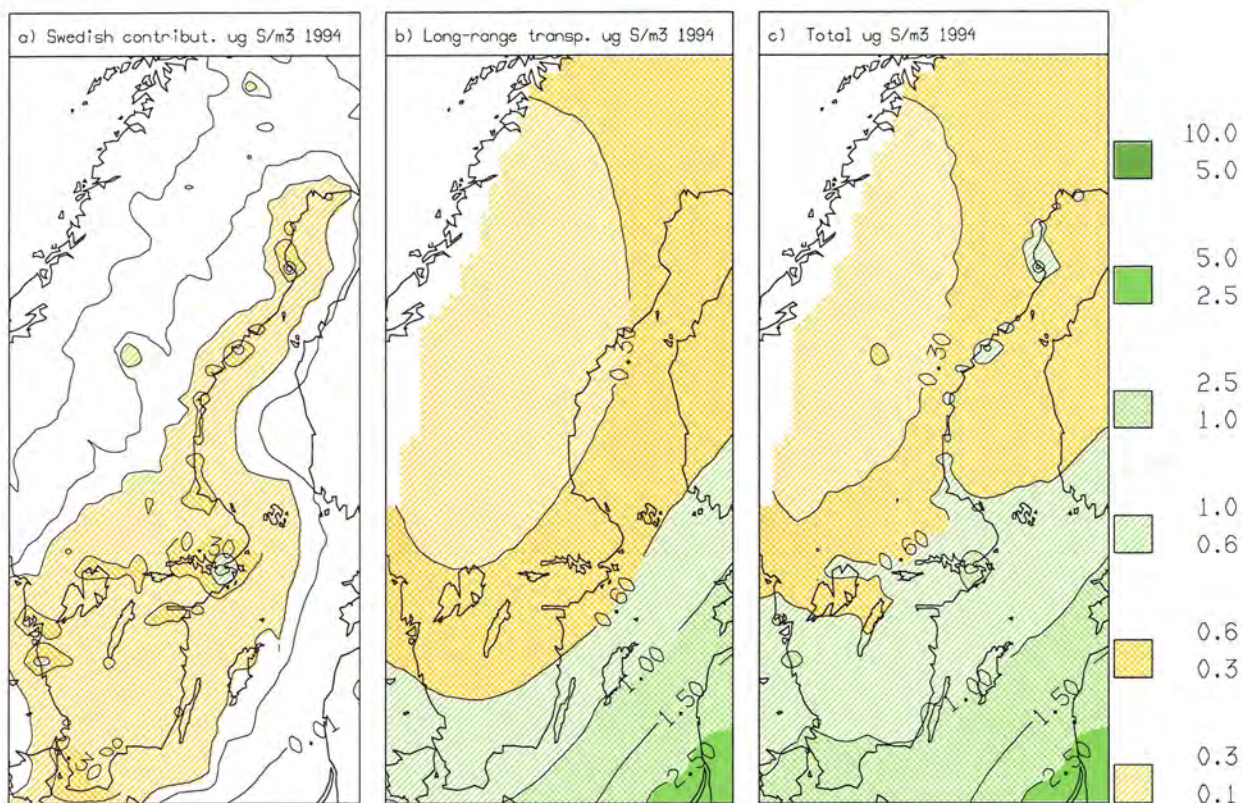


Figure 8. Comparison between calculated annual average air concentration of SO_2 for a) Swedish contribution b) long-range transport contribution c) total. Units: $\mu\text{g S/m}^3$. Isolines: 0.01, 0.05, 0.1, 0.3, 0.6, 1.5, 1, 2.5, 5, 10, 25.

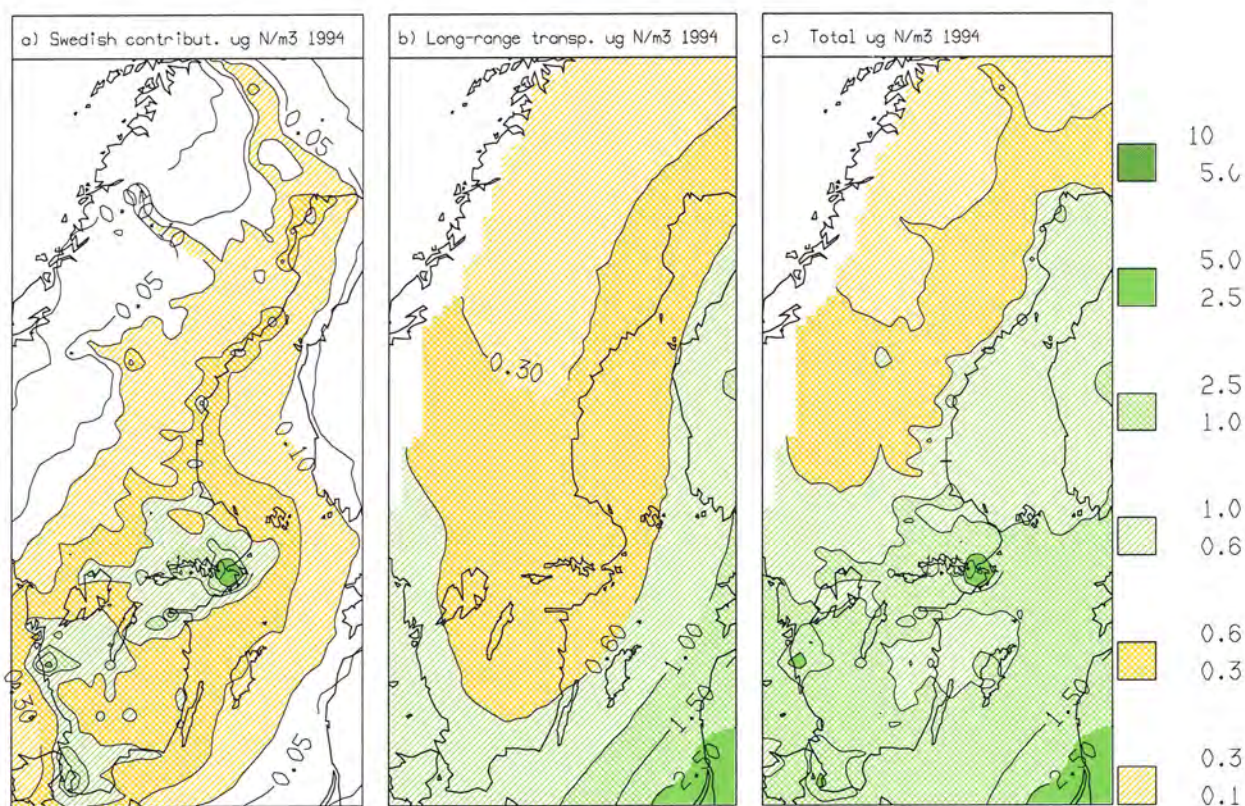


Figure 9. Comparison between calculated annual average air concentration of NO_2 for a) Swedish contribution b) long-range transport contribution c) total. Units: $\mu\text{g N/m}^3$. Isolines: 0.01, 0.05, 0.1, 0.3, 0.6, 1, 1.5, 2.5, 5, 10, 25.

