F I N A L R E P O R T
ESPRIT HPCN PST ACTIVITY
EUROAIR, 24618
STUDYING ENVIRONMENTAL PROBLEMS IN EUROPE BY USING AIR POLLUTION MODELS

ABSTRACT

It is well-known, also by the broad public in Europe, that the air pollution levels in a given region not only depend on the emission sources located in it, but also on emission sources located outside the region under consideration, and even on sources that are far away from the studied region. This is due to the transboundary transport of air pollutants. The atmosphere is the major medium where pollutants can be transported over long distances. Harmful effects on plants, animals and humans can also occur in areas which are far away from big emission sources. Chemical reactions take place during the transport. This leads to the creation of secondary pollutants, which can also be harmful. The air pollution levels in densely populated regions of the world, such as Europe, must be studied carefully to find out how the air pollution can be reduced to safe levels and, moreover, to develop reliable control strategies by which the air pollution can be kept under certain prescribed critical levels. This can be done only when large scale mathematical models, in which all physical and chemical processes are adequately described, are used. The numerical treatment of such models leads to huge computational tasks, which can successfully be solved only on high speed computers.

An improved version of the Danish Eulerian Model, which can efficiently be run on several vector and parallel computers, have been prepared within the EUROAIR Project. The possibility of applying successfully the improved version in a comprehensive study of a wide range of air pollution phenomena in a prescribed European region was demonstrated by carrying out long series of scenarios in order to investigate in a systematic way the influence of different variations of the emission sources in France and/or in the region surrounding France to the corresponding French concentrations and depositions. The results from this demonstration as well as results from other demonstrations are available in the EUROAIR WEB home pages.

1 SYNOPSIS

High air pollution levels may cause (i) acidification of the soils in some sensitive areas, (ii) damages in certain water areas (especially the closed seas as, for example, the Baltic Sea, the Black Sea and the Mediterranean) and (iii) eutrofication of eco-systems. Moreover, high concentrations of certain pollutants, first and foremost of tropospheric ozone, can directly damage plants, animals and humans. Therefore, systematic studies of the pollution levels are needed in order to answer the following questions:

1. Are certain critical levels exceeded?
2. Will the critical levels be exceeded in the near future?
3. What preventive measures could (and/or should) be taken in the efforts to avoid exceedance of the critical levels?

Such studies have been carried out with **an improved version** of the Danish Eulerian Model (an air pollution model developed at the National Environmental Research Institute, Roskilde, Denmark), which has been prepared within the EUROAIR Project. The new high performance computing modules were some of the most important improvements in the new version (because it is impossible to run long series of experiments with a large scale air pollution model, in which all physical and chemical processes are adequately described, without using efficiently high speed computers). A long series of scenarios has been prepared together with the end-user of this project, the French Institute INERIS (Institut National de l'Environment Industriel et des Risques). Then the improved model has been used to study the following issues concerning France (but it should immediately be emphasized here that similar studies can been performed for any other region in Europe):

1. different pollution levels in France in a nine-year time period (1989-1997),
2. exceedance of critical levels in certain parts of France,
3. the changes of the air pollution levels in France in the period 1989-1997 as a result of the emission changes in France and in its surrounding countries in this period,
4. the effects of systematic reductions of French emissions on the concentrations and/or the deposition of corresponding emissions,
5. the contribution from foreign emission sources to the concentrations and the depositions in the French area,
6. the representation of the French pollution levels as functions of the variation of the French emissions.

Such results can successfully be used by decision makers, scientists studying effects from high pollution levels as well as environmental specialists from both governmental and non-governmental organizations. The results from this study can be found, together with many other details about this project, in the WWW site: http://www.dmu.dk/AtmosphericEnvironment/EUROAIR. Some of the results can also be found in the WWW-site of the ESPRIT PROSOMA Project.

The participants in the EUROAIR Project are: UNI-C (the Danish Computing Centre for Research and Education, Copenhagen, Denmark), NERI (the National Environmental Research Institute, Roskilde, Denmark) and INERIS (Institut National de l'Environment Industriel et des Risques, Verneuil-en-Halatte, France). The UNI-C team contributed mainly in the efforts to produce a high performance code. The INERIS team participated actively in the preparation of a set of scenarios and in the interpretation of the results from the runs. The NERI team supported the teams from UNI-C and INERIS in the solution of their tasks, performed additional improvements in the code, carried out a long series of experiments and visualize the results.

