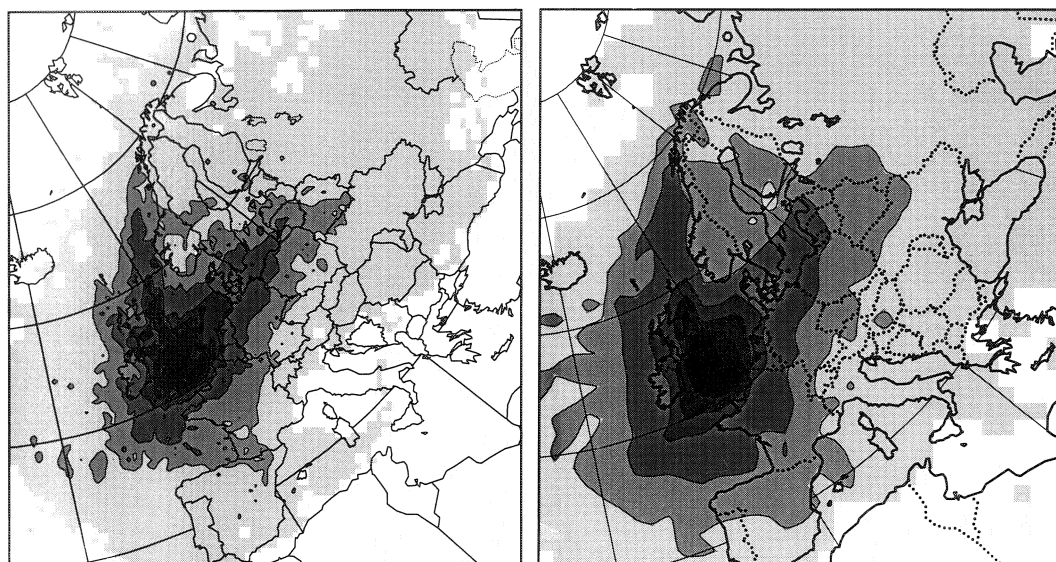


emep

Co-operative programme for monitoring
and evaluation of the long range
transmission of air pollutants in Europe

**The Receptor Oriented One-layer
Trajectory acid deposition model with
50 km x 50 km spatial resolution.**

**Preliminary results and model
intercomparisons.**



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EMEP/MSC-W Note 2/95

Date: July 1995

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Det Norske Meteorologiske Institutt

Research Report no. 20

ISSN 0332-9879

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PREFACE and ACKNOWLEDGEMENTS.

During the last year work has been performed to increase the horizontal resolution of the operational acid deposition model at EMEP/MSC-W. This work has been possible first of all because of the large computer resources available at the Norwegian Meteorological Institute. Increasing the spatial resolution requires fast computers with large internal memory. Optimization of the Fortran code is vital for numerical models of this size. Anstein Foss at The Norwegian Meteorological Institute has contributed significantly to optimize the model Fortran code. This was the first step that made it possible to run the Receptor Oriented One-layer Trajectory (ROOT) acid deposition model with a 50km x 50km horizontal resolution. The model is now optimized for running at the CRAY supercomputer at the Technical University in Trondheim, Norway.

This work has benefitted from the assistance of Helge Styve in preparing input data.

The author specially appreciates the landuse raw-data made available by RIVM (National Institute of Public Health and Environmental Protection, Netherlands) and the work of Addo van Pul (RIVM), Asgeir Sorteberg (University of Bergen, Norway) and Juha Pekka Tuovinen (Finnish Meteorological Institute) improving the deposition module.

I am particularly grateful for the discussions with all in the EMEP/MSC-W group, with special gratitude to Dr. Erik Berge, Øivind Seland and Dr. Hugo Jakobsen who provided data for the model intercomparisons.

1. INTRODUCTION

Since 1991 the meteorological data have been available from the meteorological archive at DNMI (Norewegian Meteorological Institute) in a 50km grid. In the last year, emission data in the 50 km grid have also become available for many European countries in accordance with the reporting requirements under the Convention. Up to now about 17 countries have reported sulphur emissions, 16 countries have reported NO_x emissions and 12 countries have reported ammonia emissions in a 50km grid for at least one year (Berge *et. al.* , 1995)

The draft programme for the sixth phase of EMEP (1995-1998) EB.AIR/GE.1/R.96 states that : “ *The resolution in space of the Lagrangian model will be increased to 50 km x 50km as soon as new emission inventory information becomes available* ” .

This note is a status report of this work showing some preliminary results for January and July 1992. The first version of the ROOT (Rceptor Oriented One-layer Trajectory) model with the resolution of 50 km x 50 km presented here will be under continuous improvement in the future. In particular some of the input data will require improvements and also some model processes depending on the grid size will require further investigation.

In the following ROOT-150 model refers to the operational trajectory model with horizontal resolution of 150 km (Barrett *et.al*, 1995), while ROOT-50 refers to the version with a horizontal spatial resolution of 50 km. Both ROOT model versions calculate concentrations and depositions of sulphur and nitrogen components with country allocations.

In parallel, MSC-W has under development an Eulerian model with 50 km horizontal resolution. It is important to consider the development of one of the 50 km models as supplementary to the other. The ROOT-50 model can now make use of the 50 km emission data of sulphur, oxidized and reduced nitrogen for country allocation purposes. This is presently not feasible with an Eulerian model. On the other hand, the aim of the Eulerian model is to improve European deposition maps in the future and to couple acidification to photochemical oxidants in order to support work with multi-pollutant protocols.

The aim of the ROOT-50 model is to make use of detailed emission, meteorological and land-use data to achieve an improved deposition map.

The first phase of this work has been preparation of necessary input data and to make the ROOT-50 model able to produce results “technically” i.e. to handle problems like memory use and computer time.

With regard to it's technical performance the current model version uses about 4 1/2 hour CPU time and about 240 Mbytes internal memory (each number is represented by 8 bytes) to produce one month of concentration and deposition data on a CRAY supercomputer. The main reason for the rather extensive use of internal memory is because of the country

allocation (at present maximum 60 allocation areas) of every chemical component (10 components in three phases : air concentrations, dry and wet deposition) in every arrival point (at present about 10800 points) . In addition there is also a possibility in some cases to make the code run faster by using more internal memory i.e. some of the calculations can be done once and stored in arrays instead of being calculated several times.

Short about the model development :

As a part of the EMEP (European Monitoring and Evaluation Programme) calculations of transboundary air pollution in Europe have been carried out at MSC-W (Meteorological Synthesizing Centre West). This programme was launched in 1977 as a continuation of the OECD programme on Long Range Transport of Air Pollutants. The concept of using a one-layer trajectory model with pollutants assumed to be well mixed in the boundary layer has been utilized since then.

The first model version included sulphur chemistry and the trajectories were calculated by using analysed wind fields (Eliassen and Saltbones, 1975; OECD, 1977 ; Eliassen, 1978). Since then several improvements have been introduced;

- Variable transformation rate for SO₂ and a mechanism for exchange of pollution between the boundary layer and the free troposphere (Eliassen and Saltbones, 1983).
- Utilization of meteorological data from the Numerical Weather Prediction (NWP) model at DNMI and use of a deposition velocity at 1 m depending on season and latitude (Eliassen et. al., 1988)
- Extension of the chemical scheme by the most important components of oxidized and reduced nitrogen (Hov *et. al.*, 1988; Eliassen *et. al.* 1988; Iversen 1990).
- Sub-grid scale parametrization of wet removal (Eliassen and Saltbones, 1983, Iversen et.al 1990) and more realistic fields of background concentrations (Iversen *et.al.* 1990).
- Inclusion of natural sulphur emissions from seas (Tarrason, 1991; Sandnes and Styve, 1992)
- Inclusions of new emitter regions (following the political changes in Europe) and extension of the calculation domain (Sandnes, 1993)
- New dry deposition module for SO₂, NH₃ and HNO₃ and a variable local correction factor for sulphur emissions. (Tuovinen and Krüger, 1994, Seland *et.al.*, 1995, Barrett *et.al.* 1995)

2. MODEL FORMULATION.

A complete description of the operational ROOT-150 model with nitrogen and sulphur chemistry (150km x 150km resolution) is given in EMEP/MSC-W Report 1/95 (Barrett *et.al.*, 1995). Most of the model formulation is the same for the ROOT model with 50 km resolution. Therefore only a brief summary of the model design is given here.

2.1 Transport and chemistry.

The trajectories are calculated from wind field at a level representing the average transport within the atmospheric boundary layer (height about 550m). The **advection time step** along each trajectory is reduced from 2 hours in the 150 km model version to 30 minutes in the 50 km model version. During the transport, emissions from the underlying surface, chemical transformations and dry and wet removal are taken into account. The chemistry time step is 15 minutes in both model versions. There is also an exchange mechanism of air between the boundary layer and the free troposphere, where pollution either can escape from the boundary layer or pollution can be mixed down into the boundary layer (Eliassen and Saltbones, 1983).

The trajectories arrive every 6. hour to a set of grid points regularly spaced in a 50 km by 50km grid (the subgrid shown in fig. 1) and to a set of measurement points

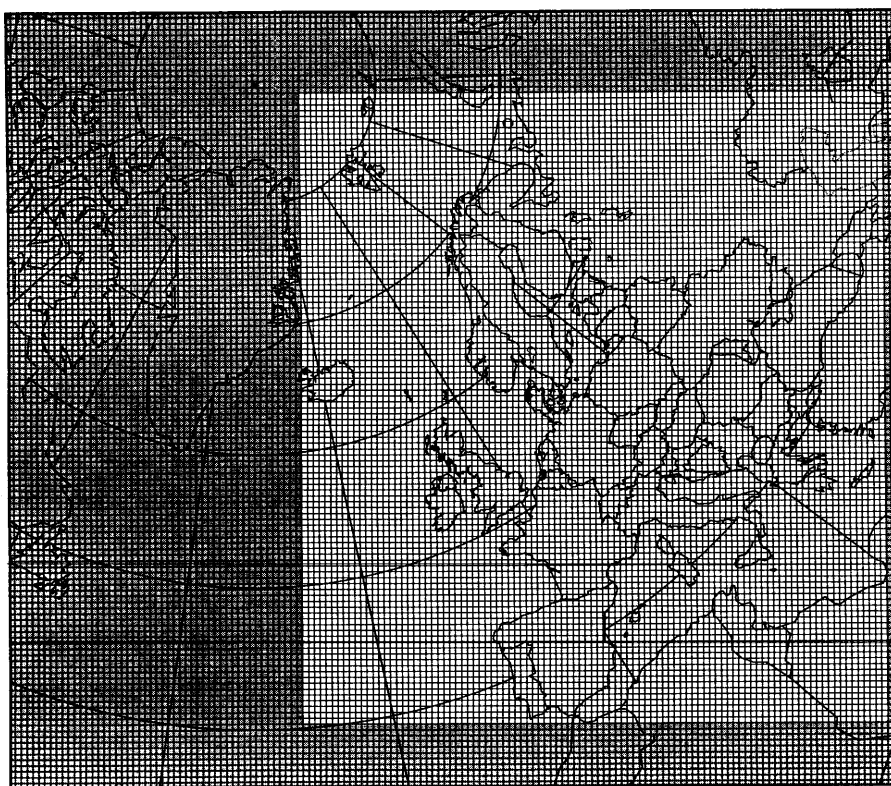


FIGURE 1. The EMEP grid with 50 km x 50 km resolution. Pollutants are followed within the whole domain (151 x 133 = 20083 grid points). Concentration and deposition fields are obtained in the white area (99 x 108 = 10692 grid points).

The model domain covers a larger area in the 50 km version of the ROOT model. Therefore it is now possible to **cover the whole of Spain and Portugal** with concentration and deposition calculations. The model domain is limited by the domain of the input meteorological data. After June 1995 this area will be extended so in the future it will also cover Cyprus.

The ROOT-model calculates country allocated concentrations, and depositions for 10 chemical species : nitric oxide (NO) , nitrogen dioxide (NO₂) , peroxyacetylnitrate (PAN), nitric acid (HNO₃) , ammonium nitrate (NH₄NO₃) , ammonium sulphate ((NH₄)_{1.5}SO₄) , sulphur dioxide (SO₂) and particulate sulphate (SO₄) . The chemical reactions are summarized in figure 2.

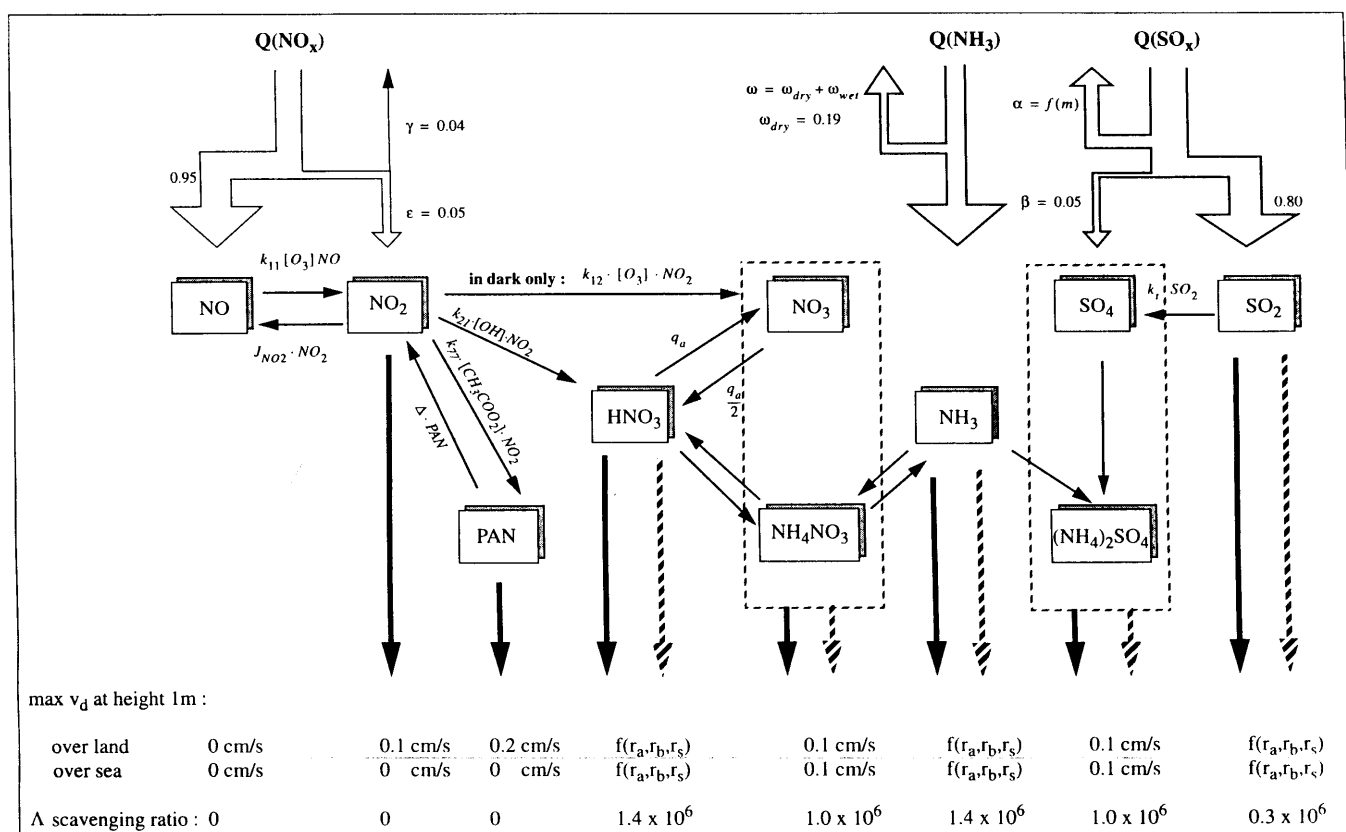


FIGURE 2. Overview of the chemical scheme including emission and deposition pathways. The concentrations of the 10 components inside solid boxes are calculated by the model. The concentrations of the components denoted in brackets are prescribed parameters. The two dashed boxes denote nitrate and sulphate particles, which both occur in two different forms in the model. For further details see Barrett *et.al.* 1995.

2.2 Dry deposition

2.2.1 Deposition velocities.

For SO₂, NH₃ and HNO₃ the new deposition module developed at RIVM is used. This module can well be adopted by a 50km version since all the input data have 50 km resolution. The module uses the meteorological data and landuse data to calculate the aerodynamic, laminar and surface resistances. (Seland *et. al.*, 1995).

For the other components (NO₂, PAN, Nitrate and Sulphate particles) deposition velocities at 50m height are estimated by the methodology previously employed at MSC-W, involving an estimate of the aerodynamic resistance up to 50m, and prescribing a deposition velocity at 1 m height. The 1-meter deposition velocity has a seasonal, diurnal and latitude variation (Barret *et. al.*, 1995) as a simple parameterization of the surface conditions.

2.2.2 Local deposition

The model assumes emissions to be instantaneously mixed in the air up to the mixing height. This leads to a systematic underestimation of ground level concentrations near emission sources and hence the dry deposition as well. Therefore a correction factor is used implying that a certain fraction of the emission is deposited locally inside the same grid square as emissions take place.

At the moment these correction factors are calculated with the same method as in the ROOT-150 model. For NO no local deposition is considered, for NO₂ the local deposition factor is 4% (of the emissions), for NH₃ 19% and for sulphur the new alfa-module is used (Tuovinen and Krüger 1994). These values are used just as a first approximation. It is expected that these local deposition factors depend on the horizontal grid resolution, however in the next phase of the work with the ROOT-50 model, more effort will be put into improvement of the local deposition factors.

2.3 Wet deposition

The wet removal, parameterized using scavenging ratios, depend on the components capacity to dissolve in water. The amount which is wet deposited depends on the scavenging ratio, the precipitation amount and on the probability at any given point inside one grid square to be hit by precipitation.

The precipitation data used in the ROOT-50 model are data from the NWP model over the whole domain, while the ROOT-150 model uses analysed precipitation fields based on observations over land areas.

The sub-grid distribution of precipitation is taken into account by using a probability function giving the fraction of the grid square that becomes wet when it rains somewhere in the

square. In the 150 km model version the wet area probability function is a function of the precipitation intensity. This function was made specially for a model with spatial resolution of 150 km. In the ROOT-50 model cloud cover is used to give the part of grid square area assumed to be wet. The advantage of using cloud cover is that the effect of stratiform and convective precipitation can be reflected. Fig. 3 show an instantaneous picture of precipitation, and figure 4 shows the wet area probability function (i.e. cloud cover) at the same moment. Frontal areas can be seen with cloudiness above 90%. In areas with more convective activities, i.e. behind large frontal systems, the cloud fraction is smaller. Minimum wet area is set to 10% of the grid under precipitation.