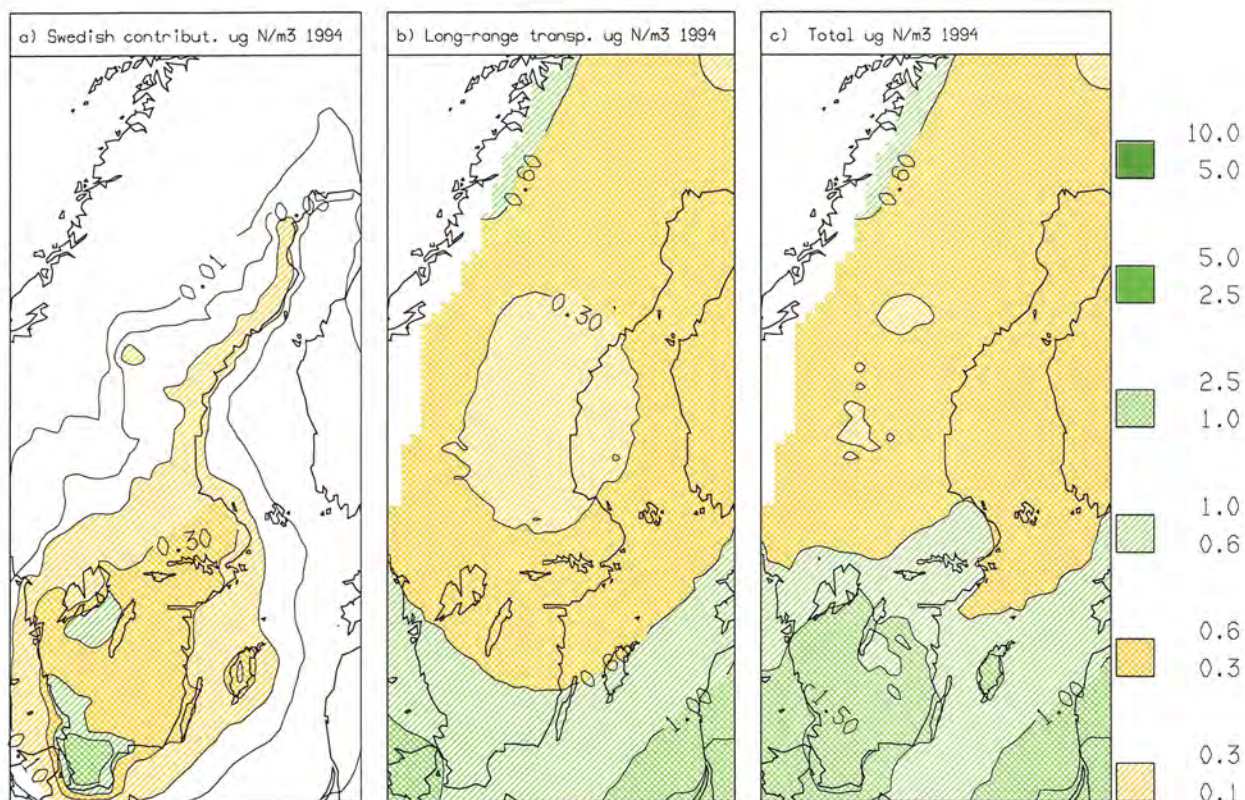


Figure 10. Comparison between calculated annual average air concentration of ($\text{NH}_4^+ + \text{NH}_3$) for a) Swedish contribution b) long-range transport contribution c) total. Units: $\mu\text{g N/m}^3$. Isolines: 0.01, 0.05, 0.1, 0.3, 0.6, 1, 1.5, 2.5, 5, 10, 25.

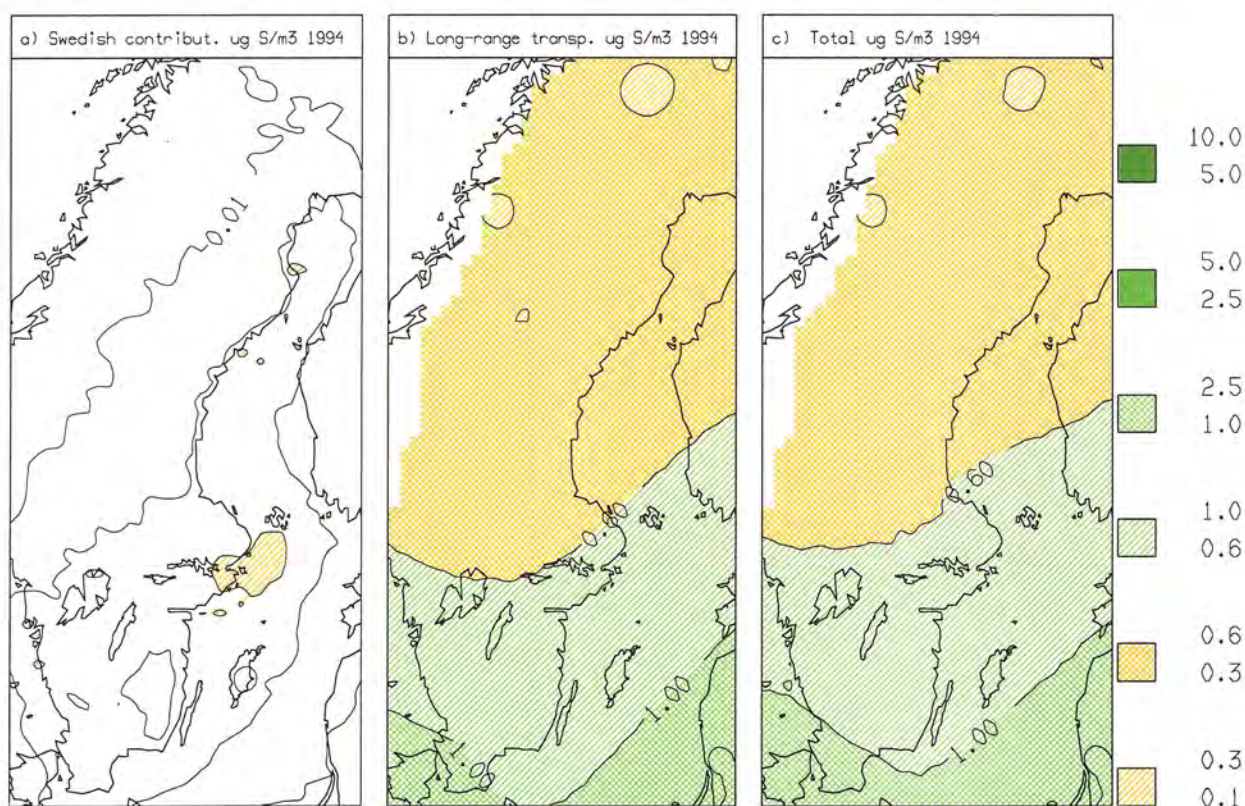


Figure 11. Comparison between calculated annual average air concentration of SO_4^{2-} for a) Swedish contribution b) long-range transport contribution c) total. Units: $\mu\text{g S/m}^3$. Isolines: 0.01, 0.05, 0.1, 0.3, 0.6, 1, 1.5, 2.5, 5, 10, 25.

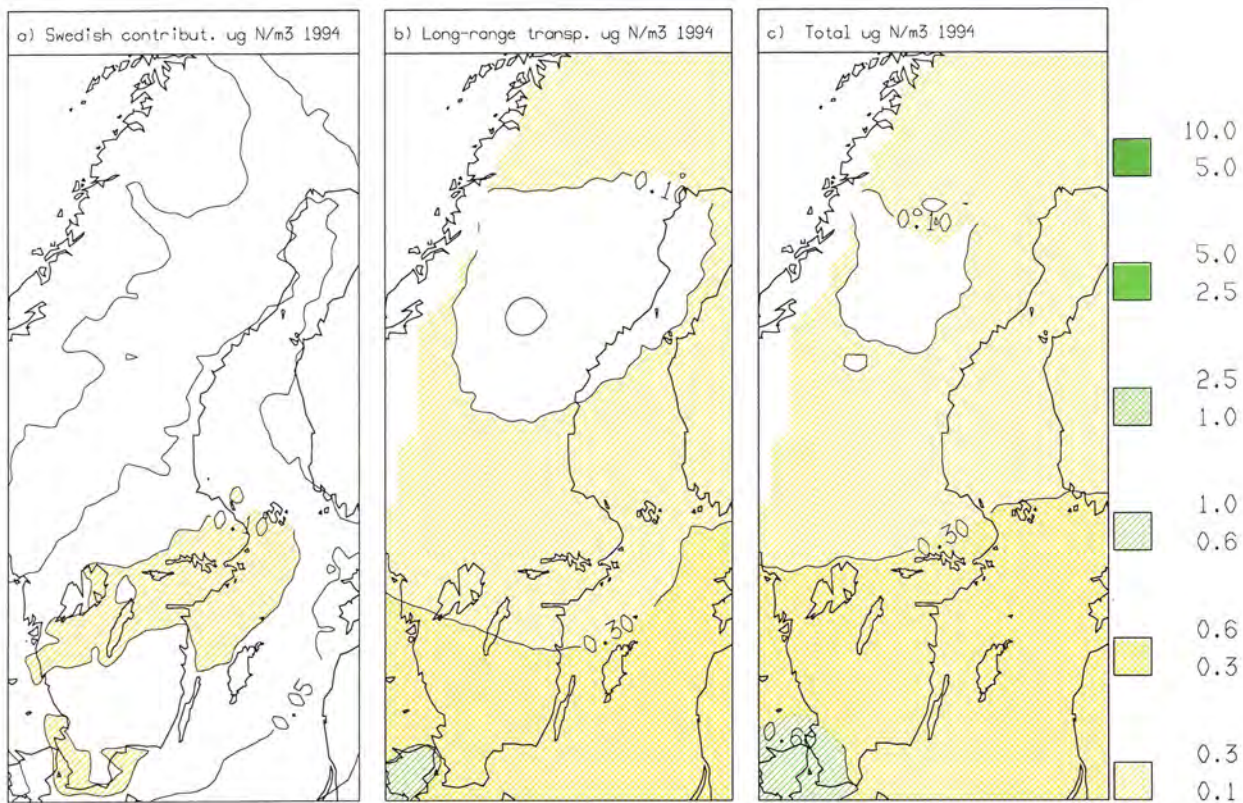


Figure 12. Comparison between calculated annual average air concentration of $(\text{HNO}_3 + \text{NO}_3^-)$ for a) Swedish contribution b) long-range transport contribution c) total. Units: $\mu\text{g N/m}^3$. Isolines: 0.01, 0.05, 0.1, 0.3, 0.6, 1, 1.5, 2.5, 5, 10, 25.