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2 EXECUTIVE SUMMARY

The environmental protection becomes a more and more important task for the modern society. Its importance will certainly be increased in the next century. If the concentrations and/or the depositions of certain air pollutants are high, then these can cause damages on

1. forests trees (as well as other plants; for example, crops),
2. the underground water,
3. lakes and seas,
4. terrestrial eco-systems,
5. other objects.

This explains why it is necessary to determine critical levels for the concentrations of the most dangerous air pollutants (i.e. the highest concentrations that will not cause damages during a long period of time, say, up to 50 years). While the determination of the critical levels is absolutely necessary, it is not sufficient. Control strategies must also be used in an attempt to reduce the depositions of the dangerous air pollutants and concentrations of photooxidants so that these are under the critical levels and/or to keep them under the critical levels. Long-range transport of air pollutants plays an important role (especially for small countries) and must be taken into account when control strategies are used. Mathematical models can successfully be used to adjust the control strategies with regard to the long-range transport.

The task of building a reliable mathematical model is very complicated. There are many reasons for this, but one of them is crucial. A reliable model, in which all physical and chemical processes are adequately described, is normally very big. The numerical treatment of such models leads to the solution of systems of ordinary differential equations (ODEs) containing up to $O(10^6)$ equations, which have to be solved at every time step. The number of time steps varies from several hundreds to about 10^5 in the different simulations. Finally, long series of experiments (several hundreds or even several thousands) are needed in comprehensive studies. This is why the large scale air pollution models must be run on modern high-speed computers and, moreover, it is necessary to ensure high performance. This causes difficulties, because

1. huge input files are needed,
2. huge output files must be prepared and saved for future use,
3. a very big and very complicated code containing a large number of subroutines must be carefully tuned to the computer under consideration, and this is a very difficult task.

An improved version of the Danish Eulerian Model (an air pollution model developed at the National Environmental Research Institute) has been prepared and tested within the EUROAIR Project. Several new modules, which allow us to run the model efficiently on different high speed computers, were constructed and attached to the model. The so enhanced model has been run on different computers:

1. vector processors,
2. parallel computers with distributed memory,
3. parallel computers with shared memory.

The improved version of the model (with these new modules attached to it) runs about five times faster than the version we had before the start of the EUROAIR Project. Much more and much bigger tasks can now be handled by using the new version.

Several additional improvements, concerning the physical mechanisms used in the Danish Eulerian Model as well as the visualization of the output data, have been achieved:

1. better modelling of the temporal variations of the emissions (including diurnal variations for the nitrogen oxides emissions),
2. introducing some time-dependent variations in the dry deposition coefficients,
3. selection of more advanced graphical tools for the visualization of the output results.

An extensive validation procedure (based on comparison of model results with measurements taken in different countries in Europe over a period of nine years) has been applied to justify the reliability of the new physical mechanisms used in the model. It should be mentioned here that the measurement stations used in the validation procedure are from the EMEP network of measurement stations (EMEP stands for European Monitoring and Evaluation Programme, which is a common European project).

A long series of scenarios has been prepared together with the end-user of this project, the French Institute INERIS (Institut National de l'Environment Industriel et des Risques). Then the improved model has been used to study the following issues concerning France (but it should immediately be emphasized here that similar studies can been performed for any other region in Europe):

1. different pollution levels in France in a nine-year time period (1989-1997),
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Such results can successfully be used by decision makers, scientists studying effects from high pollution levels as well as environmental specialists from both governmental and non-governmental organizations. The results from this study can be found, together with many other details about this project, in the WWW site: http://www.dmu.dk/AtmosphericEnvironment/EUROAIR. Some of the results can also be found in the WWW-site of the ESPRIT PROSOMA Project.

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3 ACHIEVEMENTS DURING THE WORK ON THE EUROAIR PROJECT

The achievements during the work on the EUROAIR Project will be discussed in this part of the report. Only the most important parts of the project will be discussed. However, much more details about the project and the tools used in the solution of different tasks involved in this project can be found by using the WEB home pages (see §3.4).