Since many of the components are very sensitive to the precipitation amount and distribution, these data have to be examined further in the next phase of the work

FIGURE 3. Precipitation. Date : 2/1-92 Time: 1800 Unit : mm

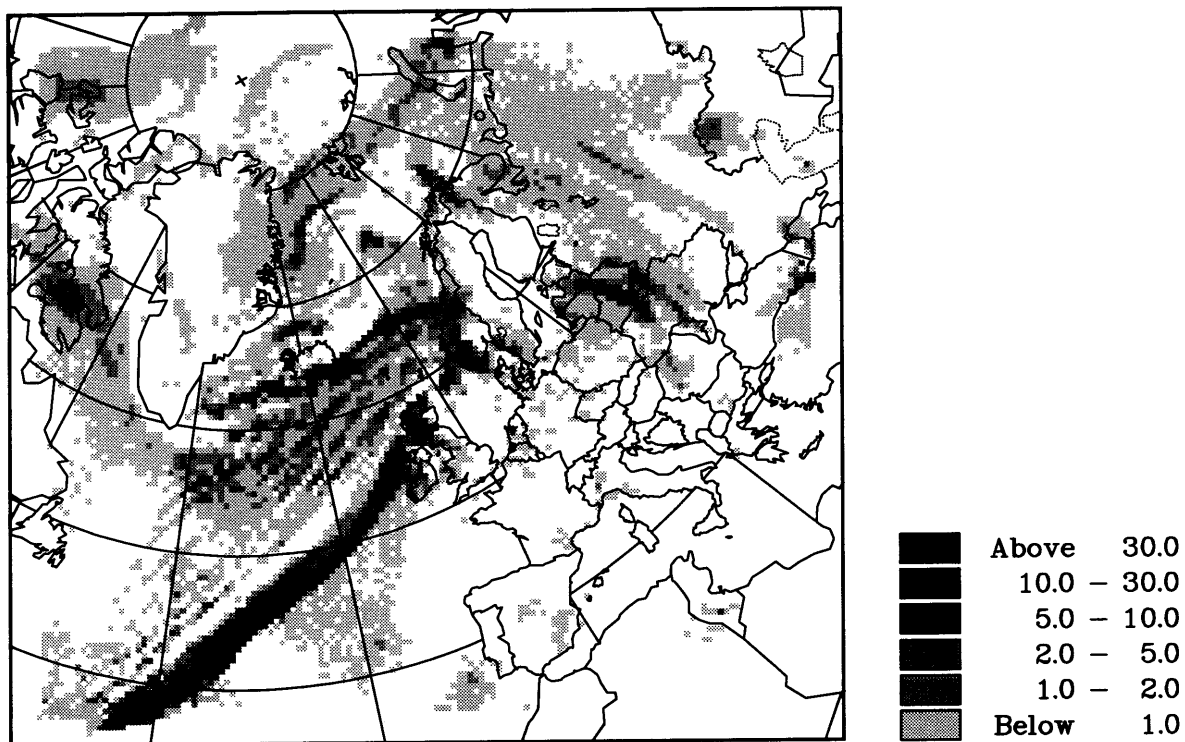
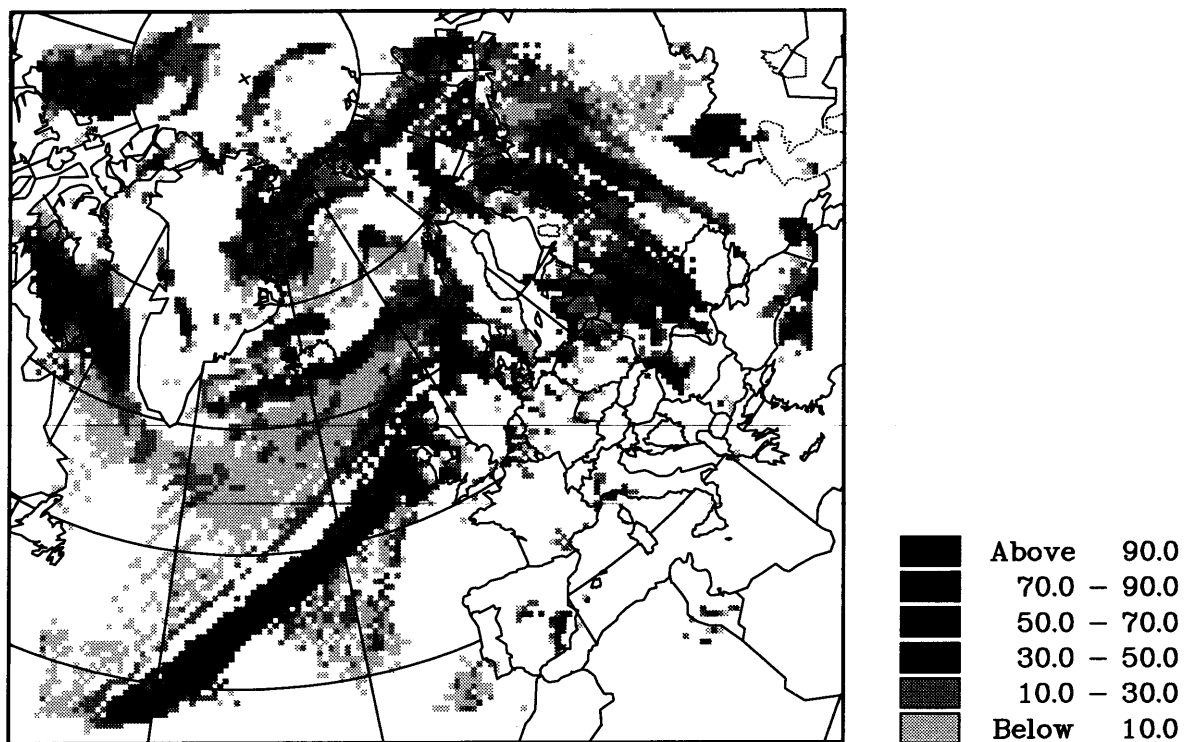


FIGURE 4. Wet area probability function (cloud cover) . Date : 2/1-92 Time: 1800 Unit : % of grid square areal.



3. INPUT DATA.

3.1 Emissions

Details and more information about the emissions can be found in EMEP/MSC-W Report 2/95 (Berge *et.al.*, 1995) and in EMEP/MSC-W Report 1/95 (Barret *et.al.*, 1995).

The model uses yearly emissions in every grid square for each country contributing in the actual grid square. A seasonal variation is then imposed in the form of a sine function with a maximum 1.33 on 1. January and minimum of 0.67 on 1. July. This function is used to calculate the seasonal variation of sulphur and high NO_x emissions (except for natural DMS emissions which have a monthly variation given by Tarrason, 1991). Low NO_x emissions are assumed to have no seasonal variation. Ammonia emissions are assumed to have a minimum of 0.7 in winter and maximum of 1.3 in early summer.

These seasonal variations do not vary with latitude or source category (except for high-low NO_x). It seems that one weak point in the emission data set at the moment is that we do not have any detailed information on the seasonal emission variation.

The emissions used here are exactly the same emissions as the ROOT-150 model use for 1992 (in sum for each country). Distribution of emissions are of course somewhat different., due to higher spatial resolution.

For the countries that have **not** reported emissions in a 50 km by 50 km grid the emission in the 150 km by 150 km were just split-up and distributed to each of the 50 km grid squares that belongs to the actual country. When doing this approximation a problem occurs in 150 km grid squares covering both land and sea. Some of the 50 km grid squares inside this 150km grid square were either pure sea or pure land grid squares. Ammonia emissions in such a 150 km grid square was then distributed to the 50 km grid squares containing land areas. For the natural DMS emissions in such land-sea 150 km grid squares, the emission was just divided by nine and set to zero in the 50 km grid squares with no sea area. For oxidized nitrogen and anthropogenic emitted sulphur the emissions was equally distributed in the nine 50 km grid squares, since these emissions could have been released both over sea and over land.

FIGURE 5. Emissions of sulphur dioxide in 1992 (unit : 100 tonnes of SO₂)

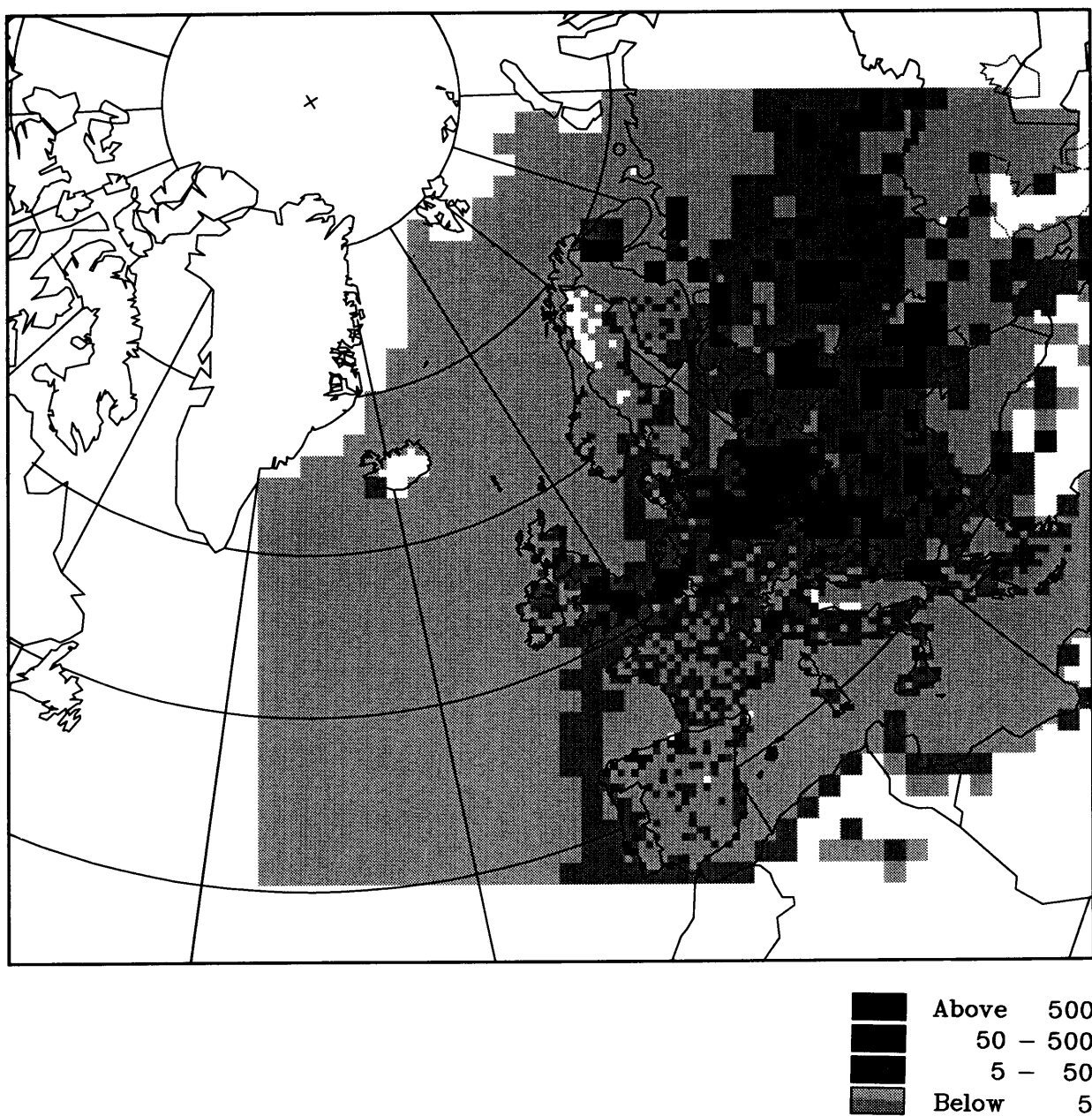


FIGURE 6. Emissions of nitrogen dioxide in 1992 (unit : 100 tonnes of NO₂)

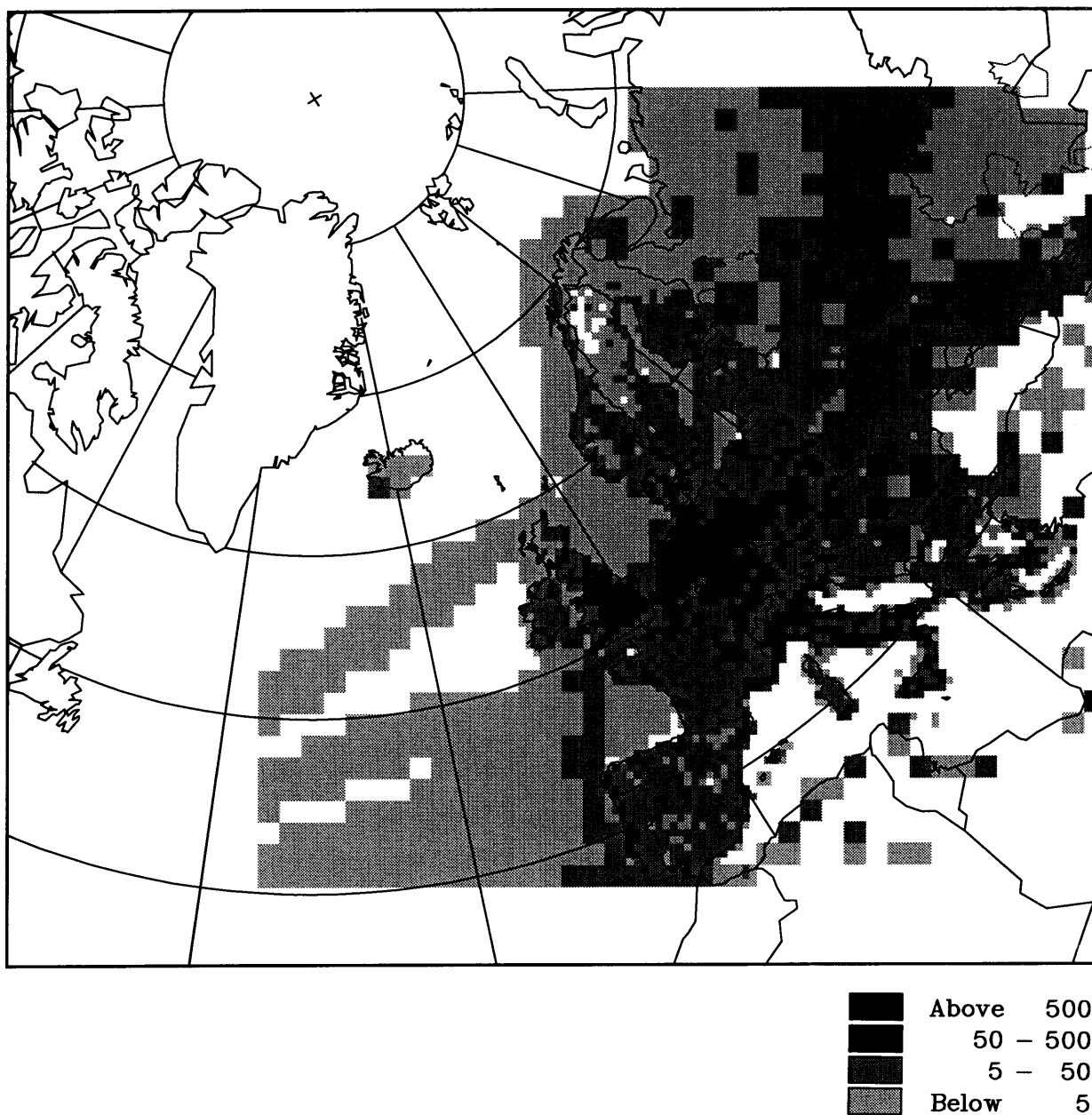
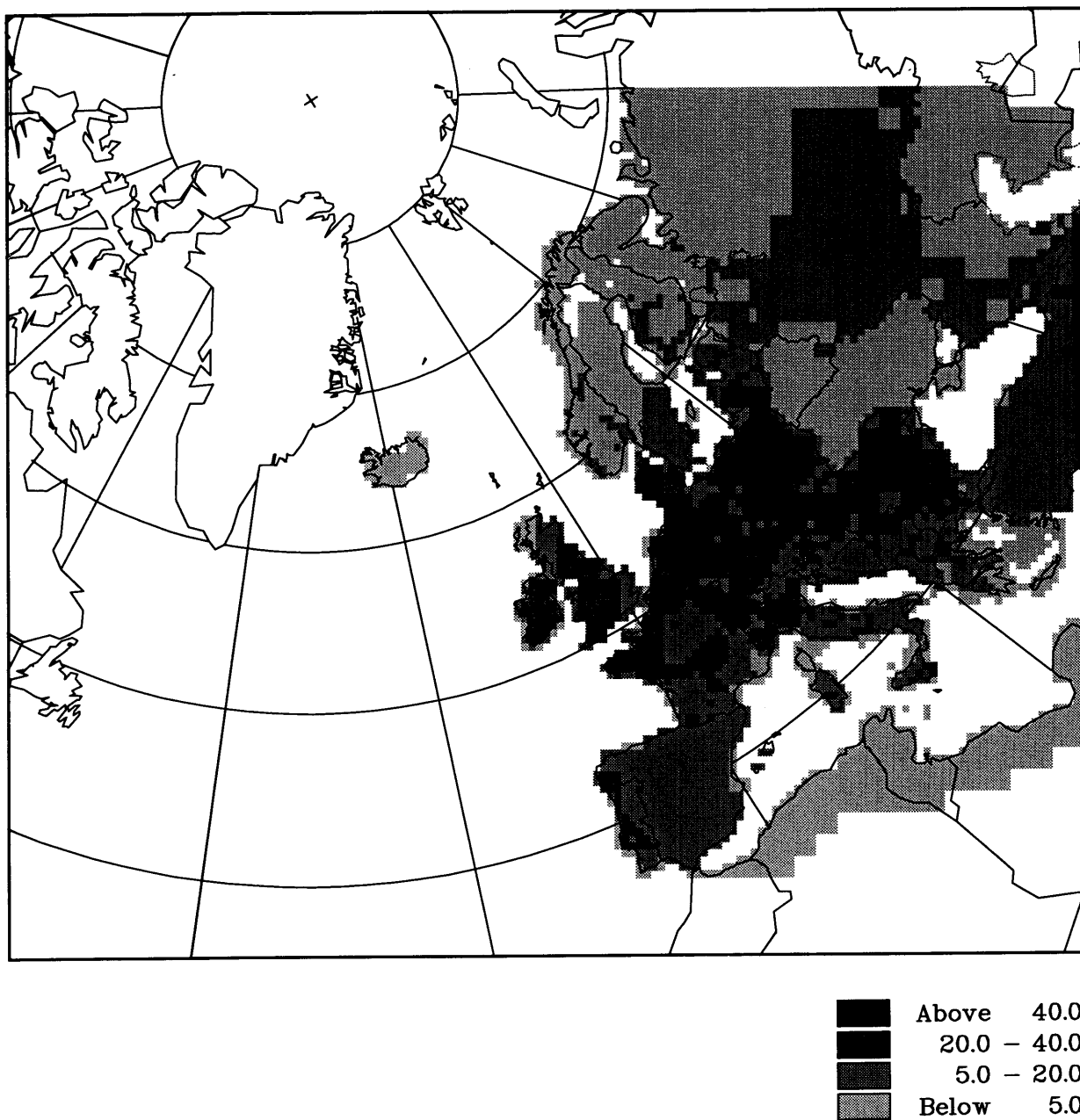


FIGURE 7. Emissions of ammonia in 1992 (unit : 100 tonnes of NH_3)



3.2 Meteorological data

The meteorological input data to the high resolution ROOT model is based on 6 hourly fields produced by the Numerical Weather Prediction model (NWP) at the Norwegian Meteorological Institute (DNMI). Since May 1991 these data have been stored every 6 hour in 20 layers with 50 km horizontal resolution. More details about the data are found in Barrett *et.al.*, 1995..

The operational ROOT-150 model uses analysed fields of observed precipitation over land areas, while the ROOT-50 model uses precipitation fields from the NWP model in the whole domain. This precipitation field is also used by the Eulerian 50 km model. The quality of these precipitation fields are described in Jakobsen *et.al.*, 1995.