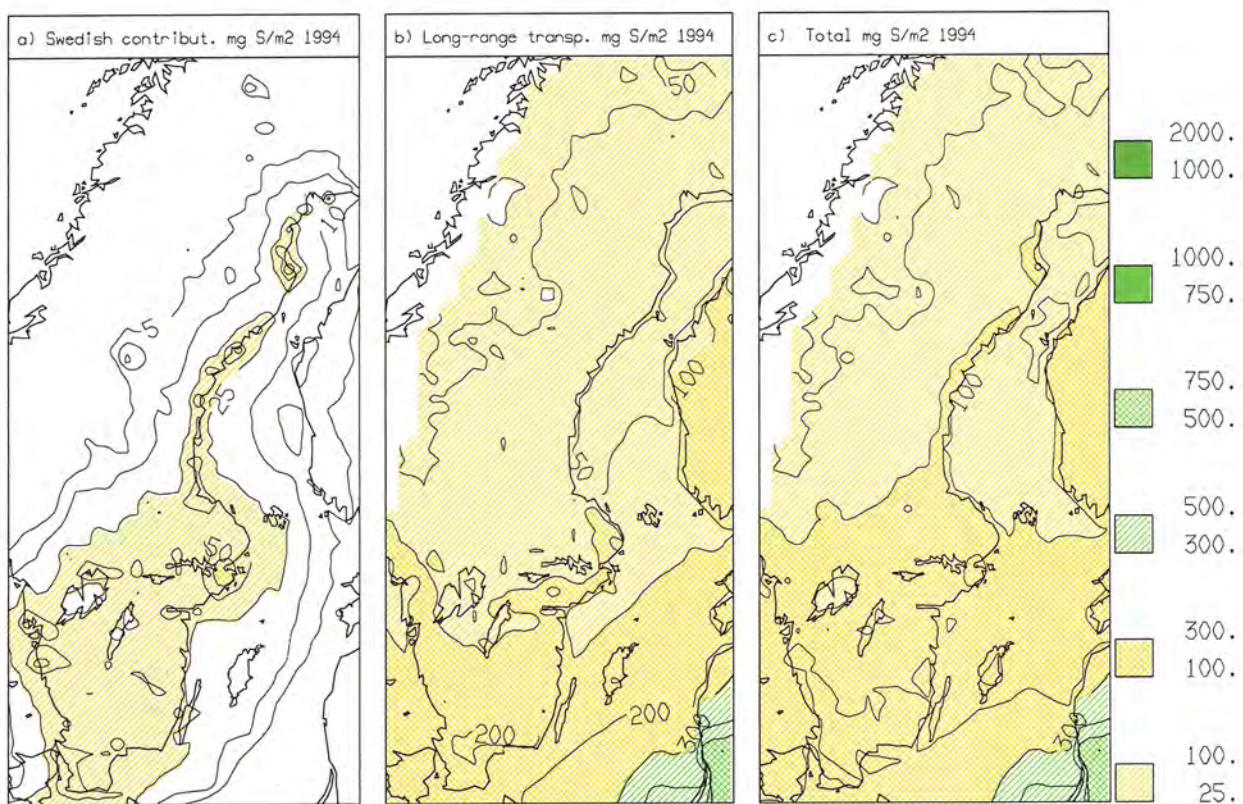


Figure 13. Comparison between calculated annual dry deposition of sulphur for a) Swedish contribution b) long-range transport contribution c) total. Units: mg S/m^2 . Isolines: 5, 10, 25, 50, 100, 200, 300, 400, 500, 600, 750, 1000, 1250, 1500, 2000.

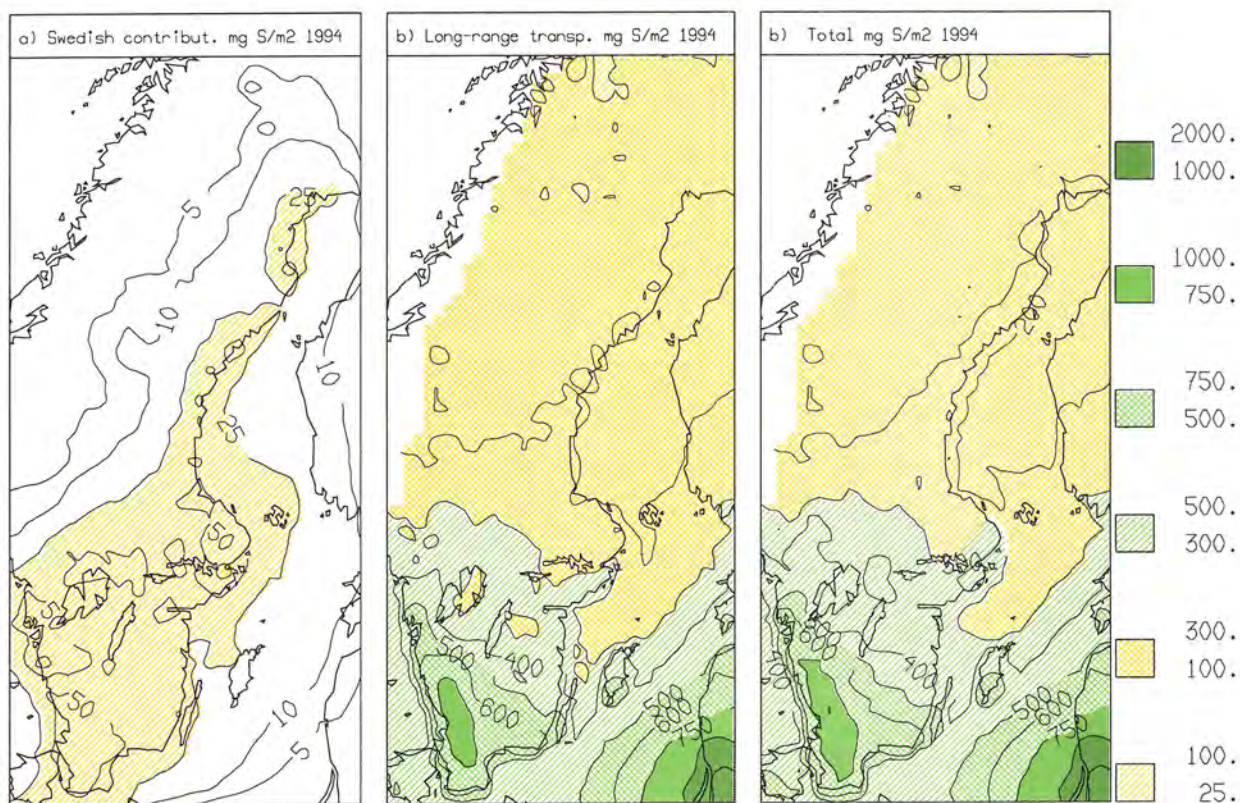


Figure 14. Comparison between calculated annual wet deposition of sulphur for a) Swedish contribution b) long-range transport contribution c) total. Units: mg S/m^2 . Isolines: 5, 10, 25, 50, 100, 200, 300, 400, 500, 600, 750, 1000, 1250, 1500, 2000.