3.1 State of the Art

Increase of the requirements for clean environments. The requirements to the environment in Europe are becoming more and more stringent. The critical levels established by the Commission of the European Union lead to more and more restrictive requirements upon industry, agriculture and traffic. On the other hand, it is vitally necessary for the modern society to achieve a permanent progress in the further development of the industry, agriculture and traffic. Therefore, enormous tasks have to be solved in the attempts to achieve well-balanced sustainable development in these three important areas. This means that the increased environmental requirements should be achieved in an optimal way. Large integrated models are needed in the solution of these problems. Many of the problems are still unresolved, and much more work is needed to achieve a balance between economical development and environmental requirements. First and foremost, it must become clear to everybody working in these areas that the two issues are very closely connected and, thus, environmental problems should be handled together with the requirement for a permanent, non-stopping economical development. While a complete integrated solution of these problems is not available at present, the development of a series of environmental models, by which large amounts of different data can be calculated and studied, can be considered as a step in the desired direction. The next step should be either the integration of these models with some economical models or the comprehensive use of the data calculated by the environmental models in economical models.

Main objectives of the EUROAIR Project. The main objective of the EUROAIR Project was to enhance the existing Danish Eulerian Model (developed at the National Environmental Research Institute) and then to use the enhanced version in studies of different air pollution phenomena in a given region of Europe. This should allow different users to get access to

1. investigations of the levels of the pollution in different parts of Europe in relation to the established critical levels,
2. illustrations of the diurnal, monthly, seasonal and long-term (up to nine years at present) variations of dangerous pollutants, including here tropospheric ozone,
3. results from long series of scenarios which are carried out in order to investigate the relationships between emissions and related concentrations or depositions.

Another objective of the EUROAIR Project was to demonstrate how interlinked and interdependent Europe is in regard to environmental issues. This increases the necessity of finding optimal solutions of different environmental problems. This also leads to the necessity of improving some important mechanisms in order to describe better the physical and chemical processes in the existing model.

It should be stressed here that it was clear from the beginning that the above two objective can be achieved only if high performance computing is extensively used. Indeed, reliable results can only be achieved by using models in which all important physical and chemical processes are adequately described. However, the numerical treatment of such models leads to the solution of systems of ordinary differential equations (ODEs) containing up to $O(10^6)$ equations, which have to be solved at every time step. The number of time steps varies from several hundreds to about 10^5 in the different simulations. Finally, long series of experiments (several hundreds or even several thousands) are needed in comprehensive studies. This is why the large scale air pollution models must be run on large high-speed computers and, moreover, it is necessary to ensure high performance. Networking is also essential in the efforts disseminate the results and, thus, to achieve broad awareness in the public and in potential industrial and non-industrial partners.

What are the needs of the users. The potential users have to know: (i) the present pollution levels, (ii) where the critical levels are exceeded or will soon be exceeded, (iii) where and by how much some relevant emission sources are to be reduced in order to reduce the pollution to the critical levels in an optimal way. The first requirement is natural. The same is true for the first part of (ii). It is necessary to run the model over a long time period (many years) in order to investigate the trends in the variations of the concentrations and/or the depositions. Then some extrapolation rules can be used to find out whether the critical levels will be exceeded in the near future. The requirement (iii) is important. The emission sources in some European regions are ten (or even more than ten) times bigger than the emission sources in other regions. Therefore "easy" solutions (as, for example, the recommendation to reduce the emissions in **all** European countries by, say, 30%) will in general be inefficient. On the other hand, it is rather difficult to find an optimal solution. This requires much more work (running a very large number of experiments, preparing carefully many scenarios, investigating systematically enormous files of output data). It is clear, however, that one should work in this direction in spite of the great difficulties.

Product and its application. The Danish Eulerian Model (an air pollution model developed at the National Environmental Institute) is the main tool that has been used during the work on the EUROAIR Project. This tool has been improved during the work on the project by

1. attaching new high performance modules to the model, which allows us to run the model efficiently on different high speed computers (vector processors, computers with shared memory and computers with distributed memory),

2. preparing new more advanced modules for some of the physical processes (diurnal variation of some emissions, seasonal variations of some dry deposition coefficients and better graphical routines for visualization of the results).