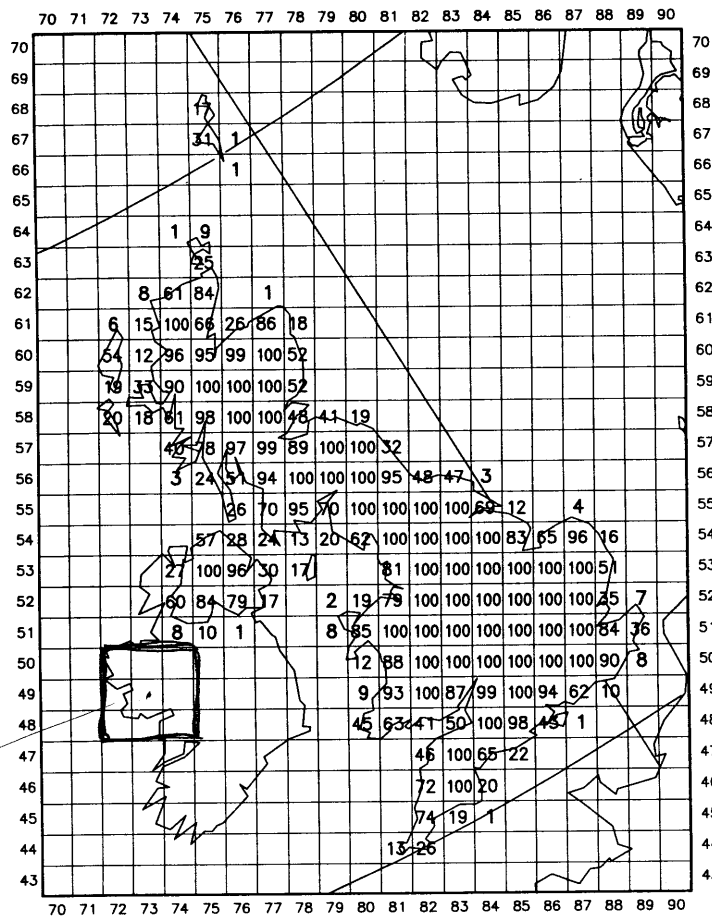
For this preliminary run the fields for mixing heights (hmix) were only available in the 150 km grid. The fields are based on analysed fields from radiosonde observations in Europe. Since the 50 km grid covers a larger area than the 150 km grid, hmix outside the 150 km area is just set to the initial value of 1000 m. This is of course a rather crude estimate but no better data set was available at the moment. A method calculating the mixing height in a 50 km grid has now been developed (Jakobsen *et.al.*, 1995) and shows promising results. As soon as possible these new mixing height data will be utilized in ROOT-50.

3.3 Other input data

3.3.1 Land area grid fractions

To be able to calculate the amount of pollution deposited in each country or receptor area, the area fraction of each of these areas has to be known in every grid square. These data have not been available before in the 50 km EMEP grid. In the ROOT-150 model these data have been found manually by going through every grid square. In a model with 50 km resolution this task had to be done automatically, because of the amount of grid squares. An algorithm for this purpose has been developed by Helge Styve using the borders of each receiving area. The data are given in % of each grid square. Just as an example the grid square area in the 50 km model for United Kingdom is given in figure 8 .

FIGURE 8. Grid square deposition areal for United Kingdom (% of grid area).



$$\frac{72-34}{3} = \frac{38}{3} = 12.6$$

$$\frac{72-33}{3} = \frac{39}{3} = 13$$

$$\frac{74-33}{3} = \frac{41}{3} = 13.6$$

13, 13

73, 49

$$\frac{73-34}{3} = \frac{39}{3} = 13$$

$$\frac{49-10}{3} = \frac{39}{3} = 13$$

3.3.2 Land-use data

For sulphur dioxide (SO₂), ammonia (NH₃) and nitric acid (HNO₃) a new deposition module is used (Seland *et.al.*, 1995) as explained earlier. One important input data set for this deposition module is the land-use data. Raw data of landuse given in a 1/6 x 1/6 degree grid have been made available by from RIVM. These data have been aggregated to 50 km by 50 km grid squares by MSC-W. In addition some of the landuse classes have been constructed from the NWP model data at DNMI (desert and ice). The RIVM land-use class water consists only of inland water, therefore MSC-W has made a "new" water class consisting of both sea and inland water. This is constructed using the sea area fraction area in each grid square. The land use class "other" is then aggregated at the end as the rest of the grid square area.

The land-use data are divided into 10 different landuse categories : Grass, arable, permanent crops, coniferous forest, deciduous forest, water, urban, other, desert and ice. In Appendix A plot of the land-use data is shown together with some more detailed information about what is included in the different landuse categories. A roughness length Z_0 is allocated to each land-use category, and this value varies in general with the time of year.

The deposition module is the same as in the ROOT-150 model except that the forest landuse category is split up in coniferous and deciduous forest. In ROOT-150 all forest is considered as coniferous forest.

The information about snow cover is also important "land-use" data for the deposition module. These data were taken from the NWP model at DNMI. One data set was constructed for each month giving grid information for snow coverage. The grid squares with snow cover for January and July are shown in Appendix A figure 11 and 12. Because of missing data the snow cover for January is taken from 1991 while the snow cover for July is from 1992.

3.3.3 Background data.

At the moment the high resolution model uses the same background data set as the 150 km model for all components (Barrett *et. al.*, 1995))

The model needs initial values of all 10 compounds in the boundary layer. In addition the model needs background values for all 10 components in the free troposphere. For trajectories starting inside the calculation domain the initial concentrations are found by using earlier calculated concentrations (assimilation). For trajectories starting outside the calculation domain and for the background concentrations in the mixing layer data from other models and from review of measurements are used (Iversen and Tarrason, 1990 ; Fehsenfeld *et.al.* 1988). The model does not include any background concentrations in precipitation.

Concentrations of O_3 , OH and CH_3COO_2 are used in NO_x chemistry reactions. These components are not calculated in but the model uses values taken from a global model (Isaksen and Hov, 1987) with some adjustments towards measurements for ozone (Logan, 1985).

4. PRELIMINARY RESULTS

The ROOT-50 model has been run for January and July 1992 calculating the concentrations and deposition of 10 chemical components, all of them with country allocation. For the same period results from the operational ROOT-150 model (Barrett *et. al.*, 1995) are available with the same type of output data. The multilayer Eulerian 50 km model (Jakobsen *et.al.*, 1995) has been run for the same period twice, first with emissions only from United Kingdom then with emissions from all contributors. Only sulphur components have been calculated in the Eulerian 50 km model for this period.

The ROOT-50 and ROOT-150 models have basically the same formulations. There are some differences in the input data because of different horizontal resolution. As mentioned earlier the precipitation field and the wet area probability function are not the same in the two model versions (chap 2.3 and chap. 3.2).

The Eulerian 50 km model use the same reaction rates for the sulphur chemistry as the ROOT models. This model use precipitation fields from the NWP model (like the ROOT-50 model). The new deposition module from RIVM has not been implemented in the Eulerian model yet. The Eulerian 50 km model is a multilayer model that also includes in-cloud scavenging.

The example of deposition caused by emissions from sources in United Kingdom only is chosen to be presented here, because all three model versions have results using these emissions and because this example illustrates the main problem for the ROOT-50 model at the moment.

In Appendix B the deposition fields (dry and wet depositions) caused by emissions from United Kingdom are presented. For comparison, sulphur depositions results from ROOT-50, ROOT-150 and the Eulerian 50 km model are shown . For nitrogen depositions only data from ROOT-50 and ROOT-150 were available.

The figures in Appendix B show that the deposition pattern from the ROOT-50 model is very similar to the two other models. The transport direction and wet deposition patters seem reasonable for all components. But the main problem seems to be too low deposition values.

Tables 2,3 and 4 contain the accumulated depositions over the whole area for sulphur, oxidized and reduced nitrogen. Table 1 show the actual emissions in the two months January and July 1992.

In January 1992 about 76 % of the emissions are deposited inside the model domain for the two models ROOT-150 and Euler-50 , while only 50% of the emitted sulphur is deposited in the ROOT-50 model.

The local deposition is slightly larger for sulphur in the ROOT-50 model compared to the ROOT-150 model. This is because of somewhat higher alpha values (local deposition corrections) over urban areas with large low level sulphur emissions in the ROOT-50 model.

In July 1992 the EULER-50 model deposits a larger fraction of the emissions compared with the deposition fraction in January. The reason for this is most likely the lower horizontal wind speed in summer compared with wintertime. The ROOT-150 model deposit almost the same fraction of the emissions in summer as in winter (about 75 % of the emissions). On the other hand the EULER-50 model deposits 12% more of the emissions than the ROOT-150 model in July, probably because of the ability in the EULER-50 model to follow the pollution in many vertical layers before deposition occur.

For oxidized nitrogen about 30% of the emission is deposited in ROOT-50, while ROOT-150 keeps track of about 65% of the emissions.

For reduced nitrogen the dry deposition amount is very similar in both ROOT models. The differences in the wet deposition part are possibly influenced by different precipitation fields

The main problem of the ROOT-50 model seems to be loss of mass, especially for those components with relatively long transport distances.

The provisional theory is that this is an effect of the exchange mechanism of air between the free troposphere and the boundary layer. ROOT-150 uses W (vertical velocities) averaged over nine 50km grid squares. As an extreme example we can assume that half these grid squares have positive W , and the rest negative W . The average W in a 150 km grid square can then be around zero. If for example the analysed mixing height field is assumed to be equal at 12 hour in two successive days, the calculated mixing height along a trajectory in the 50 km model version can then be larger than the 12 hour analysed mixing height field, leading to a larger loss of mass to the free troposphere than in ROOT-150. This is expected to be most pronounced for the components with relatively long residence time in the atmosphere like oxidized nitrogen.

In Table 1, the emissions from United Kingdom in the two actual months are presented. For the sulphur emissions the number in parenthesis are the emissions used in the Eulerian 50 km model.

TABLE 1. Emission from United Kingdom, monthly values.

	SO ₂ unit : 1000 tonnes s	NOX unit: 1000 tonnes n	NH ₃ unit : 1000 tonnes n
January	197.1 (206)	83.2	20.7
july	99.3 (104)	58.5	32.6

**TABLE 2. Accumulated deposition of sulphur in January and July 1992.
Contribution from United Kingdom. Local deposition in parenthesis. Unit : 1000
tonnes as sulphur.**

	January 1992				July 1992			
	DRY	WET	TOT	% of emis	DRY	WET	TOT	% of emis
ROOT-50	79.9 (11.3)	18.1	98.0	50	27.7 (9.2)	17.6	45.3	46
ROOT-150	113.0 (7.4)	36.4	149.4	76	36.0 (8.0)	37.0	73.0	74
EULER-50	120.0	38.0	158.0	77	45.6	43.8	89.4	86

**TABLE 3. Accumulated deposition of oxidized nitrogen in January and July 1992.
Contribution from United Kingdom. Local deposition in parenthesis. Unit : 1000
tonnes as nitrogen.**

	January 1992				July 1992			
	DRY	WET	TOT	% of emis	DRY	WET	TOT	% of emis
ROOT-50	11.6 (0.1)	14.3	25.9	31	6.5 (0.1)	11.9	18.4	31
ROOT-150	23.9 (0.1)	32.9	56.8	68	11.9 (0.1)	24.3	36.2	62

**TABLE 4. Accumulated deposition of reduced nitrogen in January and July 1992.
Contribution from United Kingdom. Local deposition in parenthesis. Unit : 1000
tonnes as nitrogen.**

	January 1992				July 1992			
	DRY	WET	TOT	% of emis	DRY	WET	TOT	% of emis
ROOT-50	8.2 (3.9)	6.2 (3.0)	14.4	70	11.9 (6.2)	11.1 (4.9)	23.0	71
ROOT-150	8.8 (3.9)	10.7 (3.1)	19.5	94	12.7 (6.2)	17.4 (5.2)	30.1	92

5. SUMMARY and CONCLUSIONS.

Two months of results have been produced with the receptor oriented one-layer trajectory model on a horizontal resolution of 50 km (ROOT-50). Results using emissions from United Kingdom have been presented just as an illustrating example. The results show that a smaller part of the emissions are deposited in the model domain with the new model compared to the 150 km Lagrangian model (ROOT-15) and the 50 km Eulerian model. (Euler-50). The difference was most pronounced for oxidized nitrogen, specially in summer time. While the difference in depositions was less significant for ammonia. The deposition pattern produced by the ROOT-50 model is qualitatively rather similar to the other models but the magnitude of the deposition seems to be underestimated.

Since the model rather recently has been set up there may still be a possibility for errors in the computer code. However the main impression is that there is a problem connected to the parametrization of the exchange of air between the boundary layer and the free troposphere.

There is room for improving input data and the local deposition module. But these effects seems to be of minor importance compared to the loss of mass described above.

Therefore in the next phase of the work with the Lagrangian model with 50 km resolution (ROOT-50) , the problem concerning the exchange of air on the top of the mixing layer should be given high priority.

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APPENDIX A.

Figures of the ten land-use categories and snow cover used in the dry deposition module :

Figure 1. Grass : Grassland for agricultural use

Figure 2. Arable : Arable land such as temporary crops

Figure 3. Permanent crops : Permanent crops such as vineyards, olives, citrus fruits etc.

Figure 4. Coniferous forest : Coniferous and mixed forest.

Figure 5. Deciduous forest : Broad-leaved forest.

Figure 6. Water: sea and large inland waters

Figure 7. Urban : Large cities in Europe (excluding : airports, large road networks and other build-up areas not directly located within city borders).

Figure 8. Other : unimproved grassland, rocks, swamps and marshland. Zones of very low productivity.

Figure 9. Desert : Desert areal from the NWP model at DNMI

Figure 10 Ice : Ice from the NWP model at DNMI modified by defining also ice over Greenland.

Figure 11 : snow cover january 1991

Figure 12 snow cover july 1992

Figure A1 : GRASS

unit : % of grid area

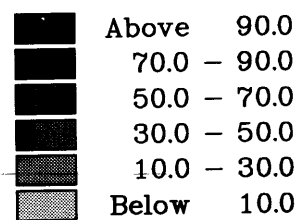
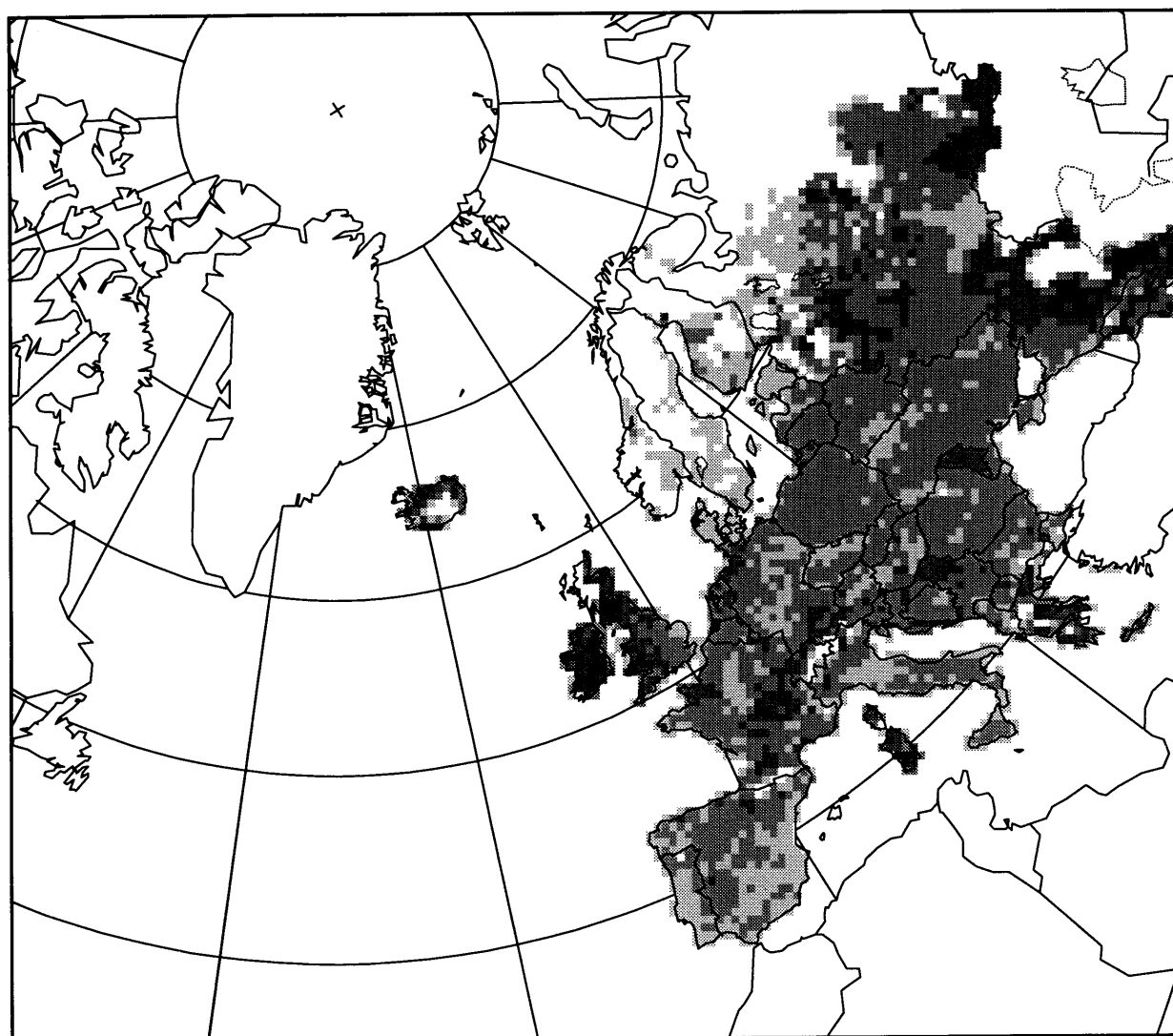


Figure A2 : ARABLE

unit : % of grid area

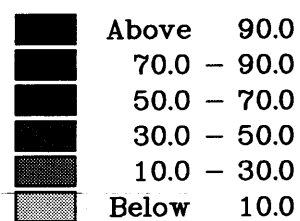
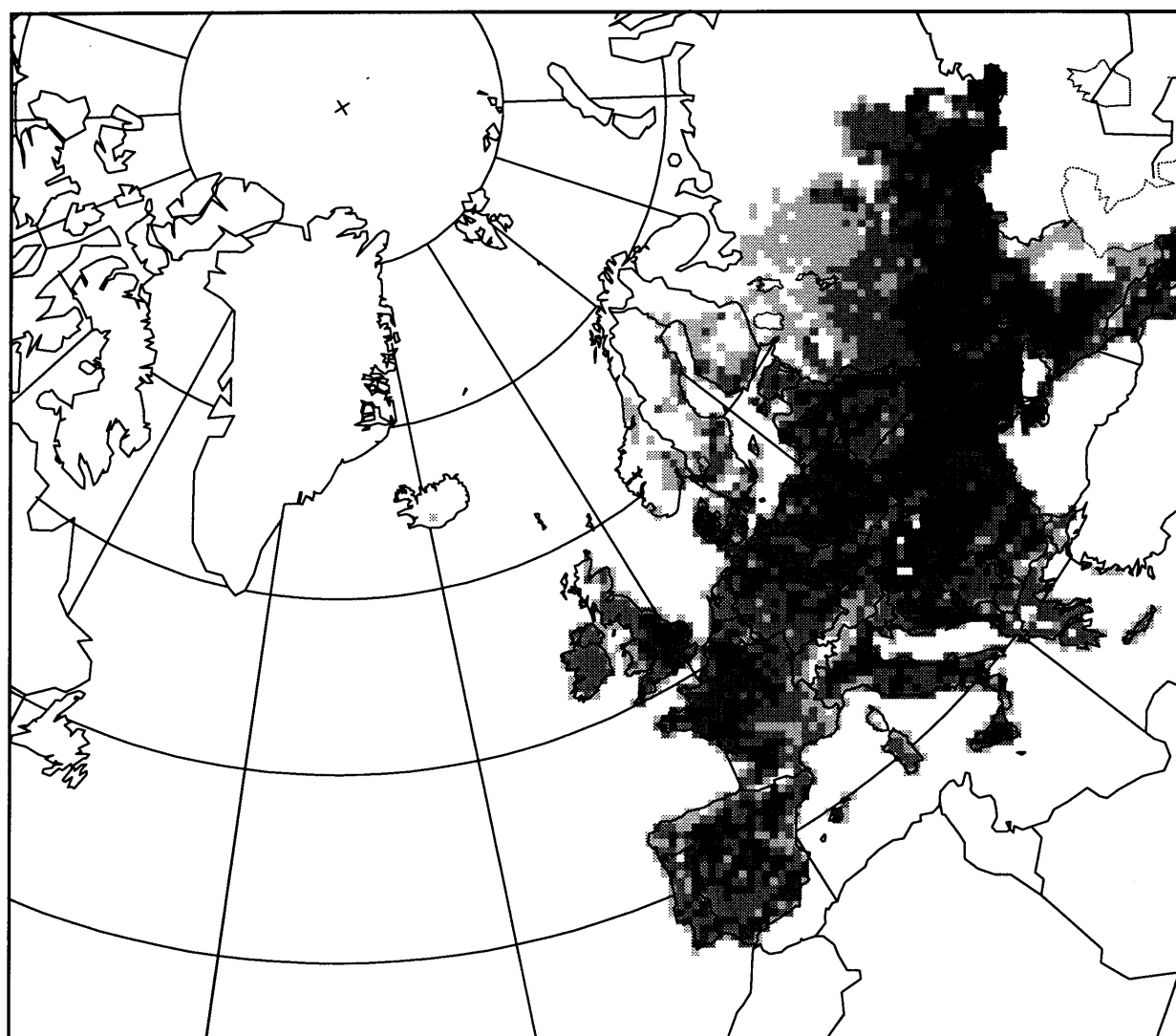