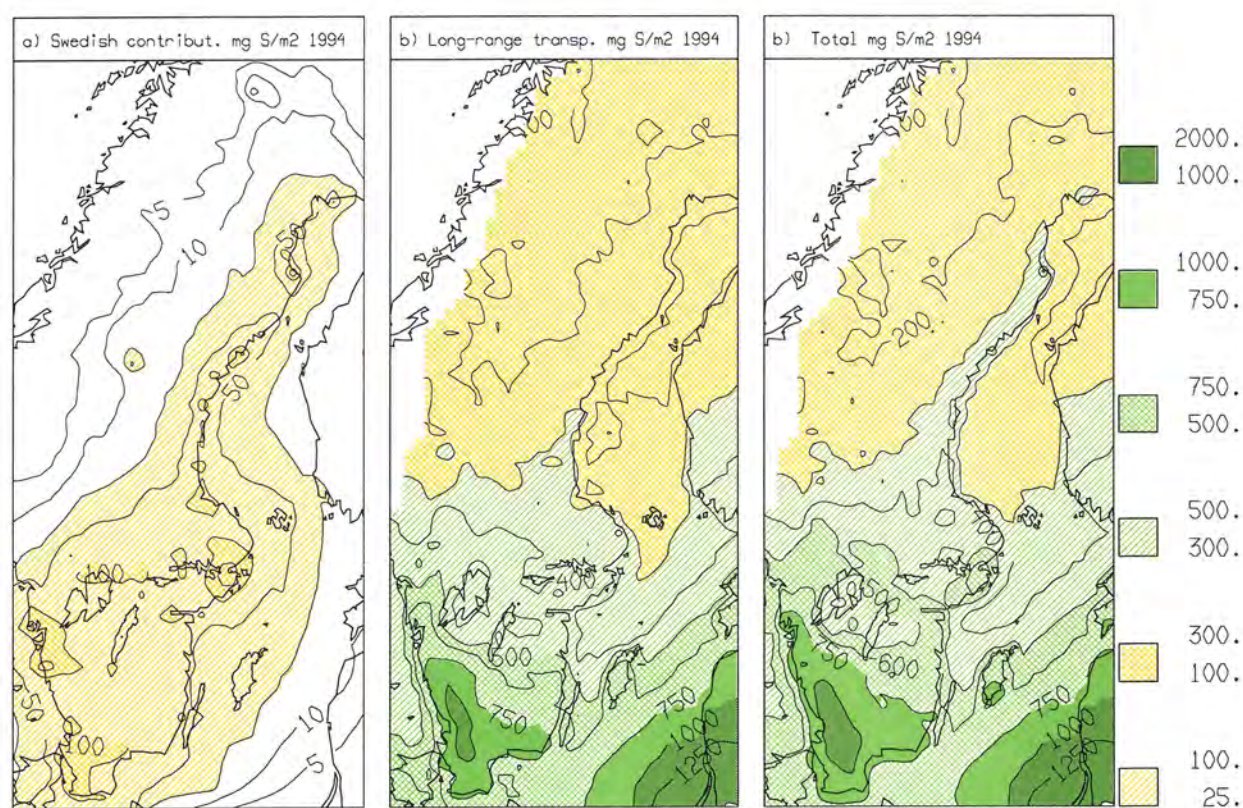


Figure 15. Comparison between calculated annual wet + dry deposition of sulphur for a) Swedish contribution b) long-range transport contribution c) total. Units: mg S/m^2 . Isolines: 5, 10, 25, 50, 100, 200, 300, 400, 500, 600, 750, 1000, 1250, 1500, 2000.

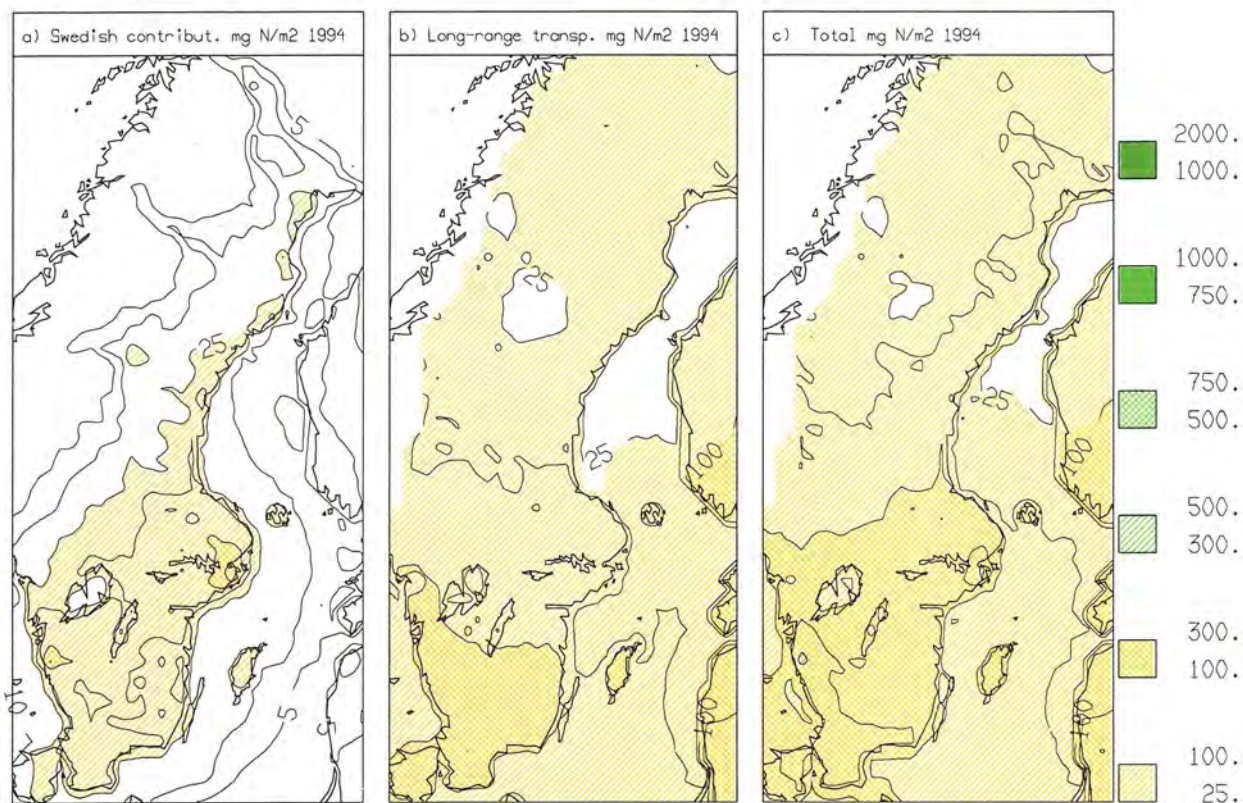


Figure 16. Comparison between calculated annual dry deposition of $\text{NO}_x - \text{N}$ for a) Swedish contribution b) long-range transport contribution c) total. Units: mg N/m^2 . Isolines: 5, 10, 25, 50, 100, 200, 300, 400, 500, 600, 750, 1000, 1250, 1500, 2000.

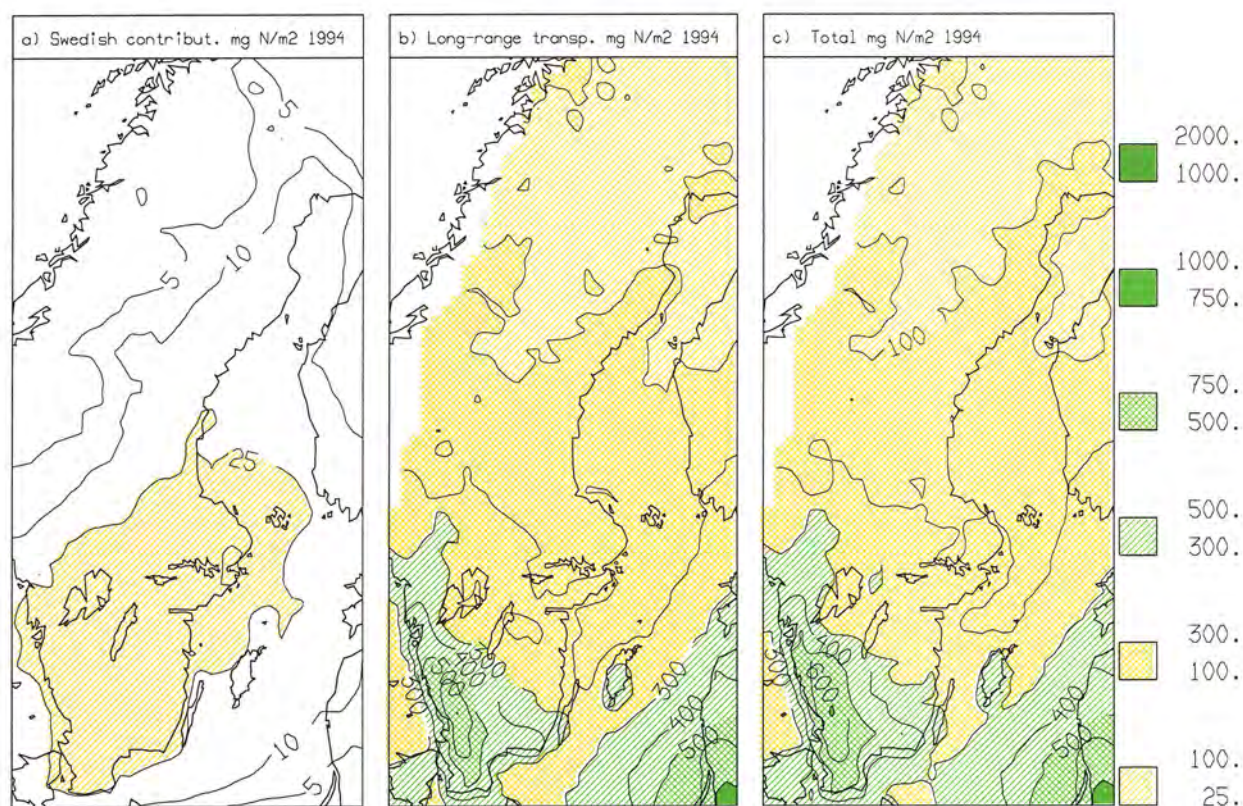


Figure 17. Comparison between calculated annual wet deposition of $\text{NO}_x - \text{N}$ for a) Swedish contribution b) long-range transport contribution c) total. Units: mg N/m^2 . Isolines: 5, 10, 25, 50, 100, 200, 300, 400, 500, 600, 750, 1000, 1250, 1500, 2000.