The improved version of the Danish Eulerian Model has been used to carry out a set of scenarios proposed by the end-user of the EUROAIR Project (the French Institute INERIS). The demonstration was related to the air pollution levels in France and the relationship between these levels and variations of the French emissions and/or emissions in the surrounding area. Similar comprehensive studies can be carried out for other regions in Europe.

Benefits. It must be emphasized that the reductions of the emissions become more and more expensive when the requirements are more and more increased. This means that finding optimal solutions not only will lead to keeping in a better way the balance between the economical development in the European countries and environmental requirements, but will also lead **to great savings of money**. Moreover, it may turn out that some of the new and more stringent environmental requirements can be satisfied only when optimal solutions are found.

Participating organizations and their role in the EUROAIR Project. The participants in the EUROAIR Project are: UNI-C (the Danish Computing Centre for Research and Education, Copenhagen, Denmark), NERI (the National Environmental Research Institute, Roskilde, Denmark) and INERIS (Institut National de l'Environment Industriel et des Risques, Verneuil-en-Halatte, France). The UNI-C team contributed mainly in the efforts to produce a high performance code. The INERIS team participated actively in the preparation of a set of scenarios and in the interpretation of the results from the runs. The NERI team supported the teams from UNI-C and INERIS in the solution of their tasks, performed additional improvements in the code, carried out a long series of experiments and visualize the results.

3.2 Approach

The Danish Eulerian Model. The Danish Eulerian Model was the main tool used during the work on the EUROAIR Project. Five major physical and chemical processes are taken into account in this large scale air pollution model:

- horizontal advection (the transport due to the wind),
- horizontal diffusion,
- deposition (both dry deposition and wet deposition),
- emission and chemistry,
- vertical exchange.

The Danish Eulerian Model is described mathematically by a system of q of partial differential equations (PDE's):

$$
\begin{aligned}
(1)\quad \frac{\partial c_s}{\partial t} &= -\frac{\partial(uc_s)}{\partial x} - \frac{\partial(vc_s)}{\partial y} - \frac{\partial(wc_s)}{\partial z} \\
&+\frac{\partial}{\partial x}\left(K_x\frac{\partial c_s}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial c_s}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z\frac{\partial c_s}{\partial z}\right) \\
&-(\kappa_{1s}+\kappa_{2s})c_s + E_s + Q_s(c_1, c_2, \ldots, c_q), \qquad s = 1, 2, \ldots, q.
\end{aligned}
$$

where the number q of equations is equal to the number of chemical species studied by the model. The horizontal advection is represented by the first two terms in the right-hand-side of (1). The fourth and the fifth terms describe the horizontal diffusion. The deposition terms, $-(\kappa_{1s}+\kappa_{2s})c_s$, are linear in the Danish Eulerian Model, while the contribution of *emission + chemistry*, given by the terms $E_s + Q_s(c_1, c_2, \ldots, c_q)$, introduces non-linearity in the model. Finally, the vertical exchange is described mathematically by the third and the sixth terms in (1). Some further information about the notation used is given below:

- the concentrations of the chemical species are denoted by c_s, $s = 1, 2, \ldots, q$,
- u, v and w are wind velocities,
- K_x, K_y and K_z are diffusion coefficients,
- the emission sources are described by the terms E_s,
- κ_{1s} and κ_{2s} are deposition coefficients (for the dry and wet deposition respectively),
- the chemical reactions are denoted by $Q_s(c_1, c_2, \ldots, c_q)$ (it will be assumed in this deliverable that the condensed CBM IV chemical scheme is used in the chemical part; this scheme has been described in Gery et al., [10]; see also Zlatev, [31]).

The space domain of the model (it contains the whole of Europe together with parts of Asia, Africa and the Atlantic Ocean) has been discretized by using a (96×96) grid. This means that (i) Europe is divided into 9216 grid-squares and (ii) the grid resolution is approximately $(50\ km \times 50\ km)$. The model can also be run on the sub-domains of the space domain sketched above.

Appropriate initial and boundary conditions are needed. Different initial and boundary conditions are discussed in Zlatev [31]. Furthermore, large sets of input data, meteorological data and emission data, are also needed in the model. The sets of input data and their reliability are described in Zlatev [31].