Figure A3 : PERMANENT CROPS

unit : % of grid area

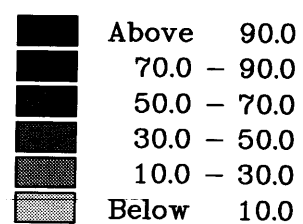
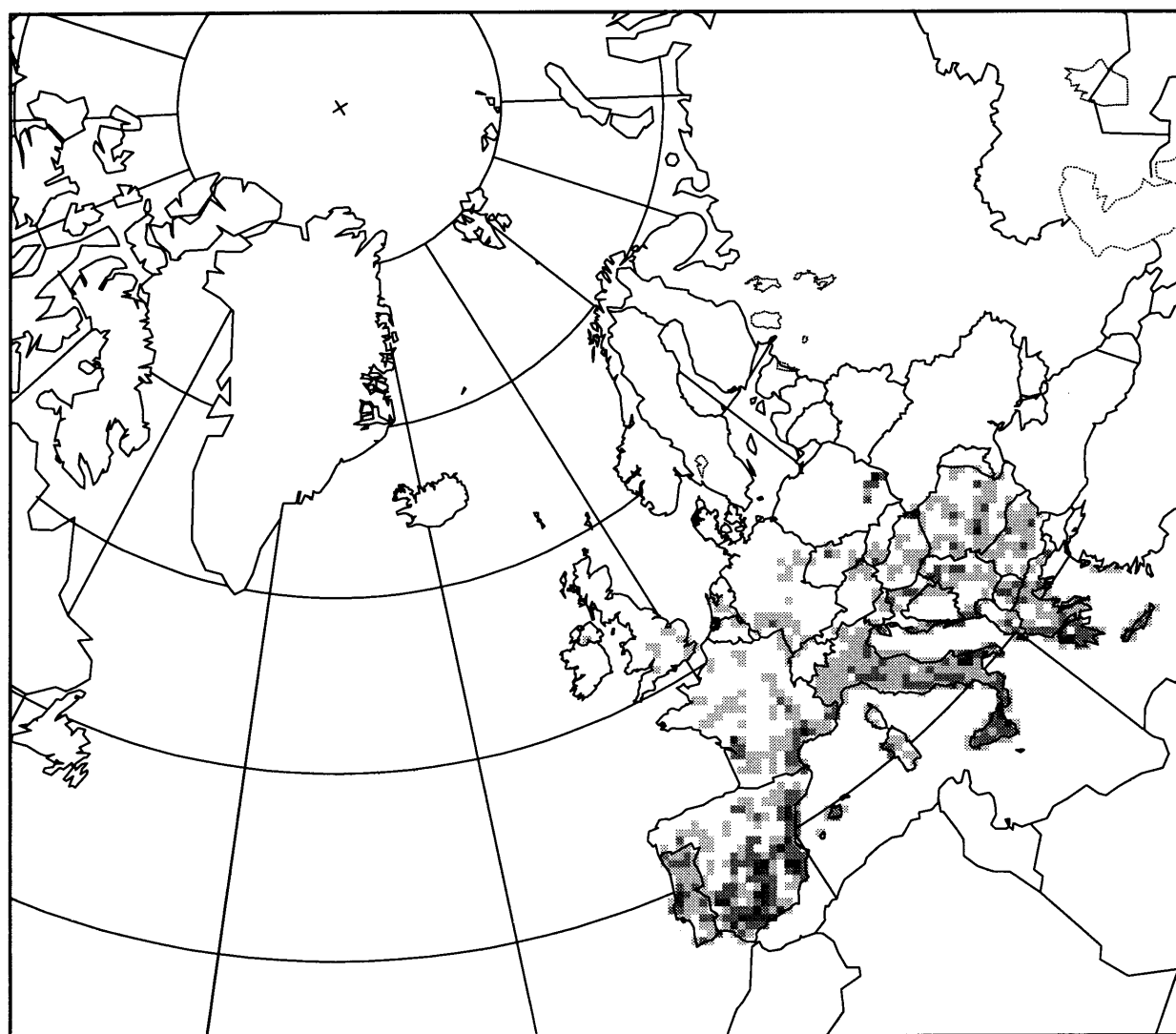


Figure A4 : CONIFEROUS FOREST

unit : % of grid area

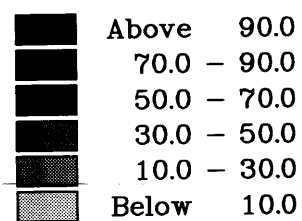
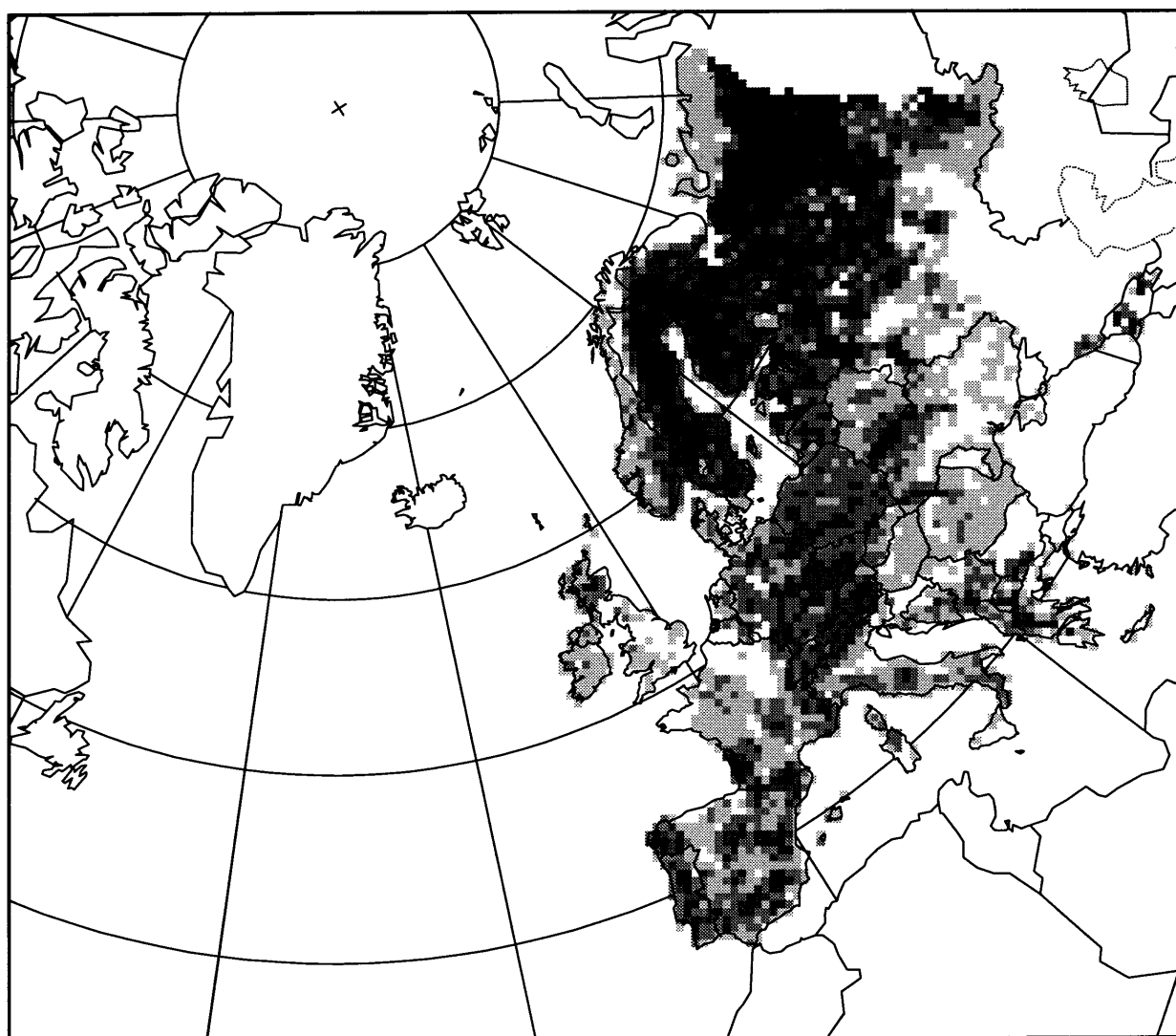


Figure A5 : DECIDUOS FOREST

unit : % of grid area

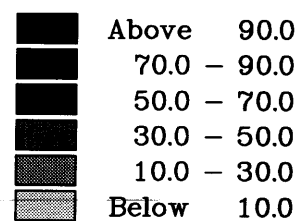
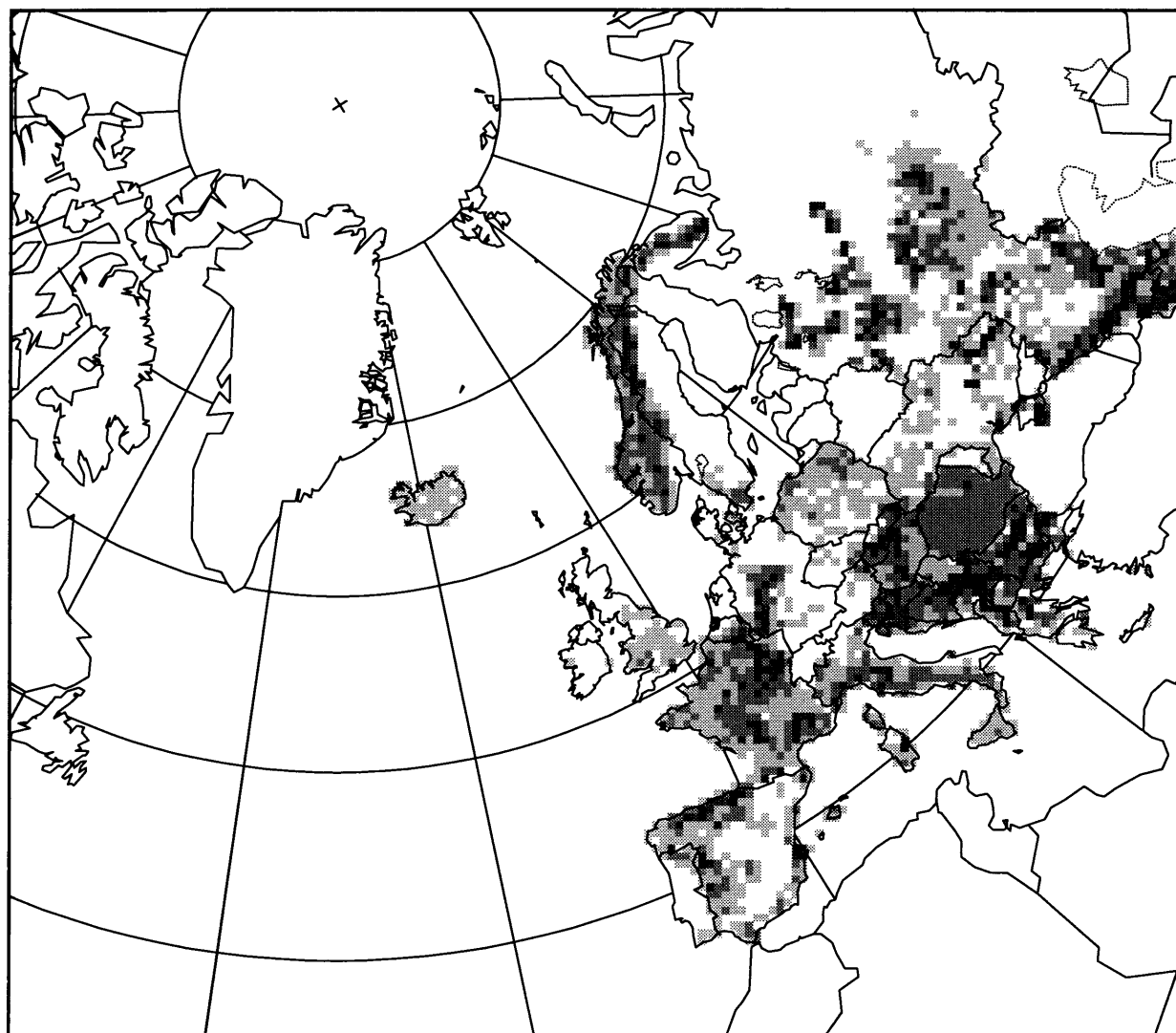


Figure A6 : WATER

unit : % of grid area

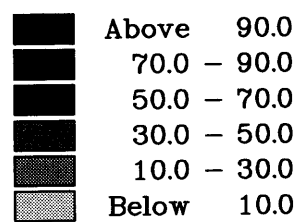
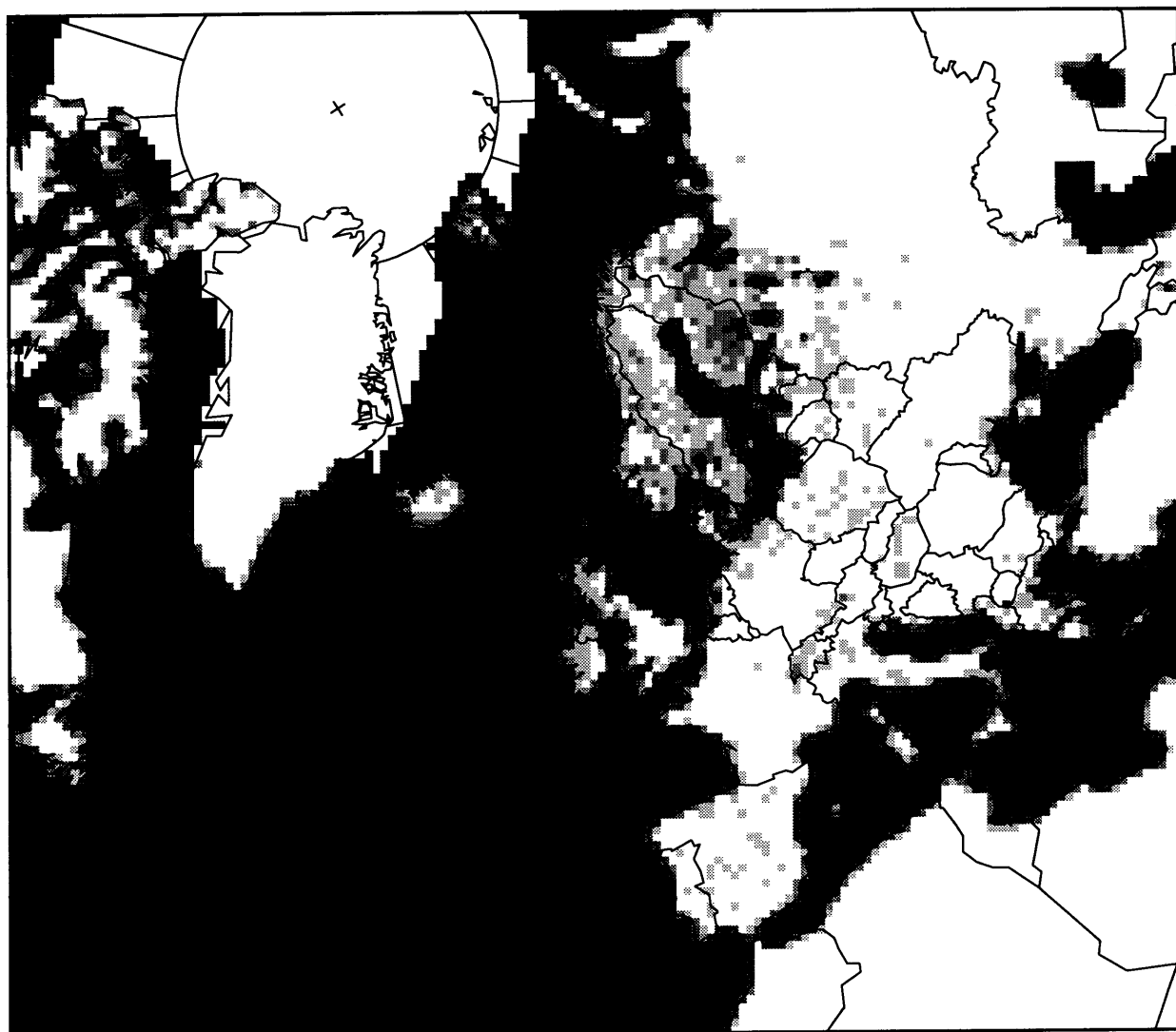


Figure A7 : URBAN

unit : % of grid area

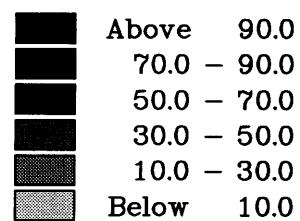
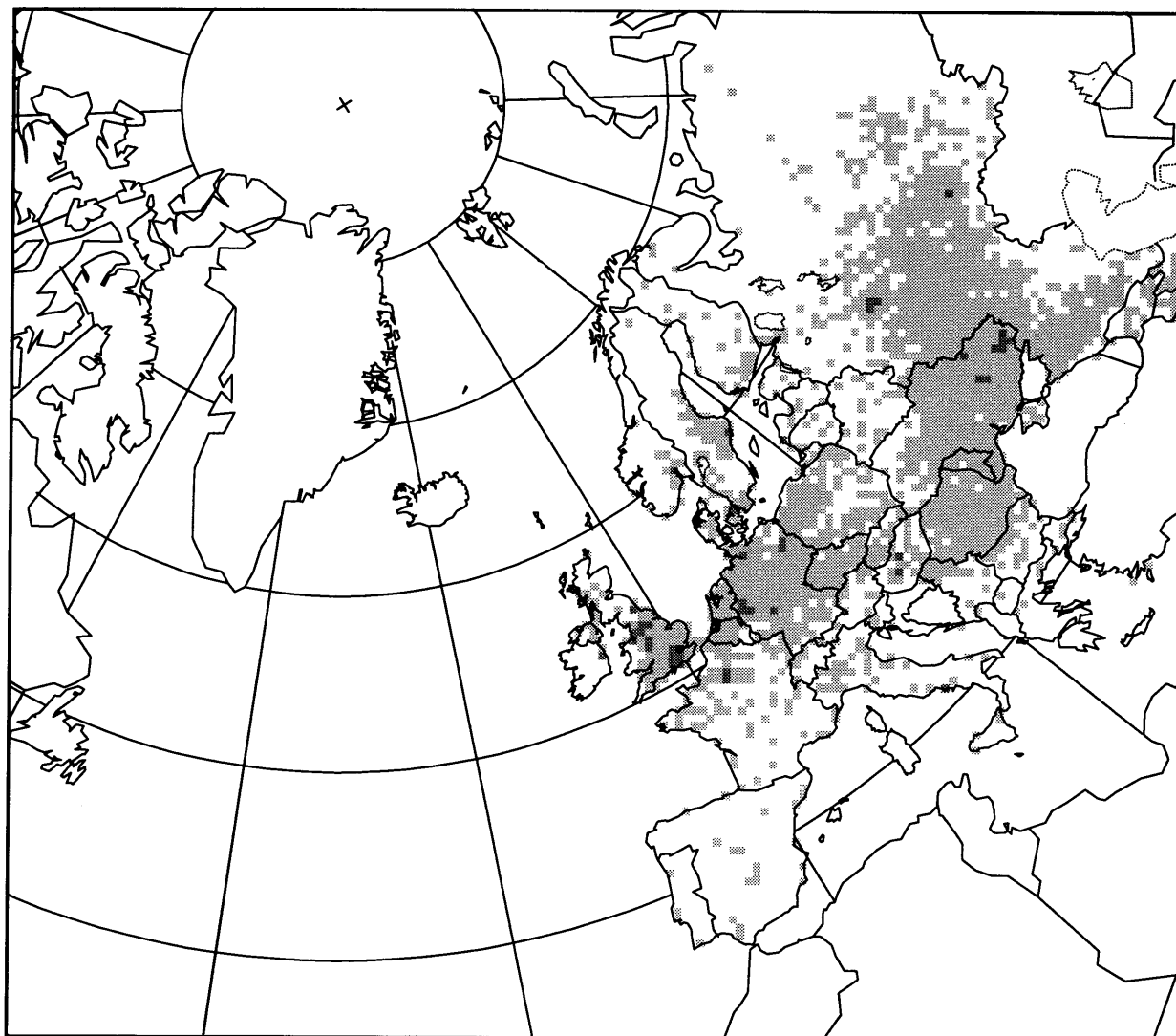