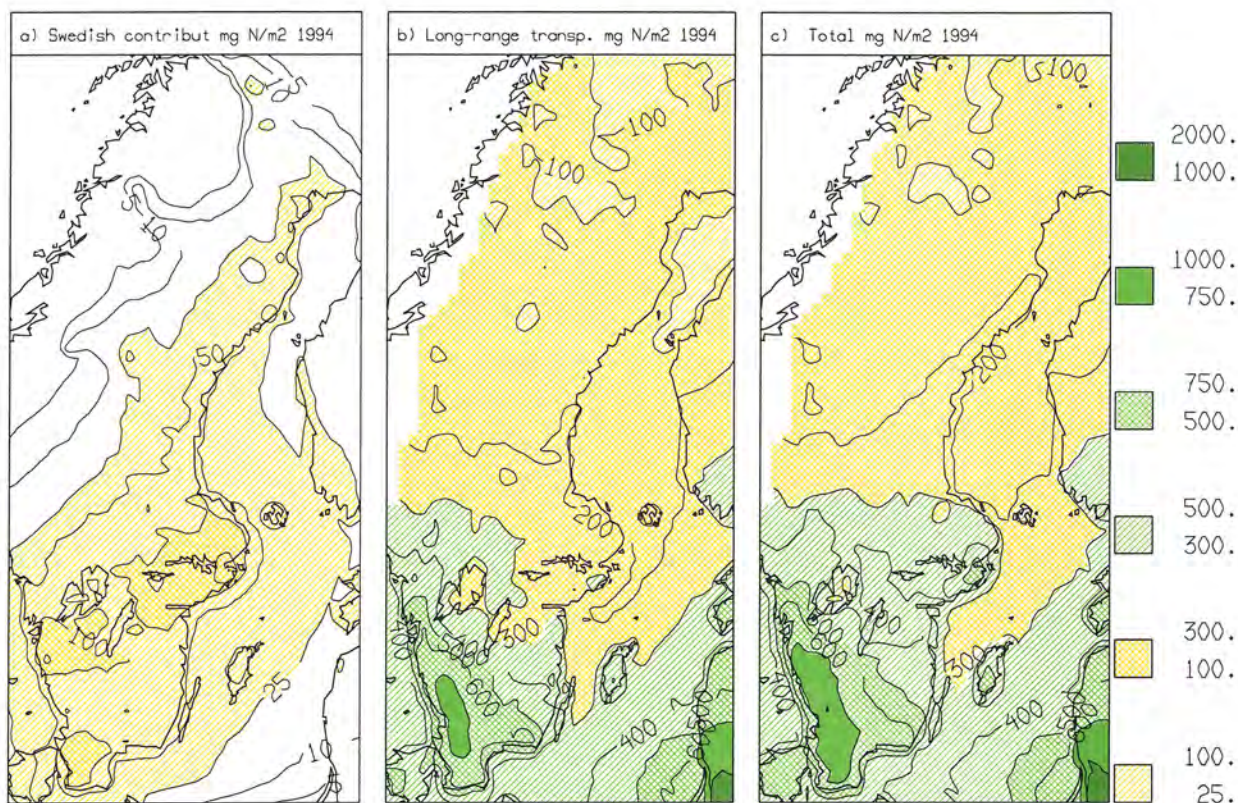


Figure 18. Comparison between calculated annual wet + dry deposition of NO_x -N for a) Swedish contribution b) long-range transport contribution c) total. Units: mg N/m^2 . Isolines: 5, 10, 25, 50, 100, 200, 300, 400, 500, 600, 750, 1000, 1250, 1500, 2000.

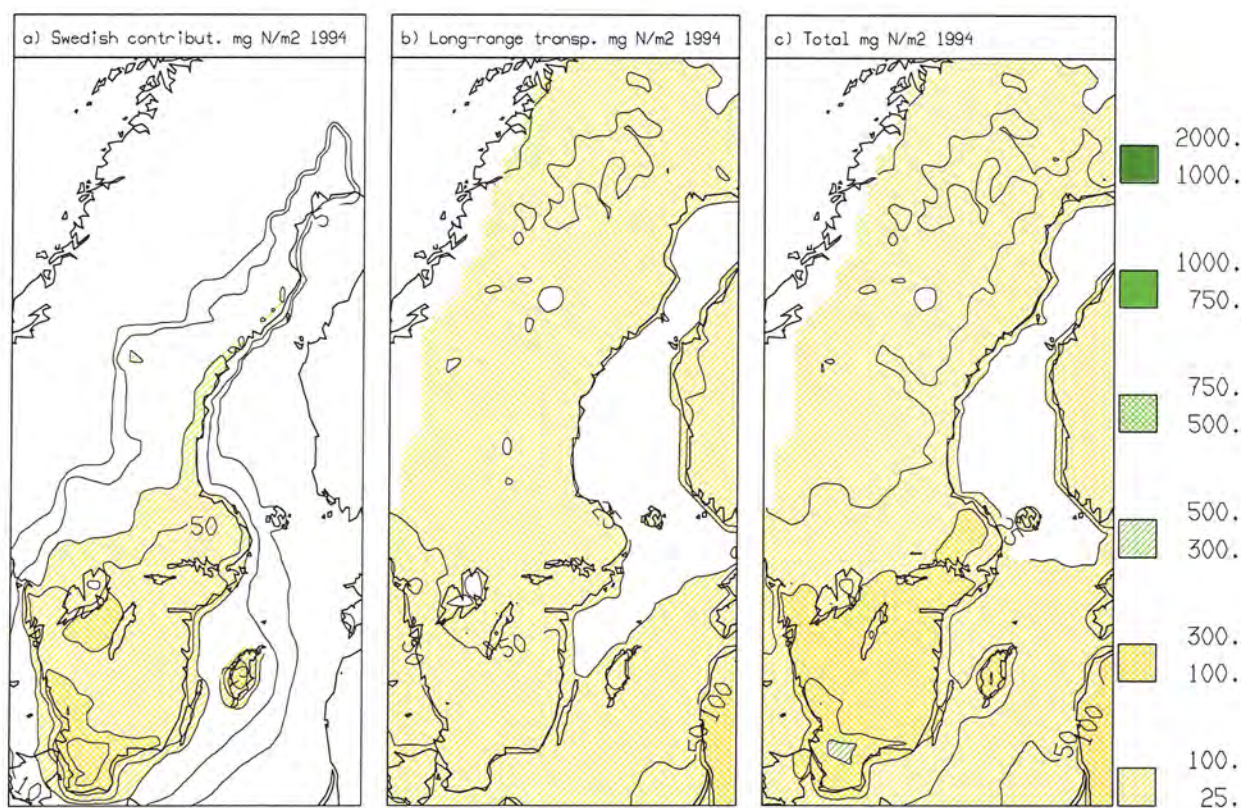


Figure 19. Comparison between calculated annual dry deposition of NH_x -N for a) Swedish contribution b) long-range transport contribution c) total. Units: mg N/m^2 . Isolines: 5, 10, 25, 50, 100, 200, 300, 400, 500, 600, 750, 1000, 1250, 1500, 2000.