There are several versions of the Danish Eulerian Model. The model is often run as a two dimensional model. The mathematical terms describing the vertical transport are removed in this situation, however some vertical exchange between the boundary layer and the free troposphere is still assumed in the two-dimensional version of the Danish Eulerian Model; see Zlatev et al. [33].

Much more details about the model can be found in Zlatev [31] and Zlatev et al. [34], [36], [37].

Need for high performance computing It is necessary to discretize the PDE system (1) and to split it (by using ideas advocated in Marchuk, [20], and McRae et al., [21]). This leads to the necessity to handle several very large systems of ordinary differential equations (ODEs) per time step. The complexity of the problems solved depends on

1. the size of the ODE systems,
2. the number of time-steps that are to be performed in the run under consideration,
3. the number of runs that are to be carried out in the selected set of scenarios.

The size of the ODE systems is equal to the product of the number of chemical species involved in the model and the number of grid-points. Some results concerning some versions of the Danish Eulerian Model are given in Table 1. It is seen that the use of more advanced chemical schemes and/or refined spatial resolution lead to a great increase of the number of equations in the ODE systems. It should be stressed that the figures are for the multi-layer (three-dimensional) version with ten layers. The figures become considerably smaller (ten times) when the one-layer (two dimensional) version is used, but the tasks are still very big.

Number of species	$(32 \times 32 \times 10)$	$(96 \times 96 \times 10)$	$(192 \times 192 \times 10)$
1	10240	92160	368640
2	20480	184320	737280
10	102400	921600	3686400
35	358400	3225600	12902400
56	573440	5160960	21381120
168	1720320	15482880	61931520

Table 1

The number of equations per system of ODE's that are to be treated at every time-step. The number of time-steps for the chemical sub-model is sometimes even larger, because smaller step-sizes have to be used in this sub-model.

The number of the time-steps depends on the particular task which is to be solved. It varies from several hundreds (pollution forecasts) to several hundred thousands (long-term calculations over a time period of ten years). Some more details are given in Table 2.

Time period	Typical task	Time-steps needed
Two-three days	Preparing pollution forecasts	> 300
One month	Studying monthly mean values	> 3400
One season	Studying summer periods for ozone	> 11000
One year	Studying seasonal variations	> 40000
Several years	Studying long-term trends	> 400000

Table 2

Approximate numbers of time-steps needed in several important types of tasks.

The number of runs can vary in a wide range (depending of the processes that are to be studied). About 720 runs were needed in the simulations carried out in Bastrup-Birk et al., [2] and Zlatev et al., [38]. Several thousand runs were performed in the comprehensive study of air pollution levels and the relationship between variations of emissions and air pollution levels, which was performed within the EUROAIR Project.

It is clear that the comprehensive studies needed in the efforts to prepare large amount of data which can be useful for biologists (studying different effects), different environmental specialists (both from governmental and non-governmental institutions) and decision makers can successfully be completed only if high performance computing is used. Indeed, this task will otherwise be impossible unless some mechanisms describing physical and chemical processes are simplified or even neglected.

Several high performance modules for the most time-consuming processes (the advection and the chemistry) were developed and attached to the model. These modules are based on numerical algorithms and ideas discussed in Alexandrov et al., [1], Bendtsen and Zlatev, [3], Brandt et al., [4], Brown et al., [5], Skelboe and Zlatev, [24], Zlatev, [28], [29], [30], Zlatev et al., [32], [35]. Some general recommendations from Hesstvedt et al., [15], Lambert, [18], Peters et al., [23], Verwer and Simpson, [27], have also been taken into account. Standard parallelization tools (MPI, the Message Passing Interface; see Gropp et al., [11]) have been used. This means that good performance should be expected on many parallel architectures. Some results obtained by using this new parallel version of the model are given in Table 3. The results on CRAY C92A are the best results which were available before the start of the EUROAIR Project. It is seen that now we are able run the model five times faster due to the new efficient modules attached to it. This gives us the possibility to treat now some big tasks which we could not solve before the start of the EUROAIR Project.