Figure A8 : OTHER

unit : % of grid area

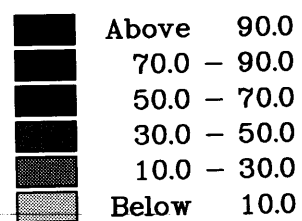
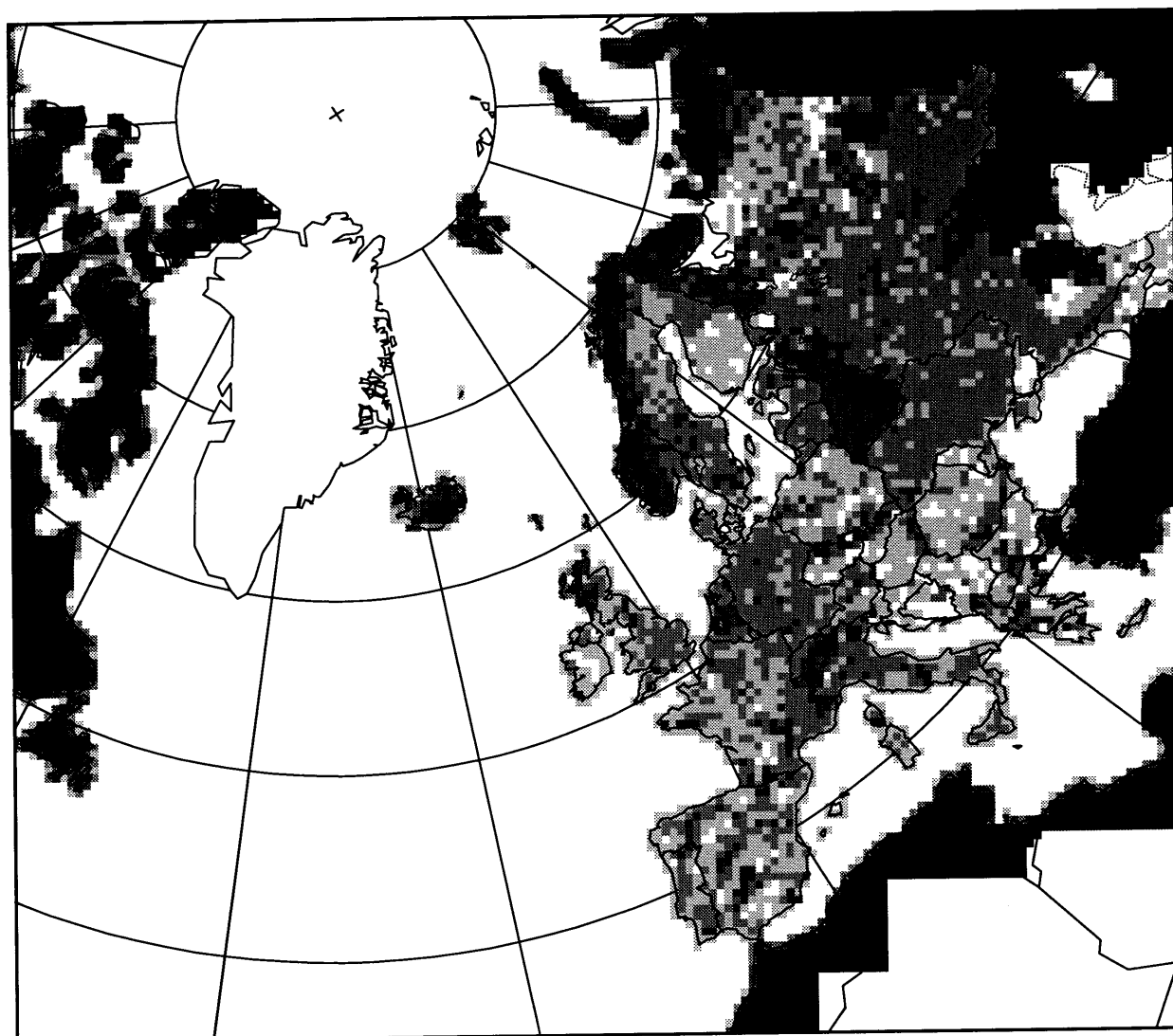
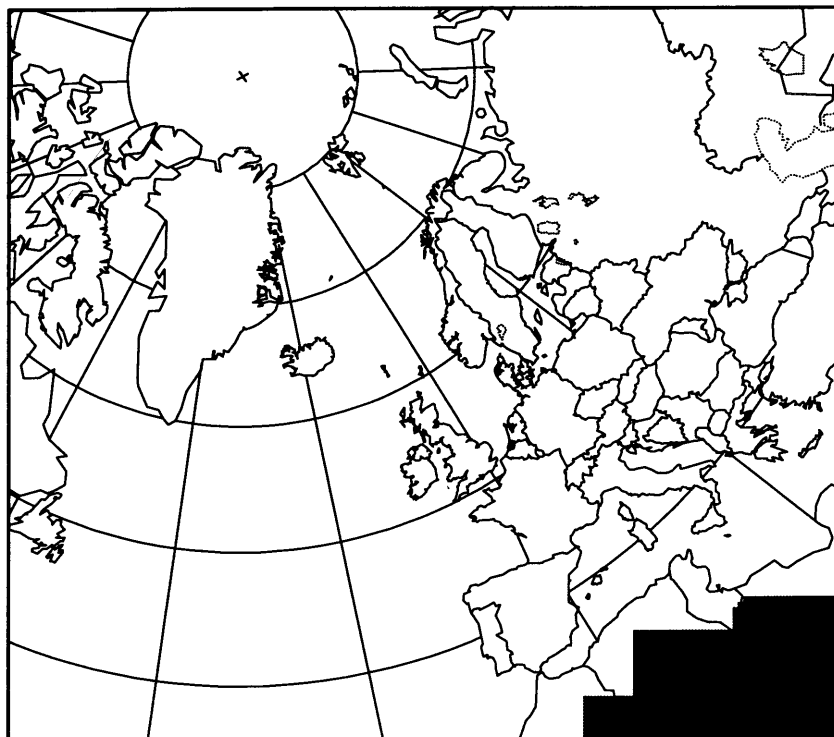


Figure A9 : DESERT



unit :
% of grid area

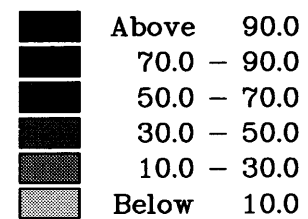
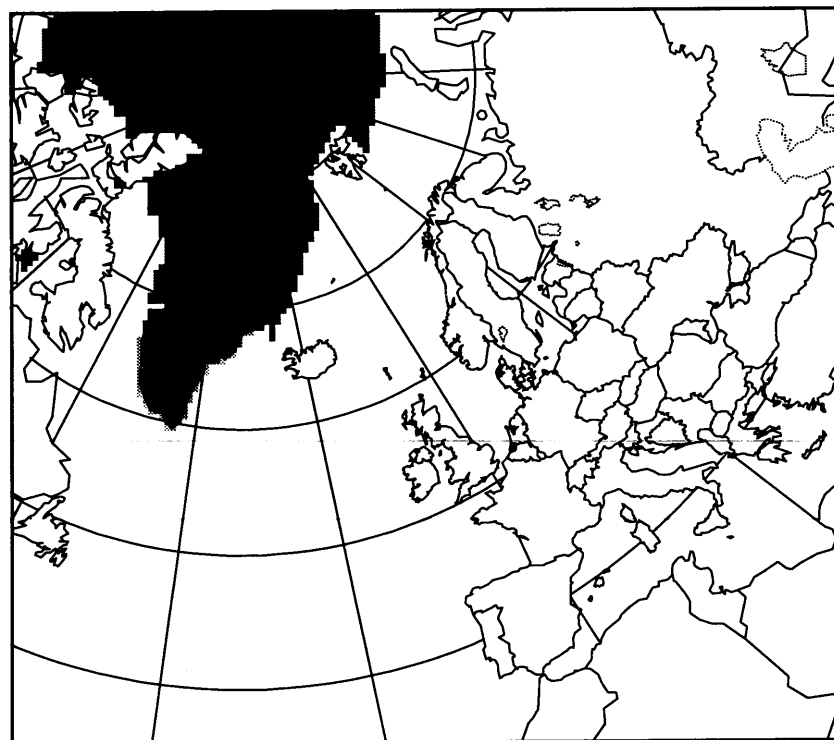


Figure A10 : ICE



unit :
% of grid area

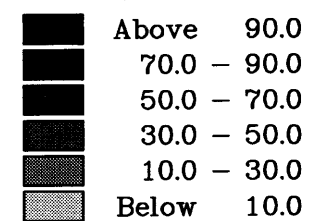


Figure A11 : SNOW COVER – january –

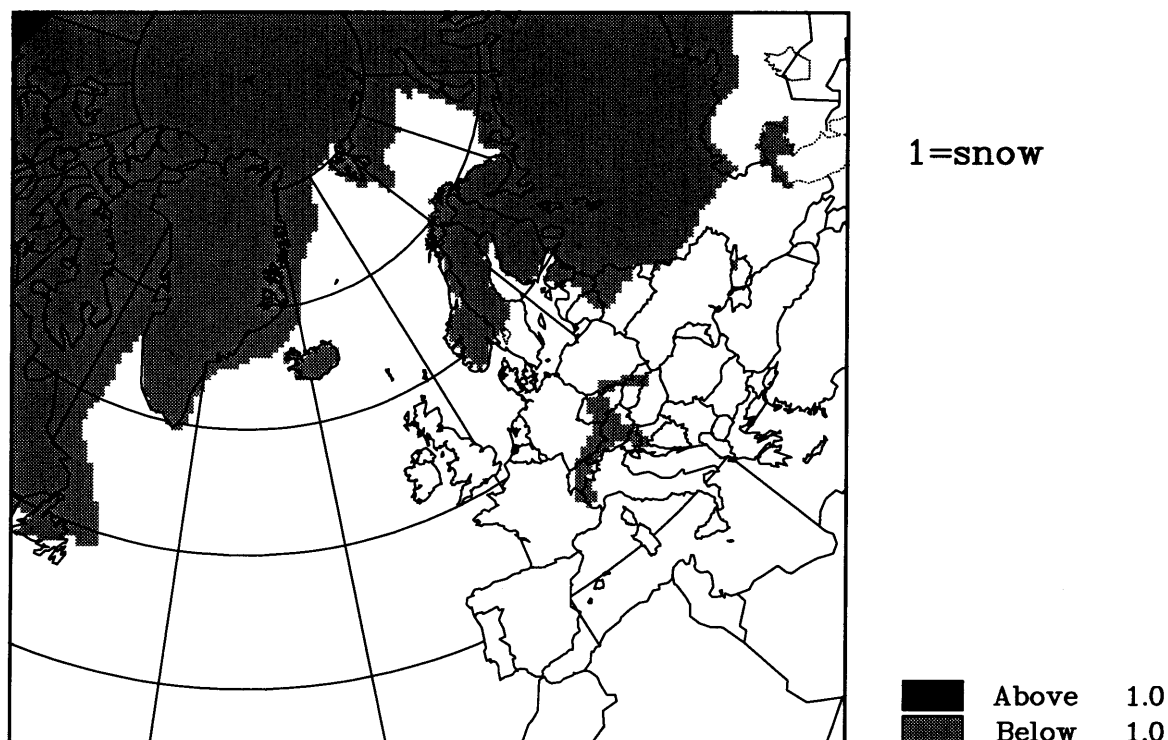
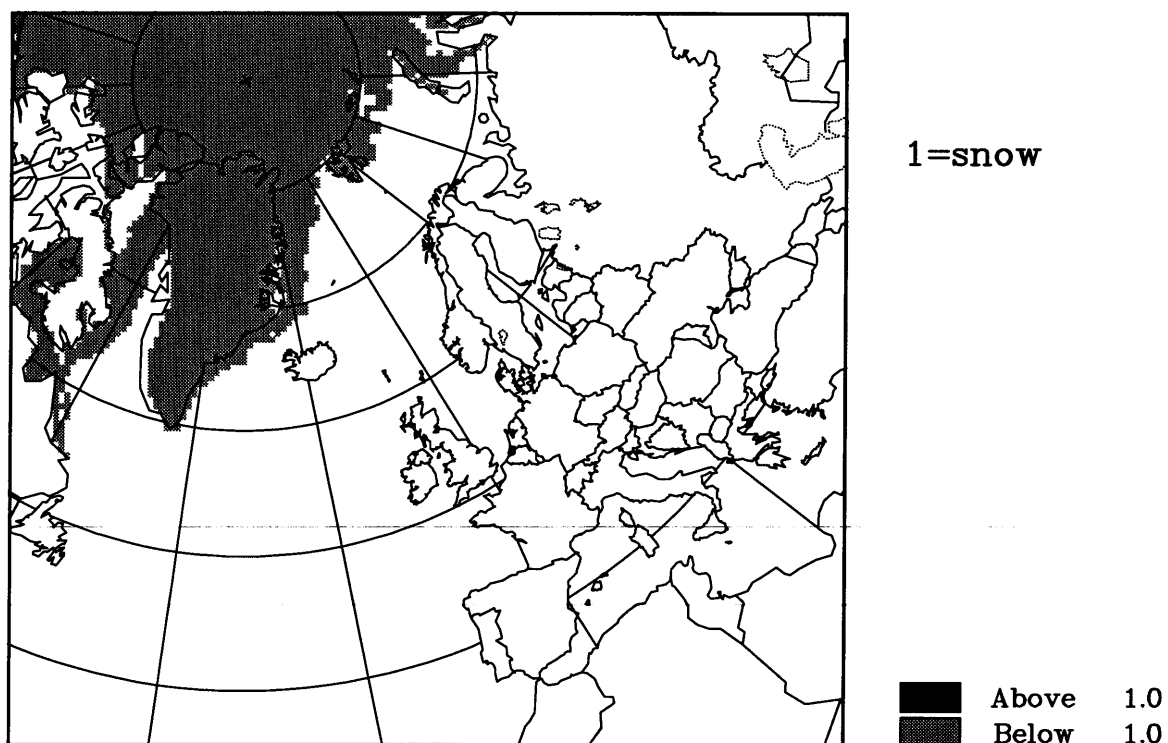


Figure A12 : SNOW COVER – july –



APPENDIX B.

Results from ROOT-50 , ROOT-150 and the Eulerian 50 km model

Figure B1-B4 : Sulphur depositions :

Figure B1 Dry deposition of sulphur . Contribution from United Kingdom
January 1992 a) ROOT-50 b) ROOT-150 c) Euler 50

Figure B2 Wet deposition of sulphur . Contribution from United Kingdom
January 1992 a) ROOT-50 b) ROOT-150 c) Euler 50

Figure B3 Dry deposition of sulphur . Contribution from United Kingdom
July 1992 a) ROOT-50 b) ROOT-150 c) Euler 50

Figure B4 Wet deposition of sulphur . Contribution from United Kingdom
July 1992 a) ROOT-50 b) ROOT-150 c) Euler 50

Figure B5-B8: Oxidized Nitrogen depositions :

Figure B5 Dry deposition of oxidized nitrogen . Contribution from United Kingdom
January 1992 a) ROOT-50 b) ROOT-150

Figure B6 Wet deposition of oxidized nitrogen. Contribution from United Kingdom
January 1992 a) ROOT-50 b) ROOT-150

Figure B7 Dry deposition of oxidized nitrogen . Contribution from United Kingdom
July 1992 a) ROOT-50 b) ROOT-150

Figure B8 Wet deposition of oxidized nitrogen . Contribution from United Kingdom
July 1992 a) ROOT-50 b) ROOT-150

Figure B9-B12: Reduced Nitrogen depositions :

Figure B9 Dry deposition of reduced nitrogen . Contribution from United Kingdom
January 1992 a) ROOT-50 b) ROOT-150

Figure B10 Wet deposition of reduced nitrogen . Contribution from United Kingdom
January 1992 a) ROOT-50 b) ROOT-150

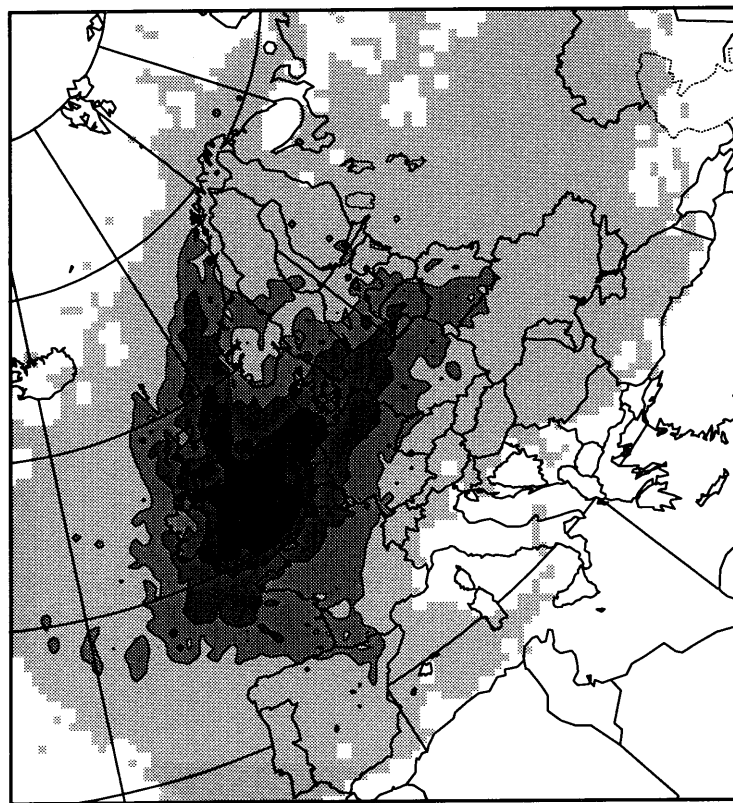
Figure B11 Dry deposition of reduced nitrogen . Contribution from United Kingdom
July 1992 a) ROOT-50 b) ROOT-150

Figure B12 Wet deposition of reduced nitrogen . Contribution from United Kingdom
July 1992 a) ROOT-50 b) ROOT-150