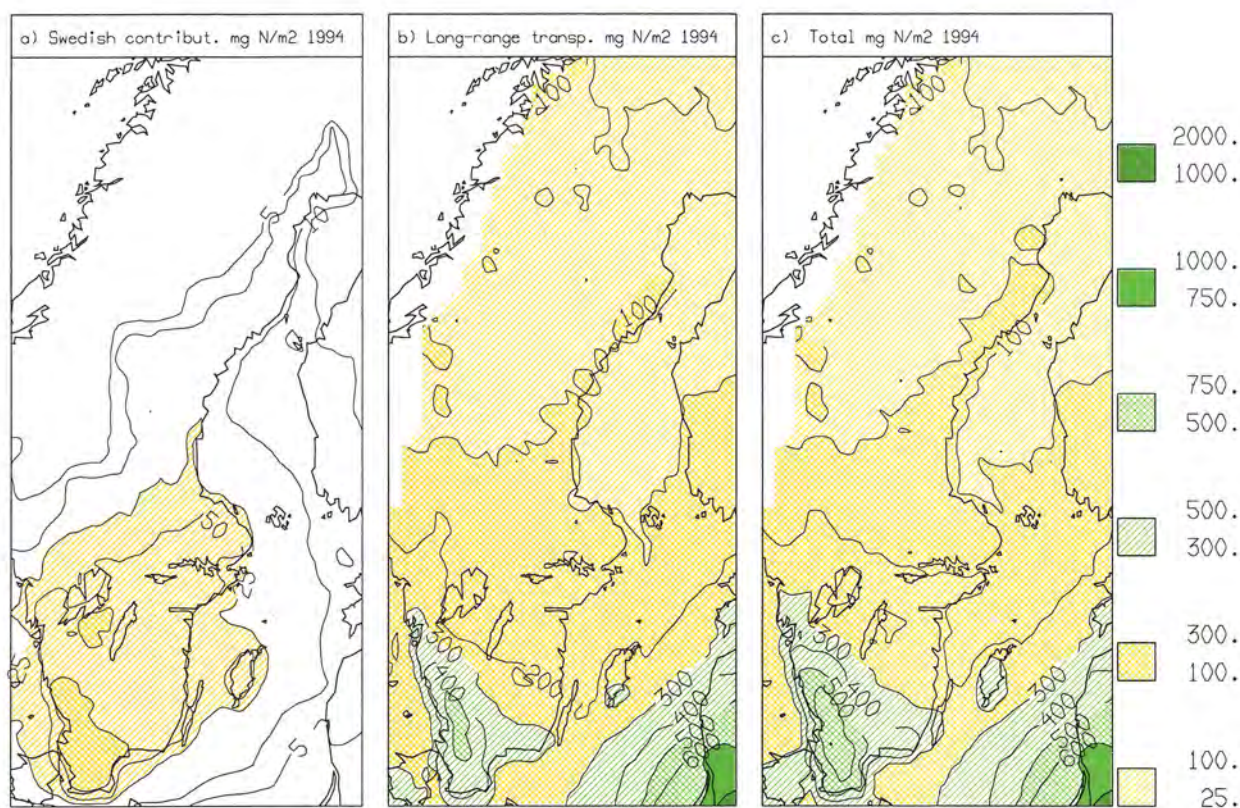


Figure 20. Comparison between calculated annual wet deposition of $\text{NH}_x\text{-N}$ for a) Swedish contribution b) long-range transport contribution c) total. Units: mg N/m^2 . Isolines: 5, 10, 25, 50, 100, 200, 300, 400, 500, 600, 750, 1000, 1250, 1500, 2000.

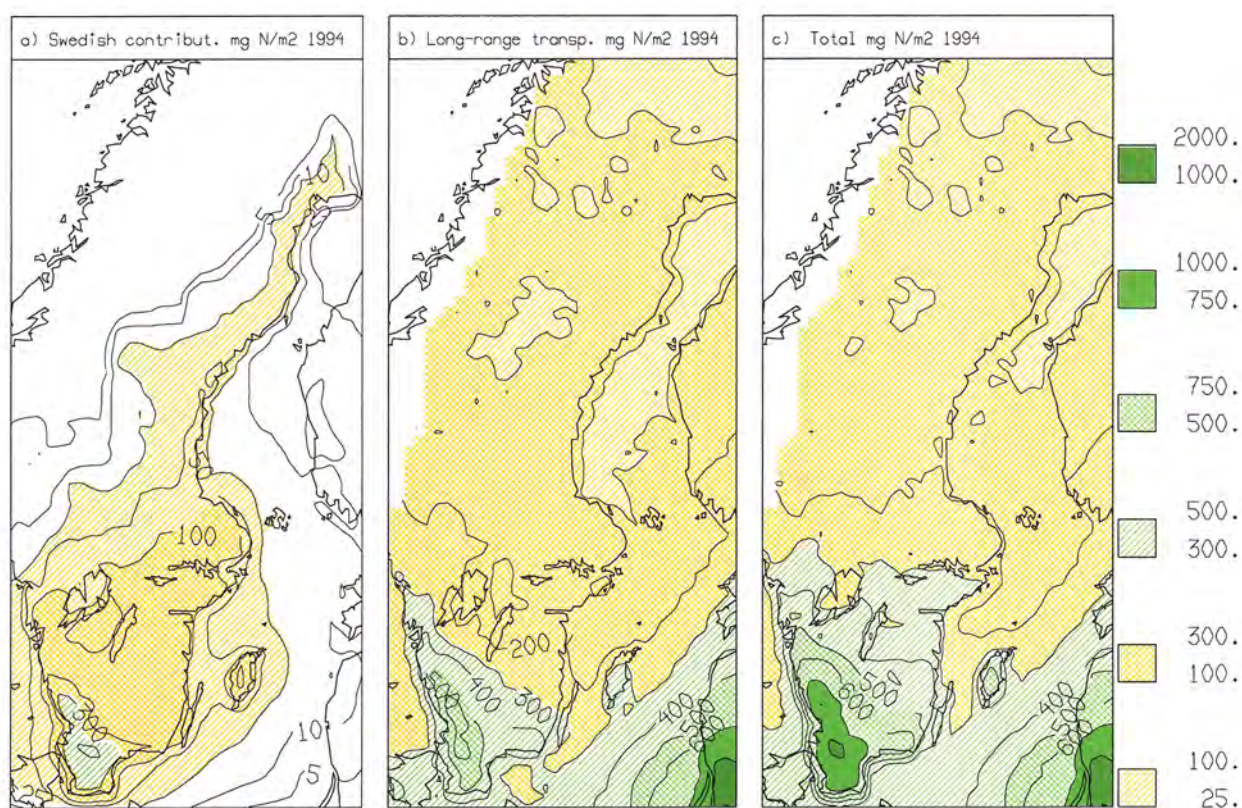


Figure 21. Comparison between calculated annual wet + dry deposition of $\text{NH}_x\text{-N}$ for a) Swedish contribution b) long-range transport contribution c) total. Units: mg N/m^2 . Isolines: 5, 10, 25, 50, 100, 200, 300, 400, 500, 600, 750, 1000, 1250, 1500, 2000.