Computer	Processors	Time	Speed	v_{max}	Efficiency
CRAY C92A	1	1050	0.460	0.9	51%
POWER CHALLENGE	8	1252	0.384	2.0	19%
IBM SP	8	611	0.791	4.0	20%
IBM SP	32	197	2.452	16.0	15%

Table 3

Results obtained on three different high speed computers. The computing times are given in seconds. The computational speeds obtained in the runs and the theoretical maxima of the computational speeds for the different architectures, v_{max}*, are measured in GFLOPS (billions of floating point operations per second).*

Improving some mechanisms used in the description of some physical processes and in the representation of the output results. The improvement of mechanisms used in the description of different physical processes is a very complicated tasks. One should be aware that, because of the uncertainties in the input data (both emission data and meteorological data), the application of more advanced mechanisms in the description of the physical processes may not result in improvement of the quality of the calculated concentrations and depositions; no improvement of the accuracy of the results will be achieved when the errors due to uncertainties in the input data are dominating over the errors due to the mechanism we want to replace with a better one. The results can even become worse when a more advanced mechanism is applied if this advanced mechanism is very sensitive to the input data and ensures more accurate results only if the input data are also very accurate. Therefore one must be very careful: the output concentrations should be validated after every change of mechanisms for description of physical processes. Some more efficient graphical tools are necessary in the efforts to facilitate the validation procedures.

After many trials, it turned out that the following three more advanced mechanisms resulted either in a better quality of the output concentrations or in a more efficient presentation of the output data:

1. introduction of diurnal variations of the emissions due to nitrogen oxides,
2. introduction of seasonal variations in some dry deposition coefficients,

3. using better and faster graphical tools.

The uncertainties in the emission data are very large. We have one figure per grid square per year in the available now emission inventories. Therefore, it is necessary to develop a model, by which temporal variations can be simulated. For the emissions of nitrogen oxides, which depend strongly on the traffic sources, the diurnal variation (using larger emissions during the day and smaller during the night) gave good results. It should be noted that some seasonal variations of the sulphur emissions have been used in the model before the start of the EUROAIR Project. Finally, it should also be mentioned that while the human-made emissions are prepared by using the EMEP inventories, the algorithm proposed by Lübkert and Schöp, [19], has been used to produce natural VOC emissions.

Extensive comparisons of model results and measurements taken in different European countries indicated that it is worthwhile to introduce some seasonal variations in some dry deposition coefficients (by which the deposition in winter is reduced, while the deposition in summer is increased). This improves the results for some pollutants (as, for example, SO_2).

The new fast-running version of the Danish Eulerian Model allows us to run the model over long time-periods. We have run the model over a time-period of nine years, because we have input data for these years (from 1989 to 1997). There is no problem to run the model over longer time-periods, if we have the necessary input data. While the CPU time does not cause very big difficulties, running the model over such long time-periods caused some another kind of difficulties. Very huge output files had to be stored and used in both the validation of the model and in representation of the data so that the trends and the relationships are easily understandable also for non-specialists. Therefore new graphical subroutines were prepared by which the scope of visualizations was enlarged and/or the visualization process became faster. Also new animation programs were developed and used in the studies.

Validation of the output results. The model results must be validated before starting to use the model in long series of scenarios in order to study the variations of the calculated concentrations and depositions caused by variations of certain important parameters (as, for example, the emissions sources). There are two different ways to validate the results:

1. The ability of the numerical algorithms used in the model to produce accurate results can be checked by constructing test-examples the solution of which is known.
2. The ability of the model to calculate reliable concentrations and/or depositions can be checked by comparing the calculated by the model concentrations and/or depositions by corresponding measurements taken at stations in different countries.

Both checks are needed. If the first series of checks is successfully passed, then this means that the errors due to the numerical algorithms used are small. Thus, if we study the response of the model to the variations of some physical parameter (say, the emissions), then the errors due to the numerical algorithms will not interfere with the changes due to the variation of the parameter chosen, and correct conclusions about the relationship between the model results and the parameter varied can be drawn. If the second series of checks gives good results, then one should expect the model to produce reliable results also in situations where either the measurements needed are not available or measurements are not existent (air pollution forecasts, different control strategies studied by appropriate scenarios, etc.). In connection with the EUROAIR Project the second series of checks is much more important. This is why only the main ideas behind the first series of checks will be sketched and then the use of the second series of checks will be discussed in some more detail.