B

Figure B1 Dry deposition of sulphur. Contribution from United Kingdom
January 1992

a) ROOT-50



unit: mg(s)/m²

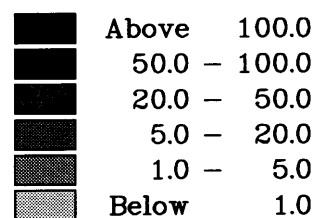
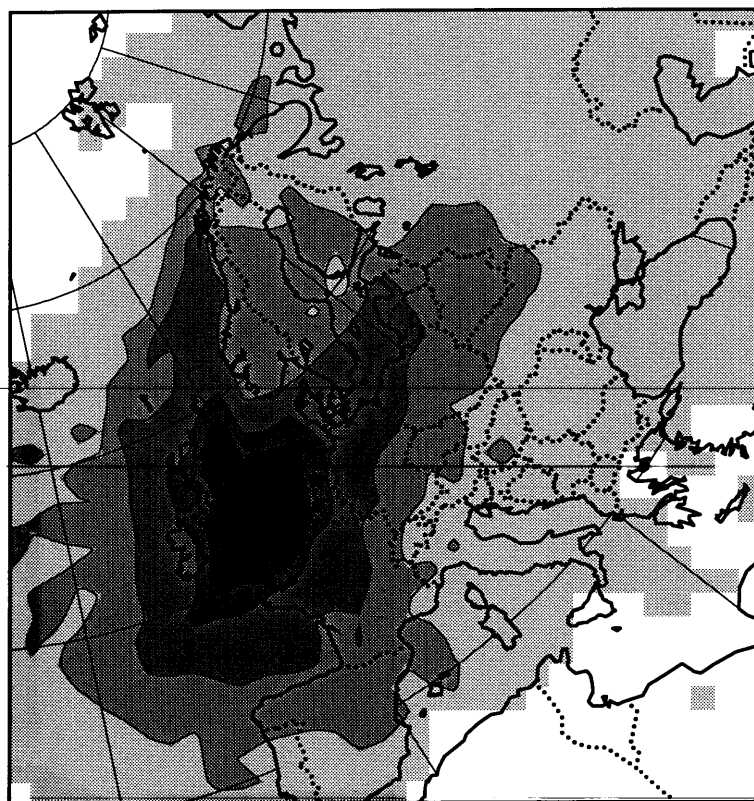


Fig. B1 b) ROOT-150



unit: mg(S)/m²

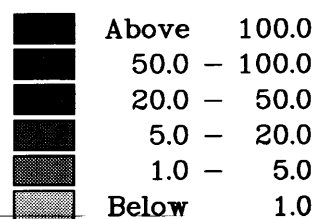
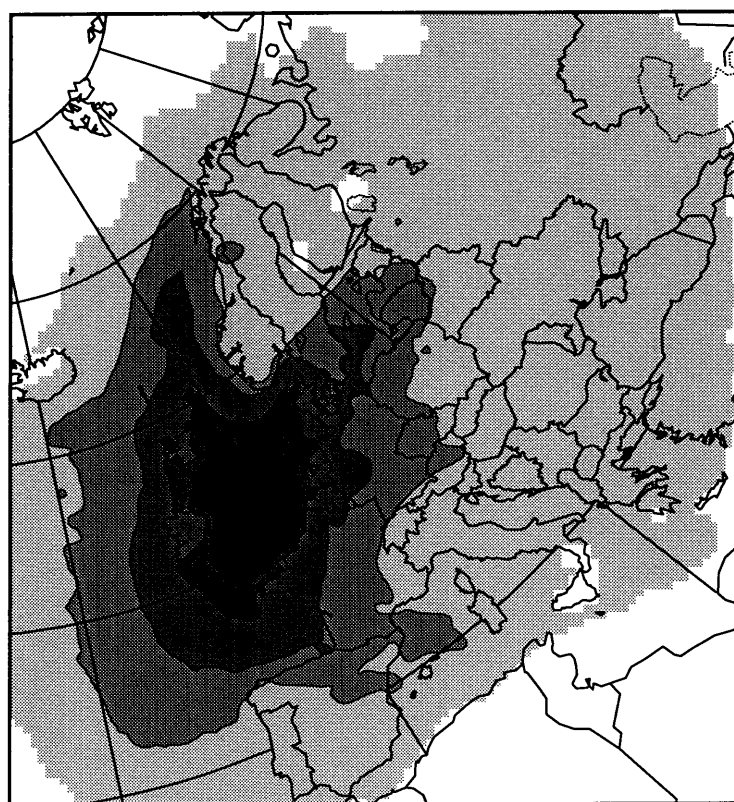


Figure B1 Dry deposition of sulphur. Contribution from United Kingdom
January 1992

c) Euler-50



unit: mg(s)/m2

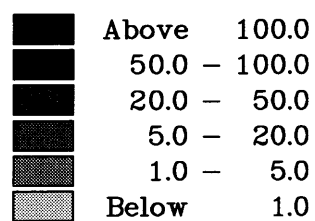
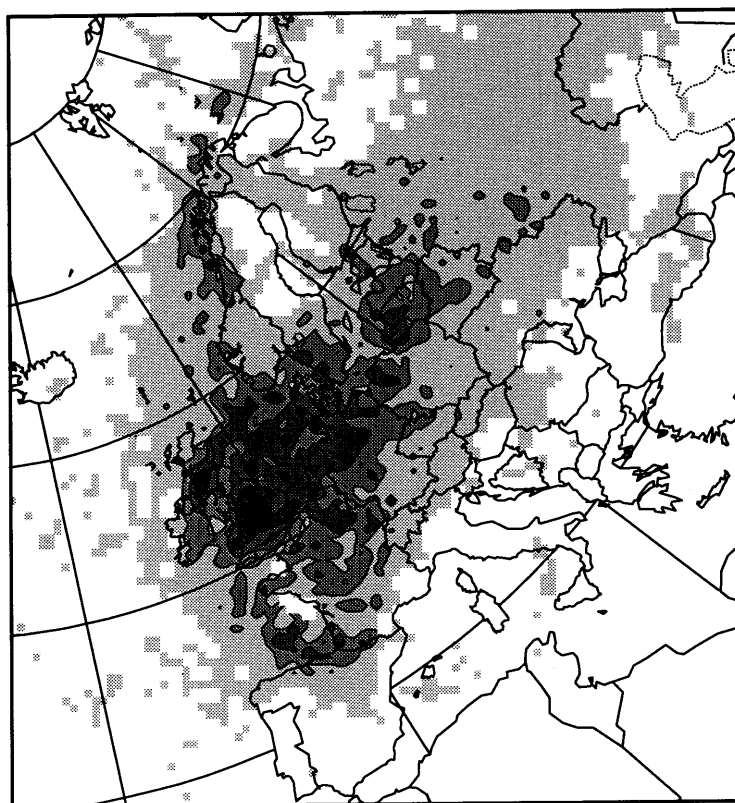
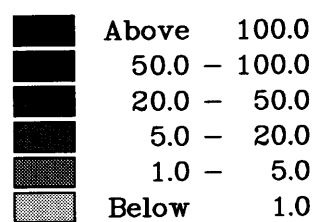


Figure B2 Wet deposition of sulphur. Contribution from United Kingdom
January 1992

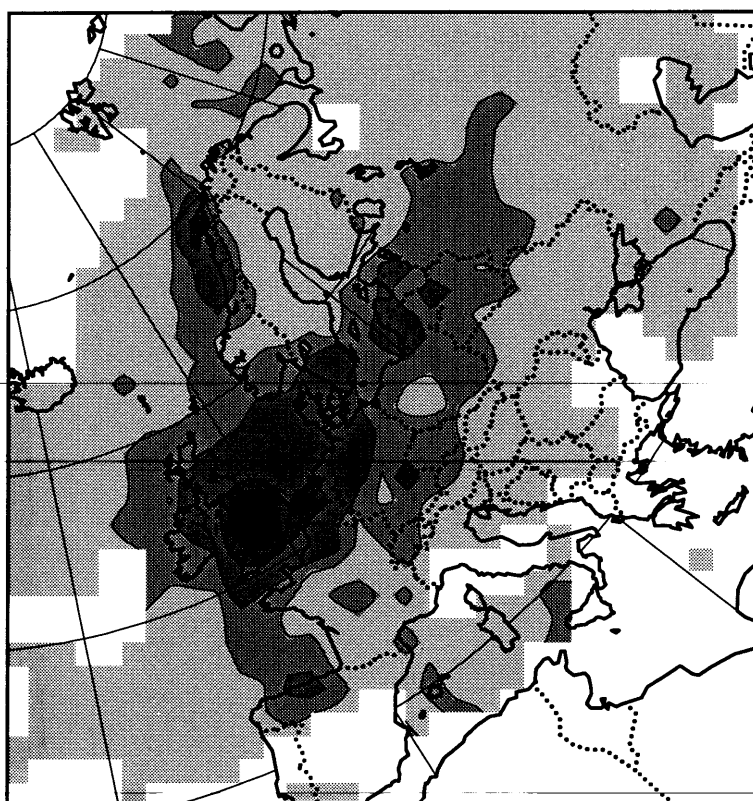
a) ROOT-50



unit: mg(s)/m2



b) ROOT-150



unit: mg(S)/m2

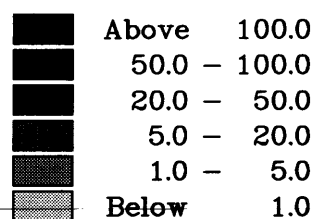
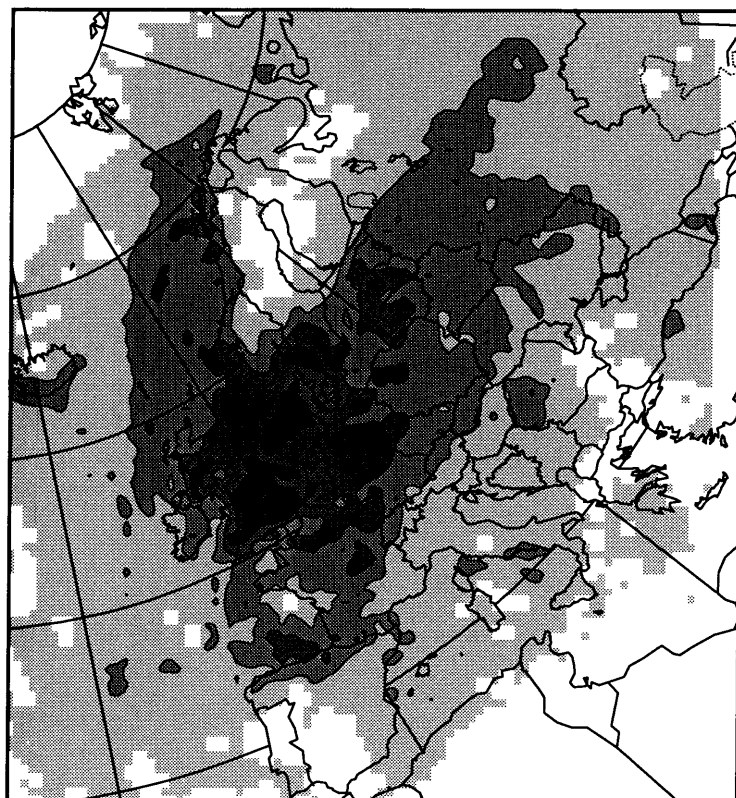


Figure B2 Wet deposition of sulphur. Contribution from United Kingdom
January 1992

c) Euler-50



unit: mg(s)/m²

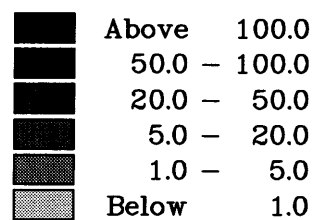
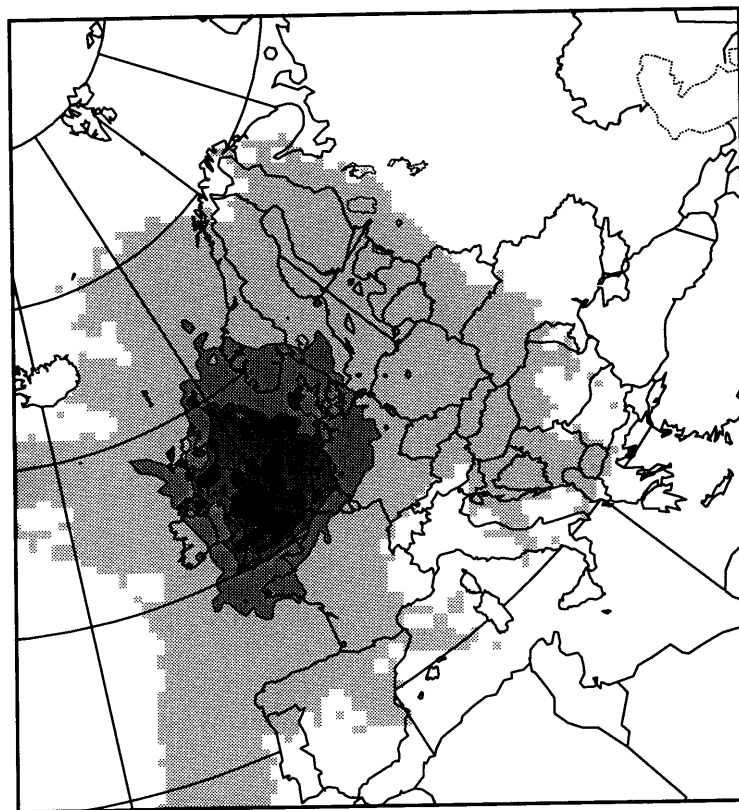
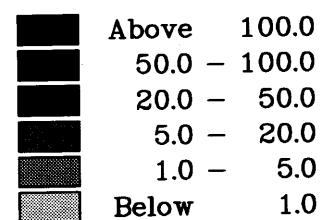


Figure B3 Dry deposition of sulphur. Contribution from United Kingdom
July 1992

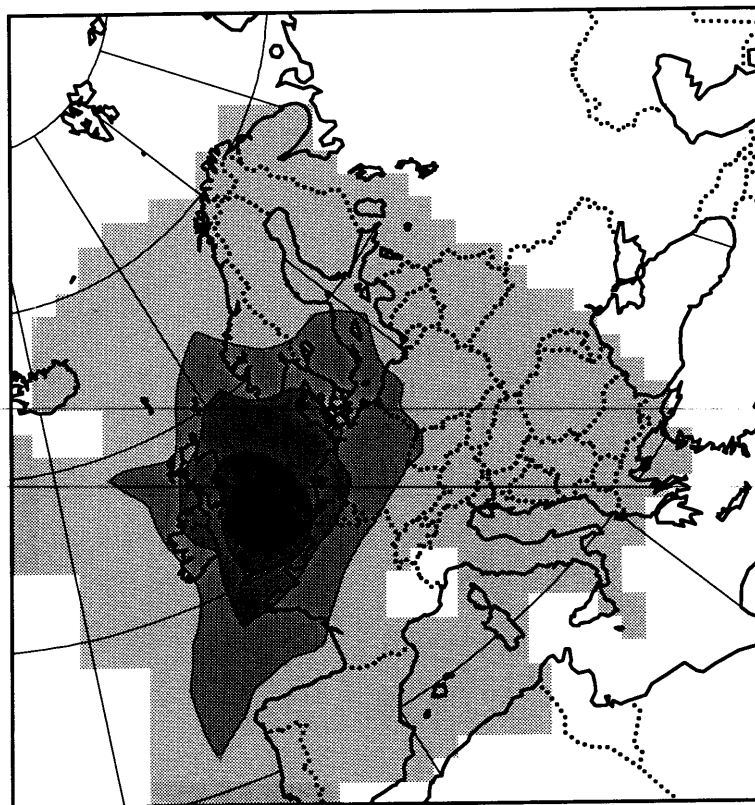
a) ROOT-50



unit: mg(s)/m²



b) ROOT-150



unit: mg(S)/m²

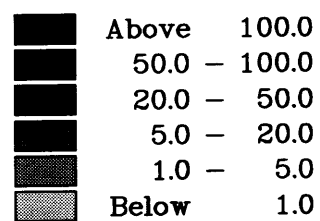
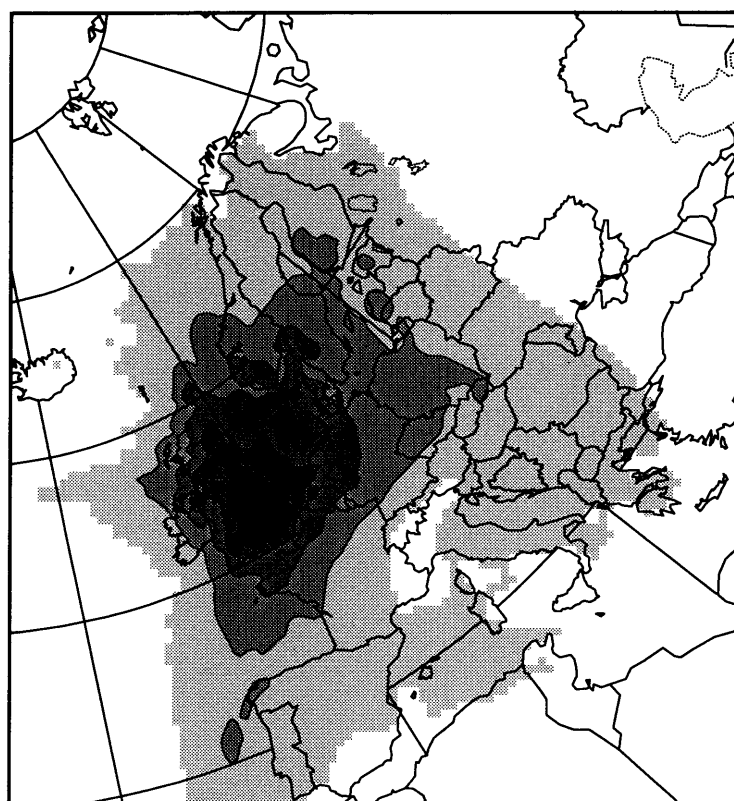
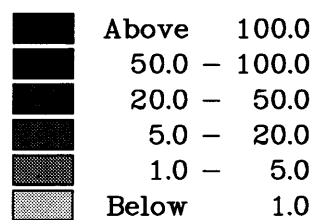