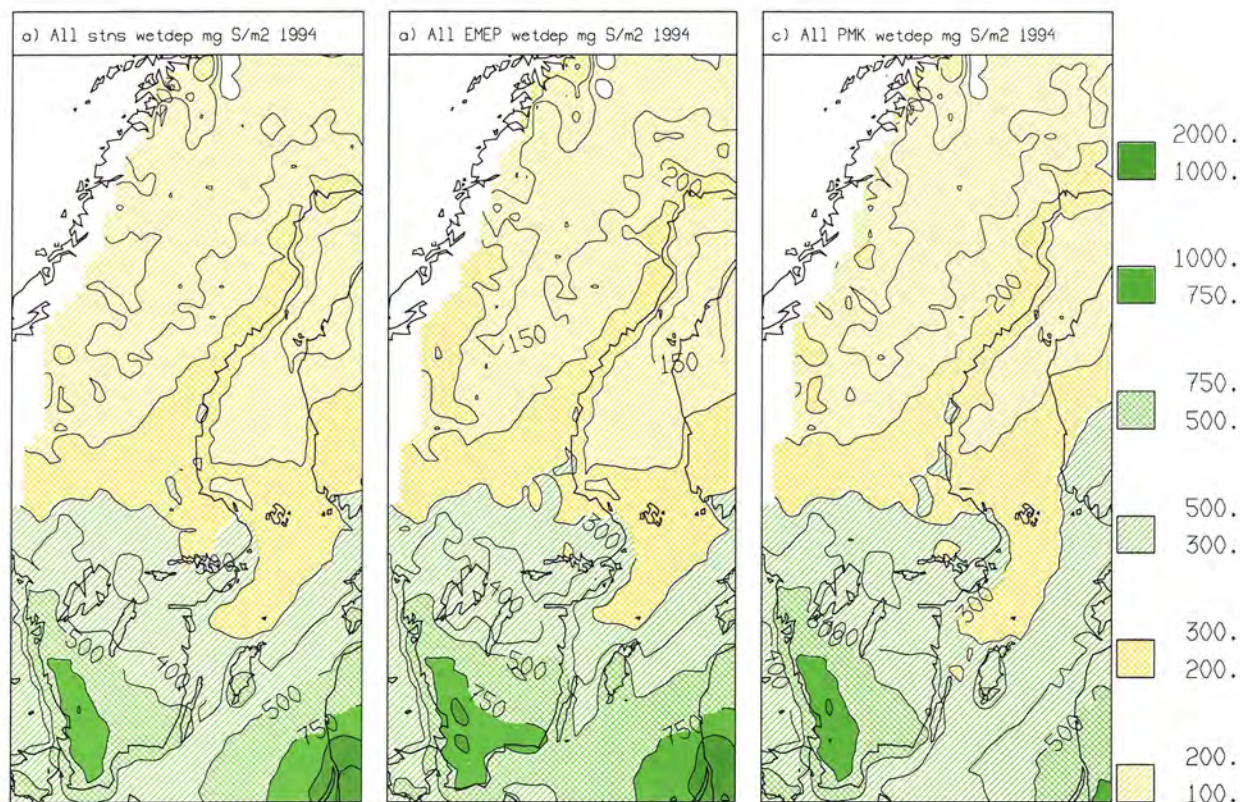


Figure 22. Comparison between MATCH-estimated annual, 1994, wet deposition of sulphur based on a) All stations b) EMEP network c) PMK network. Units: mg S/m². Isolines: 5, 10, 25, 50, 100, 200, 300, 400, 500, 600, 750, 1000, 1250, 1500, 2000.

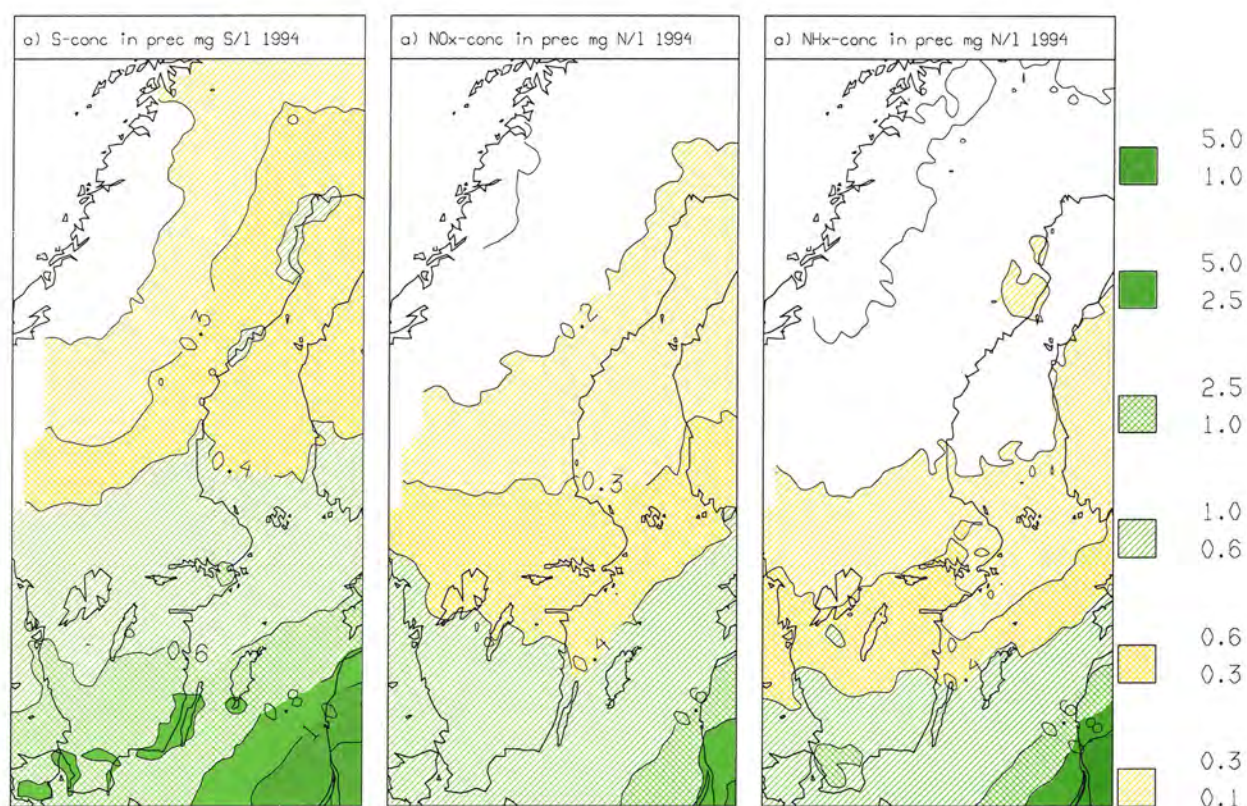


Figure 23. Comparison between MATCH-estimated, based on all stations, annual, 1994, mean concentration in precipitation of a) sulphur b) NO_x-N c) NH_x-N. Units: mg (S or N)/L. Isolines: 0.1, 0.2, 0.3, 0.4, 0.6, 0.8, 1.5.

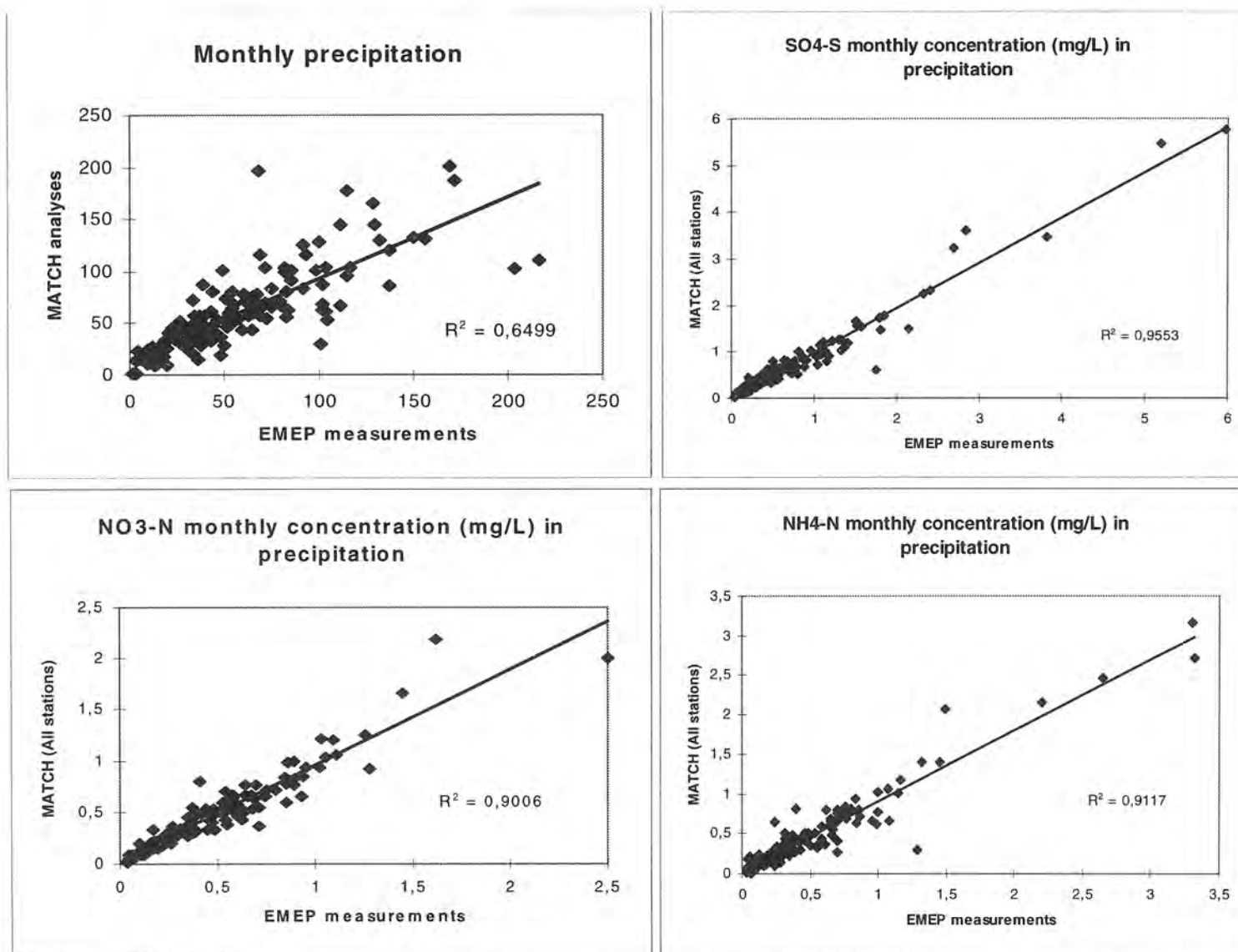


Figure 24. Scatter plots showing EMEP-measurements compared to MATCH-estimates based on all stations. Monthly data, 1994, for precipitation amounts (mm/month) and concentration in precipitation of $\text{SO}_4\text{-S}$ (mg S/L), $\text{NO}_3\text{-N}$ (mg N/L), $\text{NH}_x\text{-N}$ (mg N/L).