The well-known rotation test is normally used in the first series of checks. For the simple case where pure advection (horizontal transport in the atmosphere) is studied the rotation test has simultaneously been proposed in 1968 by two meteorologists (Crowley, [8] and Molenkampf, [22]). After that, this test has been used in several hundred publications. This test has been extended for the more complicated case where both advection and chemistry are studied in Hov et al., [16]. This extended version of the rotation test has been used in our experiments. The results indicate that both the algorithms chosen for the advection sub-model and the algorithms chosen for the chemical sub-model perform very well. It should be mentioned that some other tests (discussed in detail in Zlatev, [31]) have also been used in the efforts to evaluate the accuracy of the numerical methods used in the improved version of the Danish Eulerian Model.

The second series of tests is related to use of measurements in the validation procedure. There is a rather big network of measurement stations in Europe, which has been established about 20 years ago within EMEP (the European Monitoring and Evaluation Programme). The results of the measurements taken in all stations, which are located in different European countries, are collected at NILU (the Norwegian Institute for Air Research). After a careful control and calibration of the measured results, these can be used by air pollution modellers to validate the results of their models. Measurements for the period from 1989 to 1995 are at present available at NERI (we hope that we shall soon receive measurements for 1996 and 1997). All available data have been used to compare the calculated by the model concentrations and depositions with measurements. Some other measurements (mainly from Danish stations) have also been used in the comparisons. It should be mentioned here that results from comparisons with measurements have been presented in many publications; see, for example, Bastrup-Birk et al., [2], Harrison et al., [12], Zlatev et al., [33], [34], [38].

The results of the comparisons of the calculated by the improved version of the Danish Eulerian Model concentrations and depositions with the correspondent measurements taken at stations in different European countries have been presented by using

1. scatter plots
2. plots in which the temporal variations of the calculated concentrations and depositions are given together with the temporal variations of the correspondent measurements at the station under consideration.

The conclusion, drawn after a careful investigation of many hundreds of plots, is that the model is able to produce reliable results. The same conclusion can also be drawn by comparing the results obtained by the Danish Eulerian Model by results obtained by some other models (as, for example, the models discussed in Carmichael et al., [6], Chang et al., [7], Ebel et al., [9], Hass et al., [13], [14], Jakobsen et al., [17], Stockwell et al., [25], Venkatram et al., [26]). Two illustrations are given in this report:

1. The first illustration consists of four scatter plots; see Fig. 1 - Fig. 4.
2. the second illustrations shows comparisons of calculated and measured ozone concentrations over a long-term period (1989-1995); see Fig. 5 - Fig. 8.

Some comments are needed in connection with the second illustration. While the human-made emissions were in general reduced in many European countries in the period 1989 - 1995, no reduction of the monthly mean values of the ozone concentrations can be seen in Fig. 5 - Fig. 8. This is true both for the calculated and the measured ozone concentrations. This indicates that the mean monthly values of the ozone concentrations are rather insensitive to changes of the emissions. It will be shown in the next sub-section, however, that the changes of the emissions have some influence on the number of days in which the critical levels for ozone proposed by the Commission of the EU (the draft of the EU OZONE Directive from June 1998) are exceeded: the number of days in which the critical level of 120 ppb ozone concentrations is exceeded is reduced considerably when the human-made NO_x and VOC emissions are reduced. Thus, this example illustrates also the important fact that one should be very careful when conclusions are to be drawn.