Figure B3 Dry deposition of sulphur. Contribution from United Kingdom
July 1992

c) Euler-50



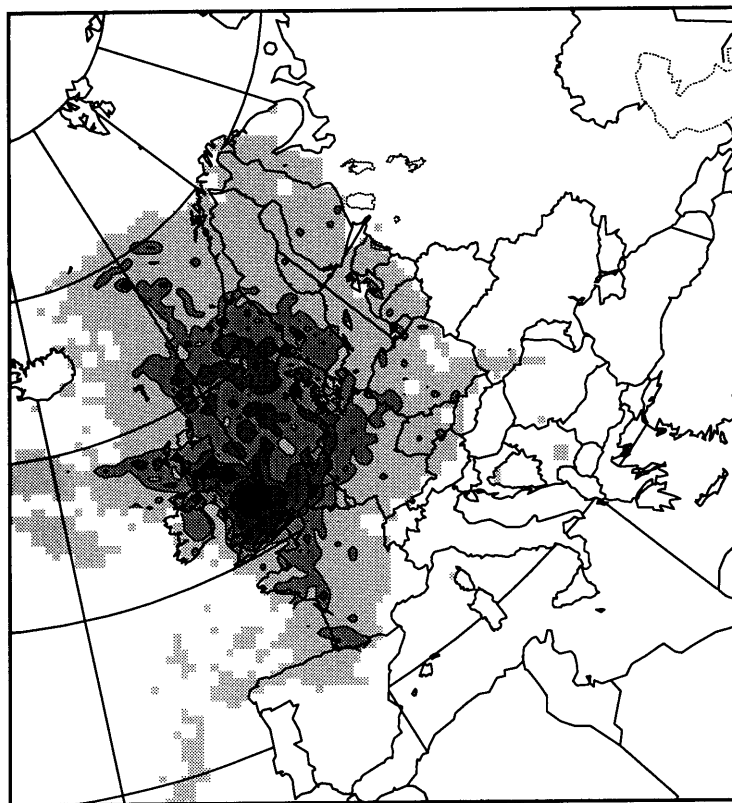
unit: mg(s)/m²



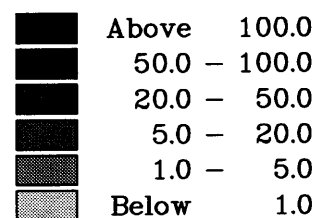
B

Figure B4 Wet deposition of sulphur. Contribution from United Kingdom
July 1992

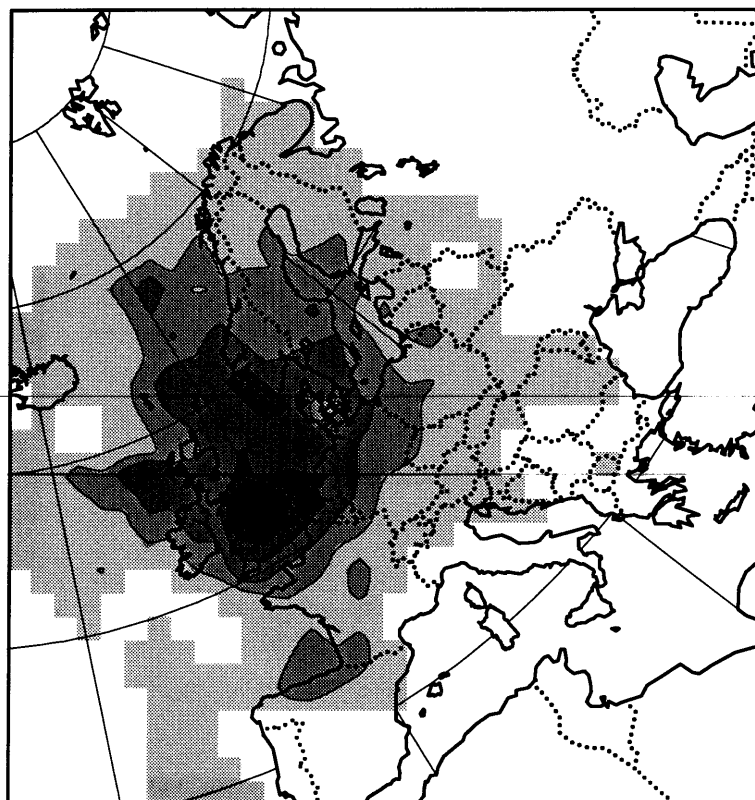
a) ROOT-50



unit: mg(s)/m²



b) ROOT-150



unit: mg(S)/m²

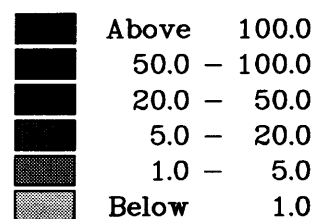
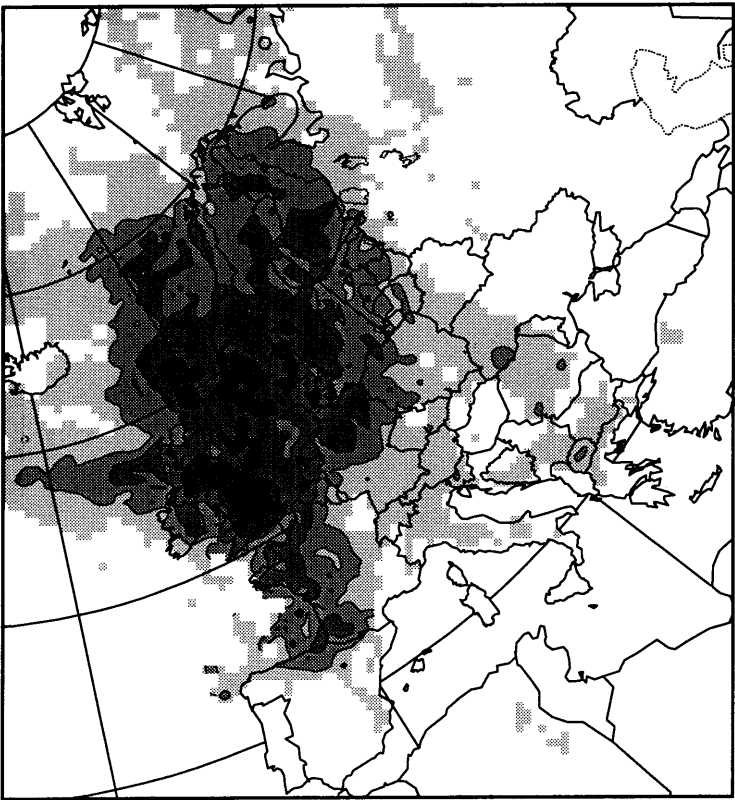
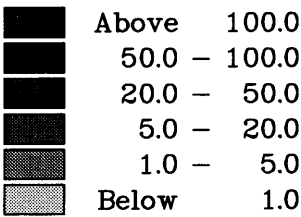


Figure B4 Wet deposition of sulphur. Contribution from United Kingdom
July 1992

c) Euler-50



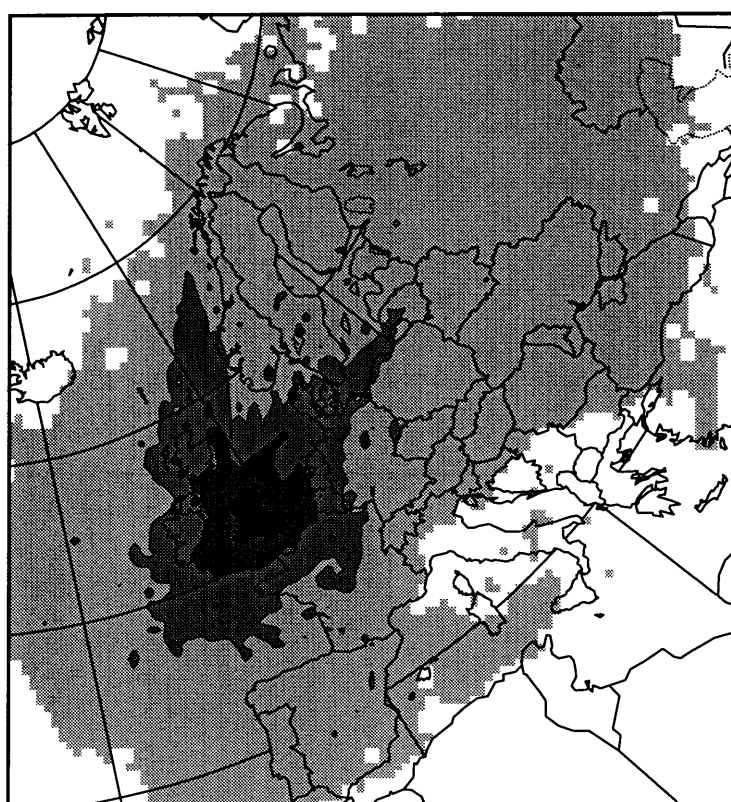
unit: mg(s)/m2



B

Figure B5 Dry deposition of oxidized nitrogen. Contribution from United Kingdom
January 1992

a) ROOT-50



b) ROOT-150

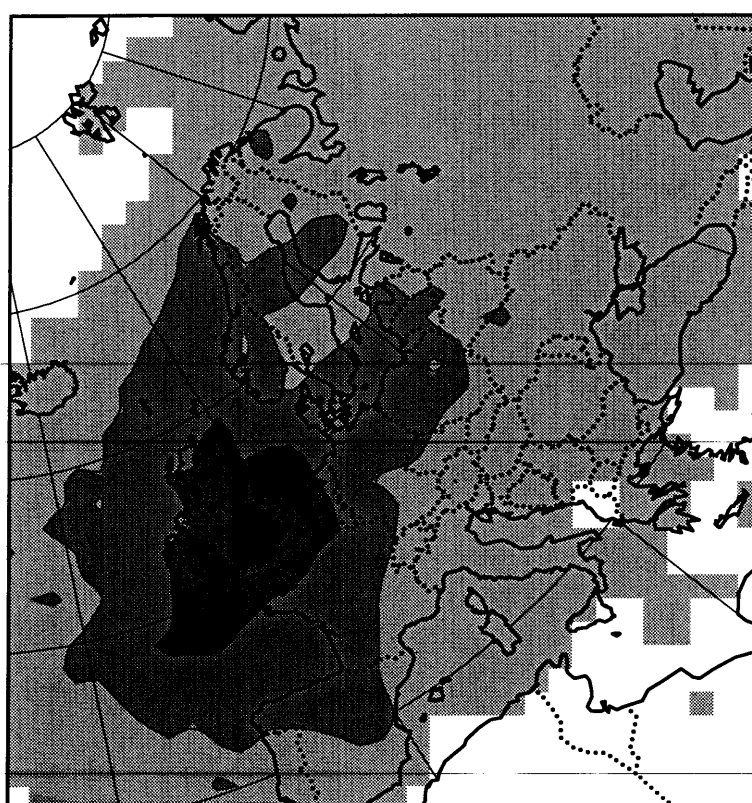
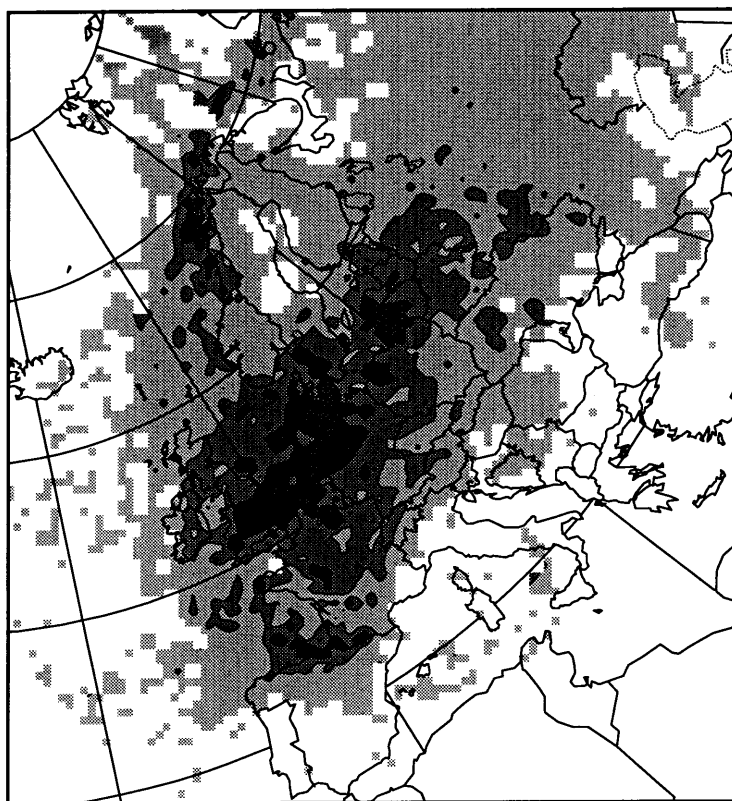
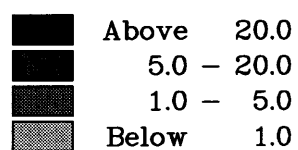


Figure B6 Wet deposition of oxidized nitrogen. Contribution from United Kingdom
January 1992

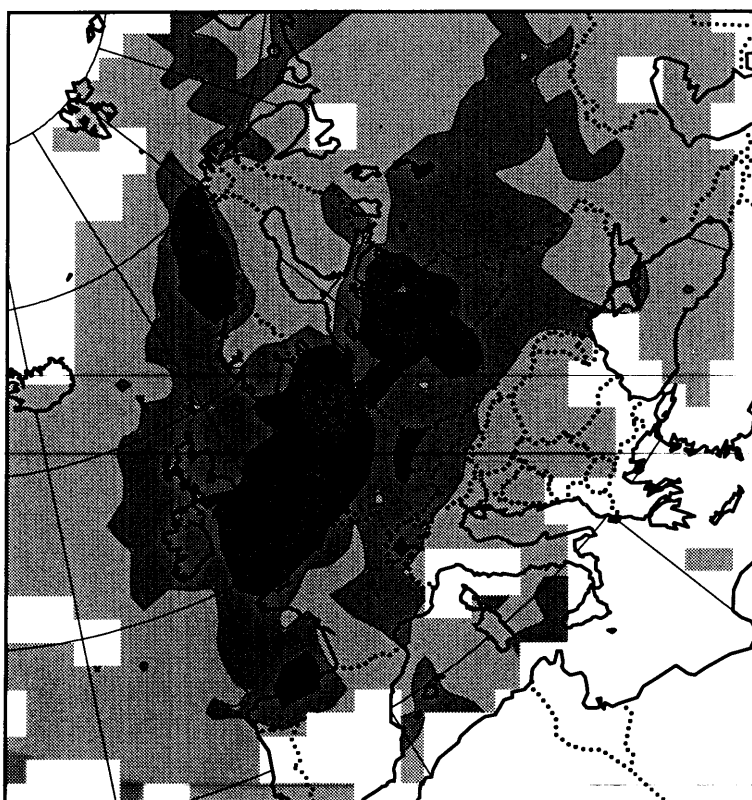
a) ROOT 50



unit: mg(n)/m2



b) ROOT-150



unit: mg(N)/m2

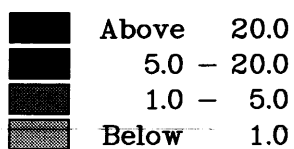
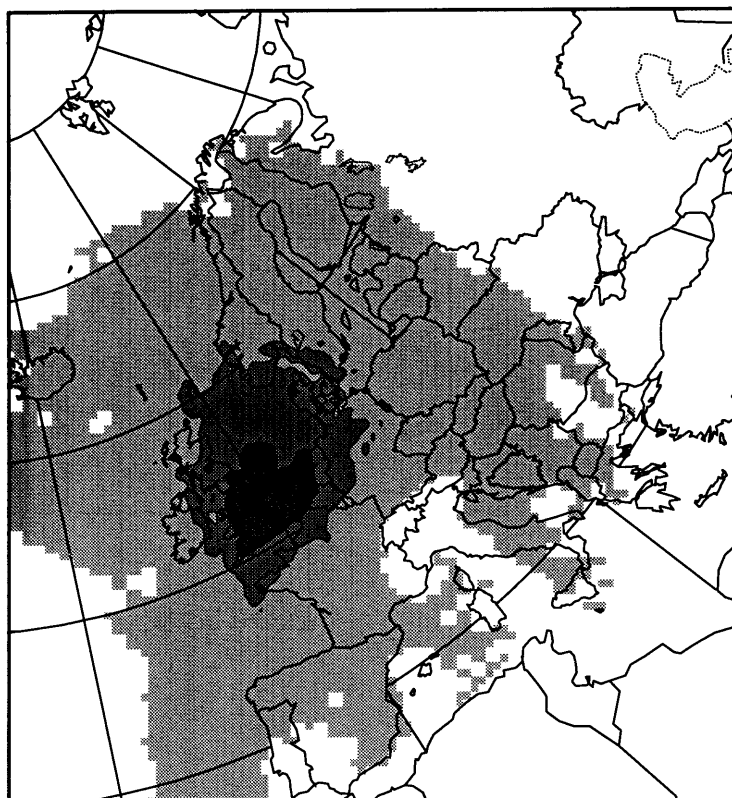


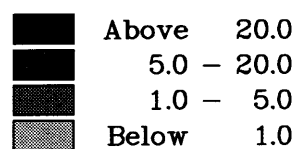
Figure B7 Dry deposition of oxidized nitrogen. Contribution from United Kingdom

July 1992

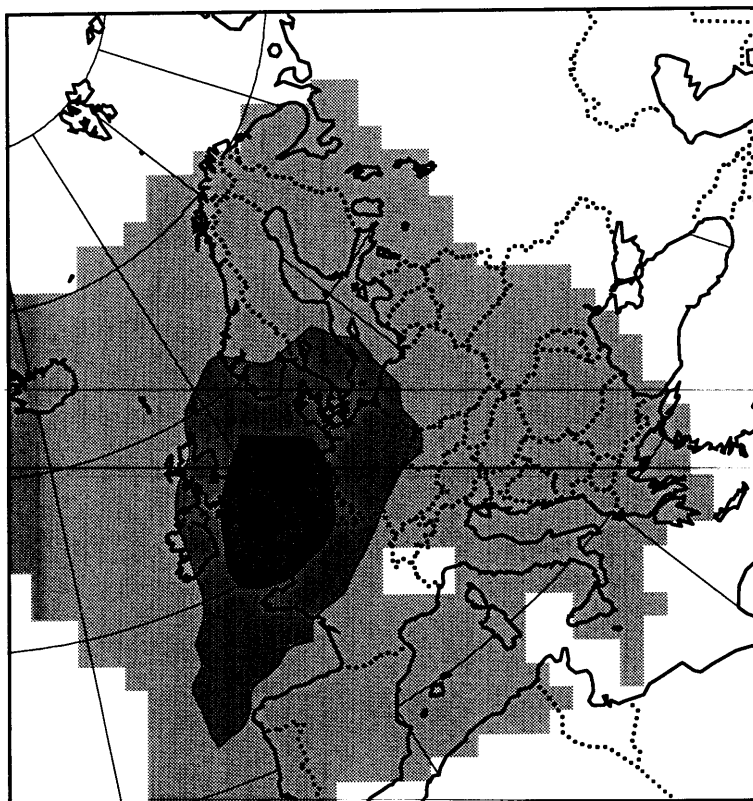
a) ROOT-50



unit: mg(n)/m2



b) ROOT-150



unit: mg(N)/m2

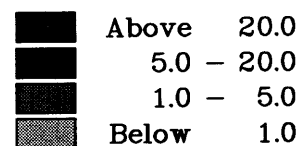
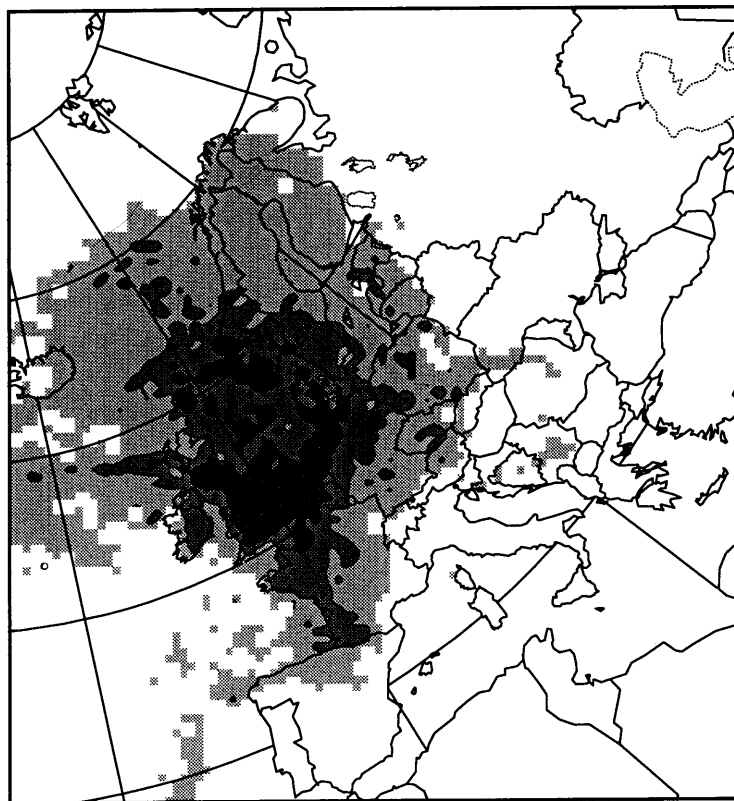
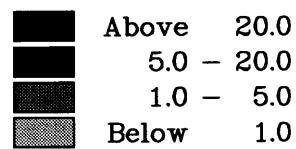