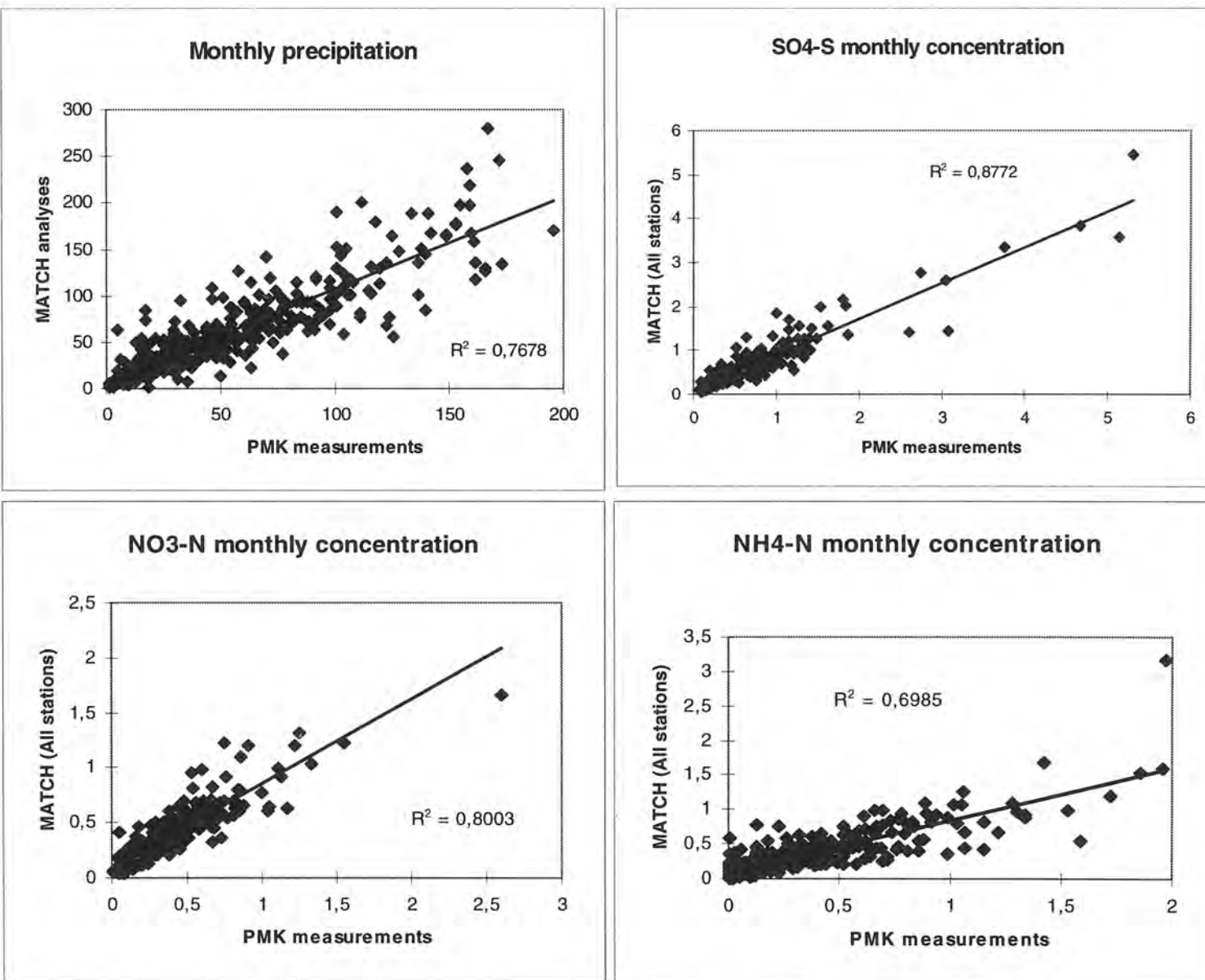


Figure 25. Scatter plots showing PMK-measurements compared to MATCH-estimates based on all stations. Monthly data, 1994, for precipitation amounts (mm/month) and concentration in precipitation of $\text{SO}_4\text{-S}$ (mg S/L), $\text{NO}_3\text{-N}$ (mg N/L), $\text{NH}_x\text{-N}$ (mg N/L).

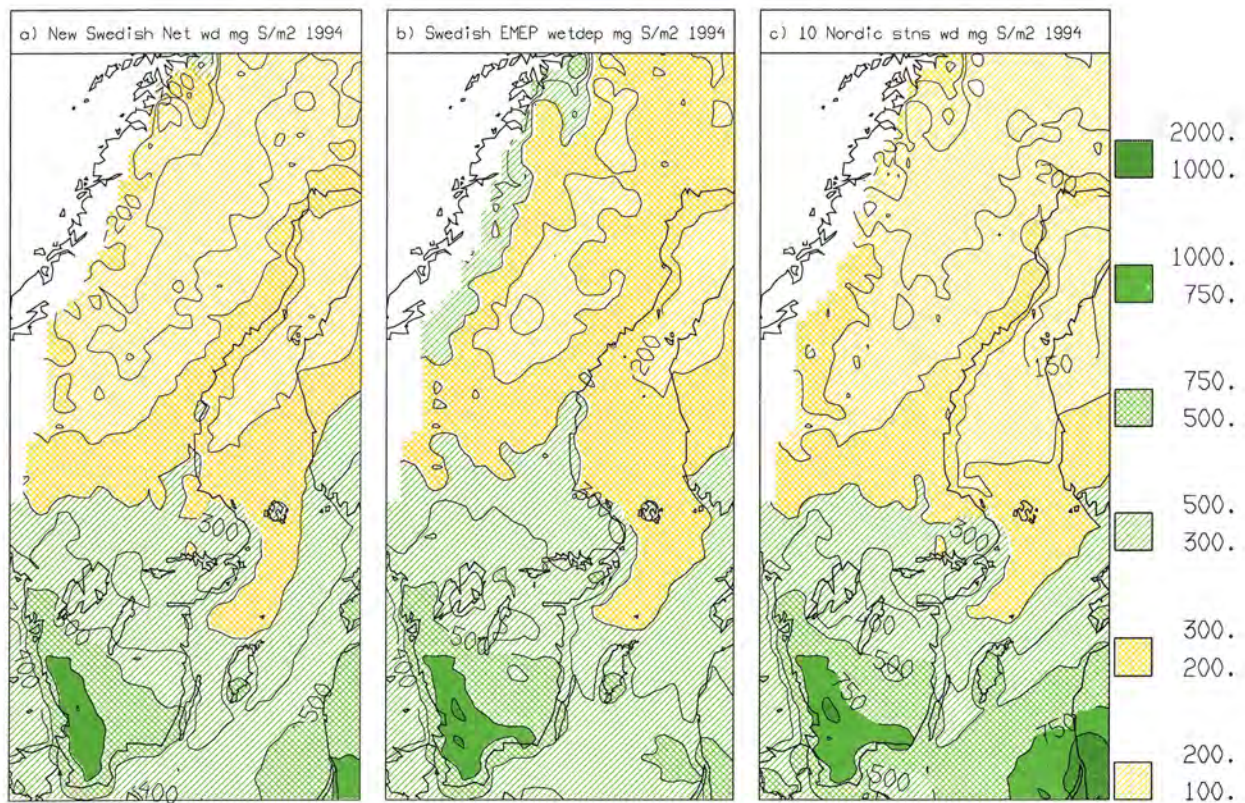


Figure 26. Comparison between MATCH-estimated annual, 1994, wet deposition of sulphur based on a) New proposed Swedish network b) Swedish EMEP stations c) 10 Nordic stations outside Sweden. Units: mg S/m². Isolines: 5, 10, 25, 50, 100, 200, 300, 400, 500, 600, 750, 1000, 1250, 1500, 2000.

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Swedish Meteorological and Hydrological Institute
S-601 76 Norrköping, Sweden. Tel. +4611158000. Telex 644 00 smhi s.

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