Figure B8 Wet deposition of oxidized nitrogen. Contribution from United Kingdom
July 1992

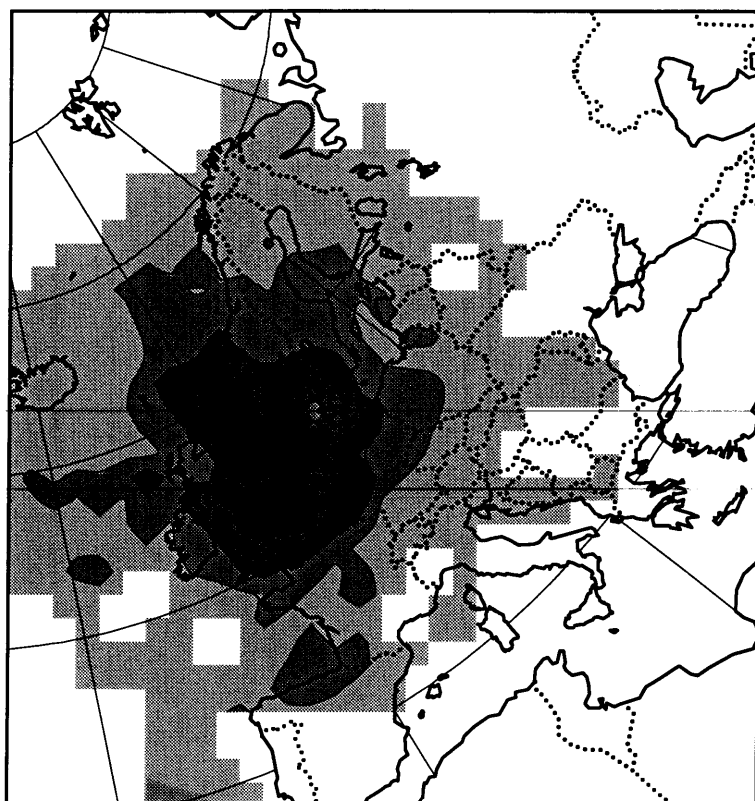
a) ROOT-50



unit: mg(n)/m2



b) ROOT-150



unit: mg(N)/m2

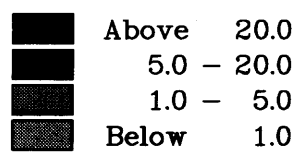
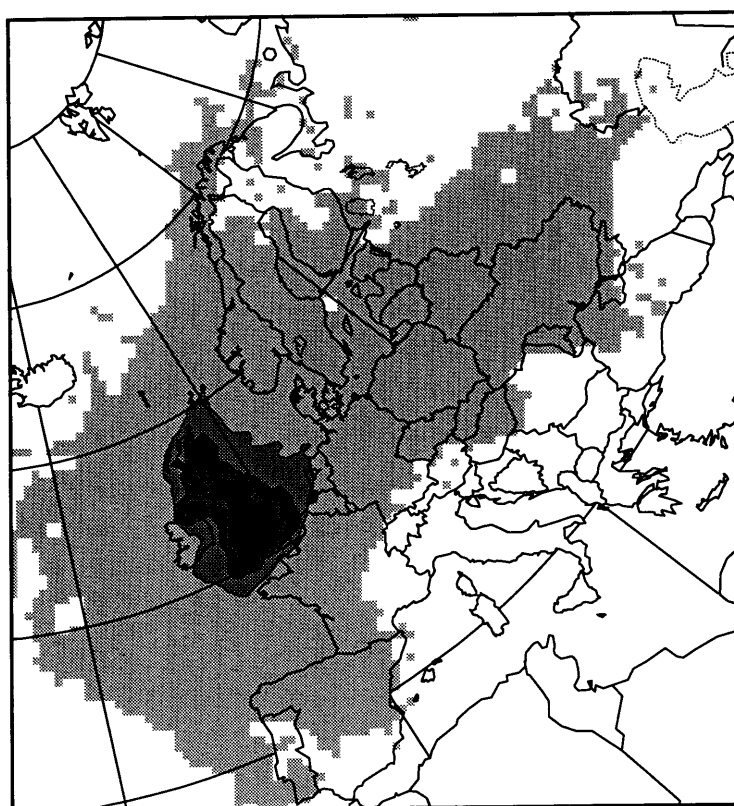
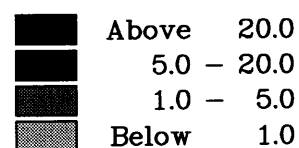


Figure B9 Dry deposition of reduced nitrogen. Contribution from United Kingdom
January 1992

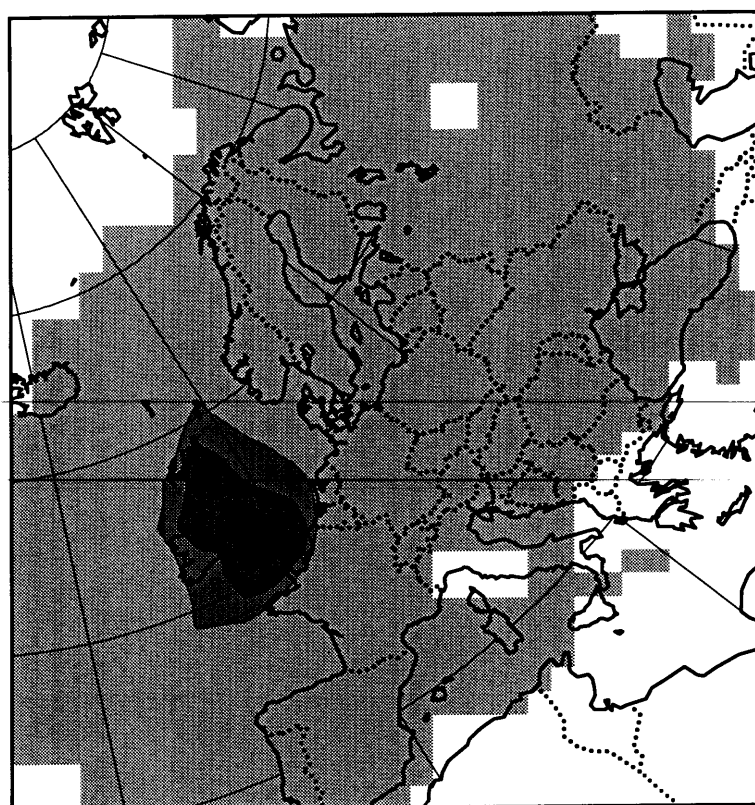
a) R00T-50



unit: mg(n)/m2



b) R00T-150



unit: mg(N)/m2

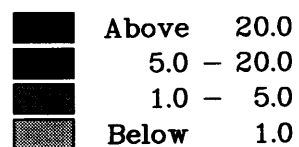
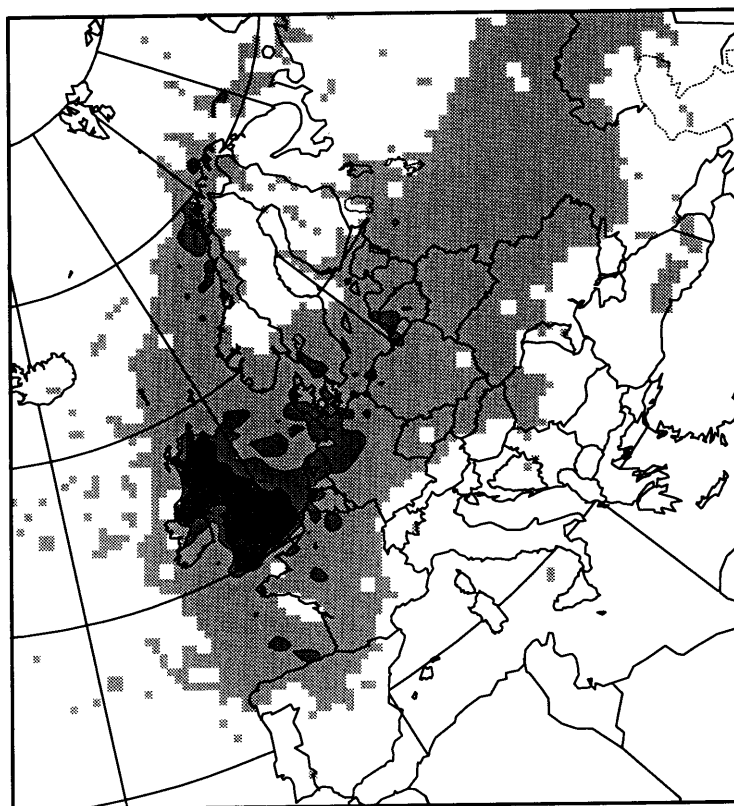
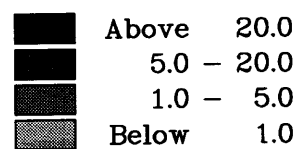


Figure B10 Wet deposition of reduced nitrogen. Contribution from United Kingdom
January 1992

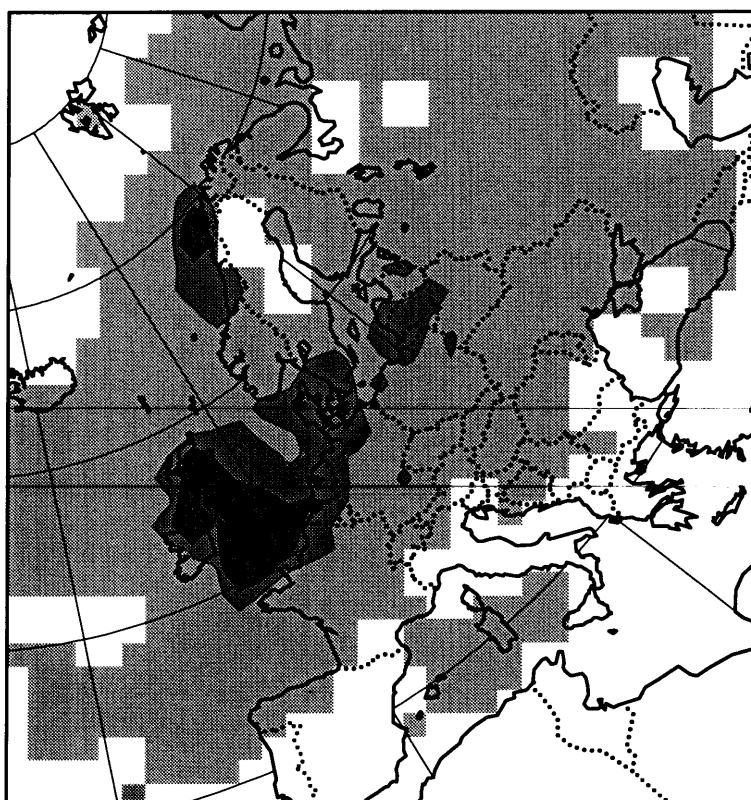
a) ROOT-50



unit: mg(n)/m2



b) ROOT-150



unit: mg(N)/m2

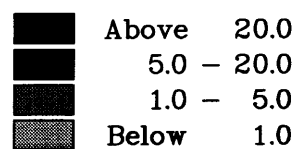
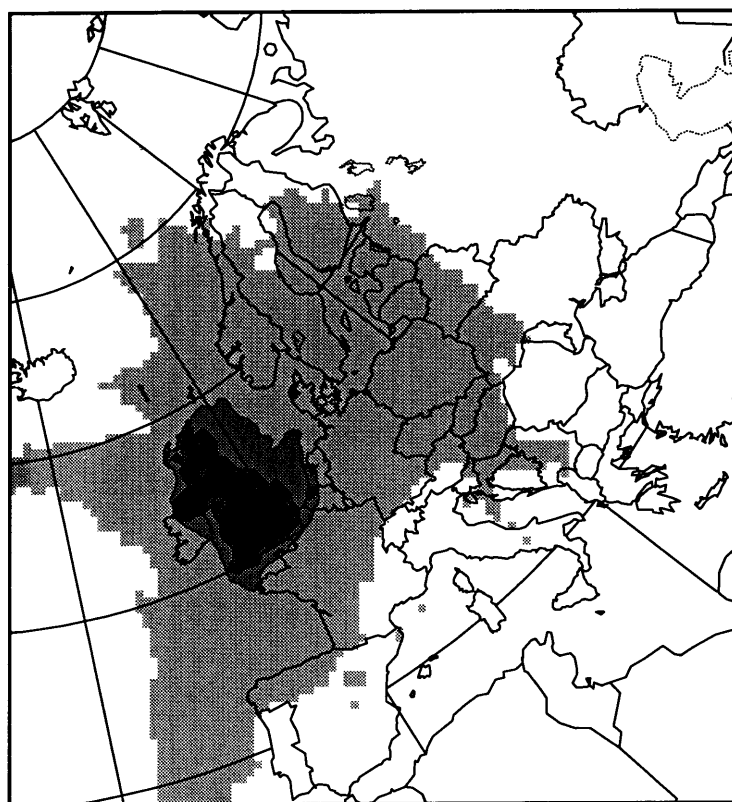
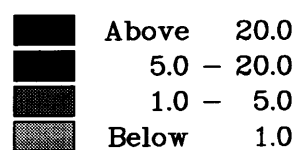


Figure B11 Dry deposition of reduced nitrogen. Contribution from United Kingdom
July 1992

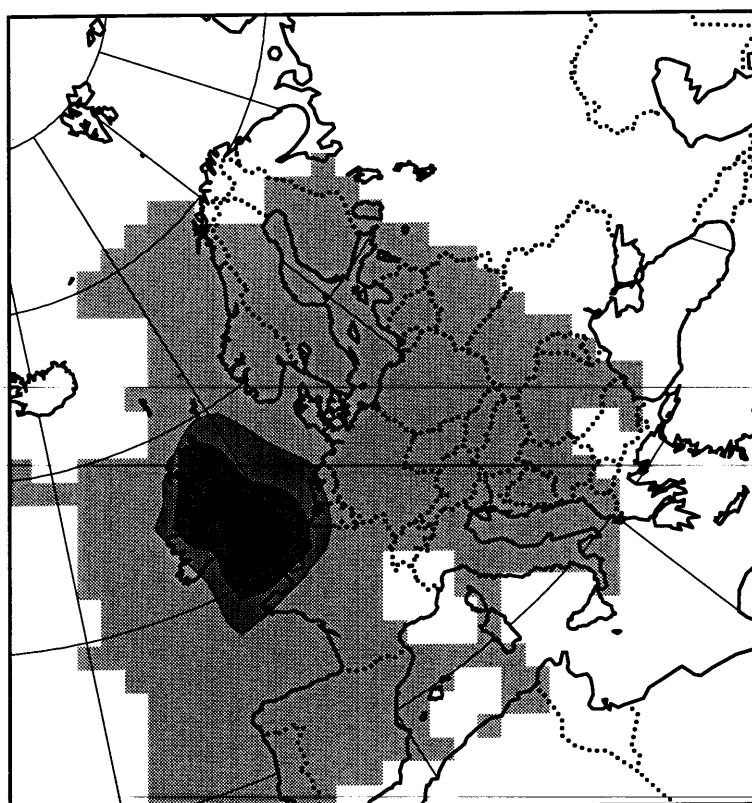
a) ROOT-50



unit: mg(n)/m²



b) ROOT-150



unit: mg(N)/m²

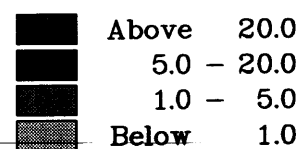
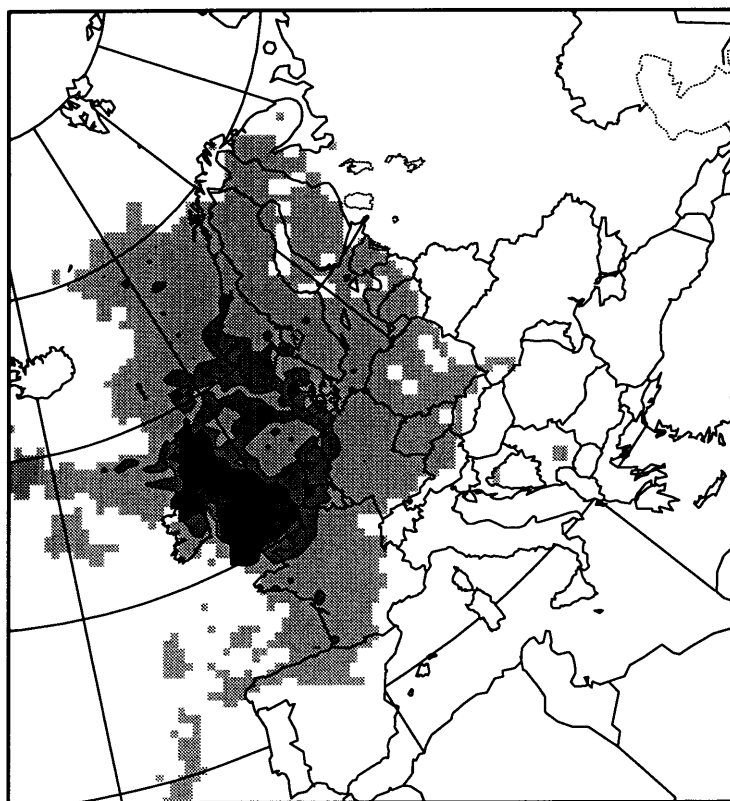
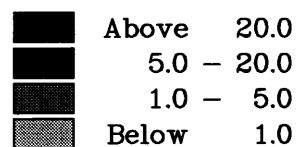


Figure B12 Wet deposition of reduced nitrogen. Contribution from United Kingdom
July 1992

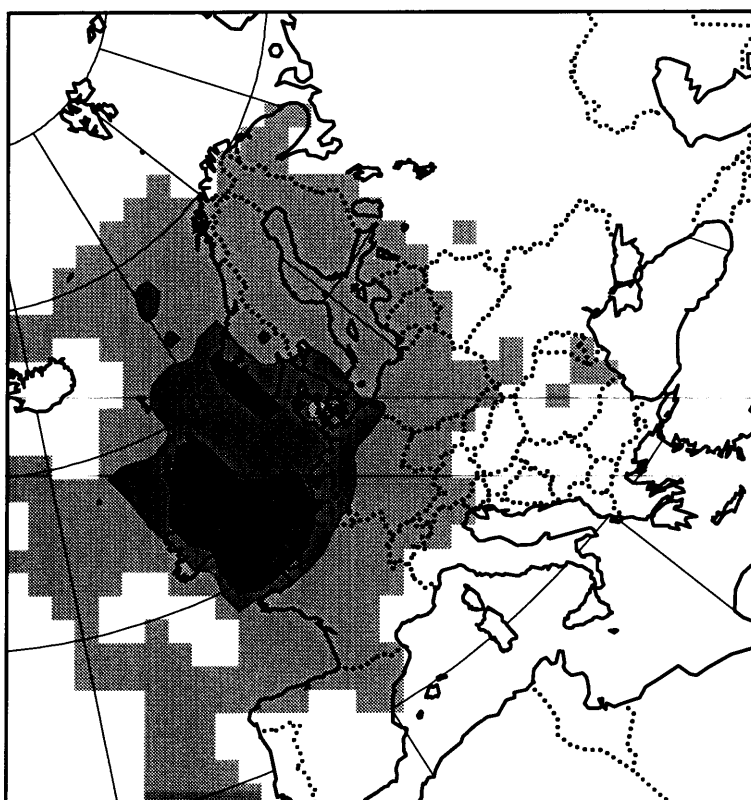
a) ROOT-50



unit: mg(n)/m2



b) ROOT-150



unit: mg(N)/m2