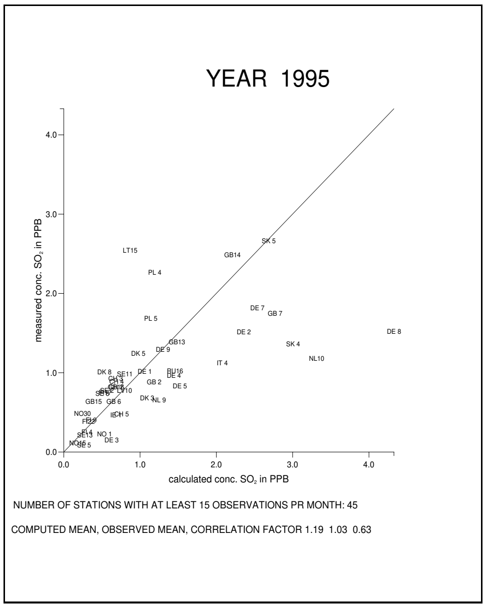

Figure 1. Calculated versus measured SO_2 concentrations

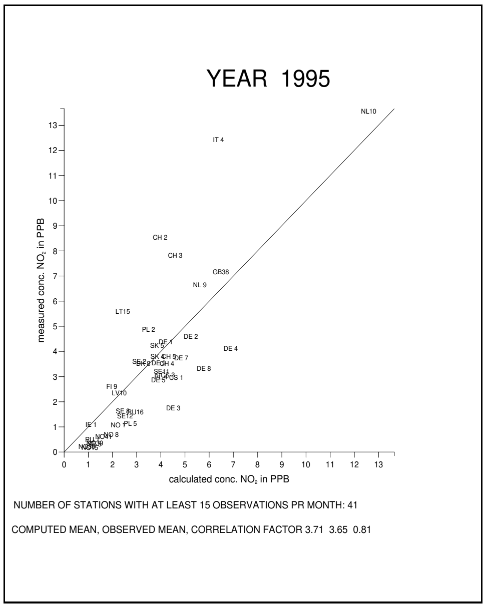

Figure 2. Calculated versus measured NO_2 concentrations

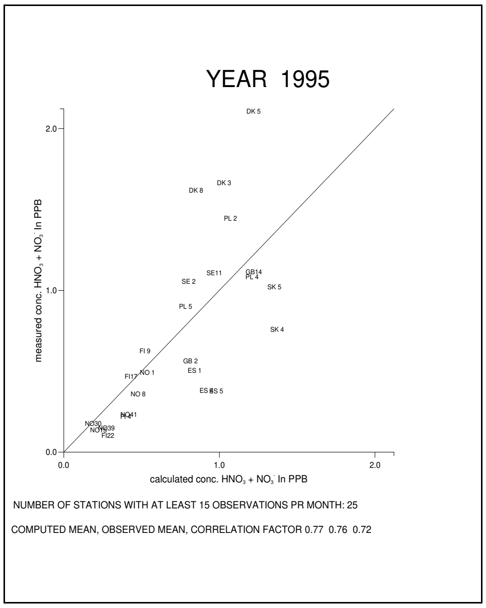

Figure 3. Calculated versus measured $HNO_3 + NO_3^-$ concentrations

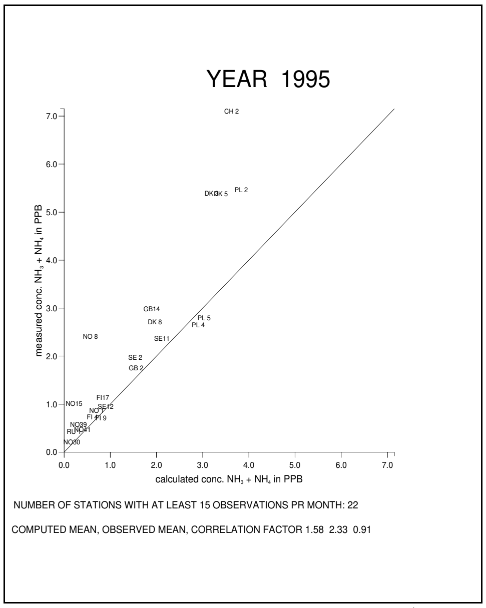

Figure 4. Calculated versus measured $NH_3 + NH_4^+$ concentrations

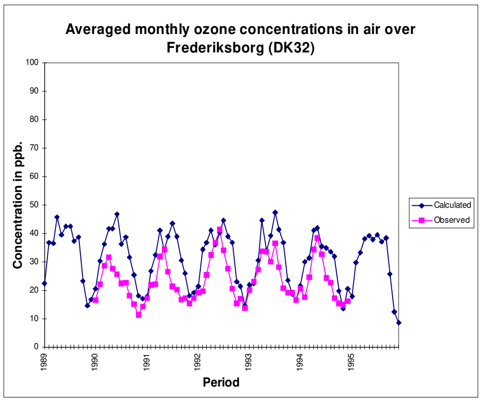

Figure 5. Comparison of averaged monthly calculated and measured ozone concentrations at Frederiksborg (Denmark) over a seven year period.

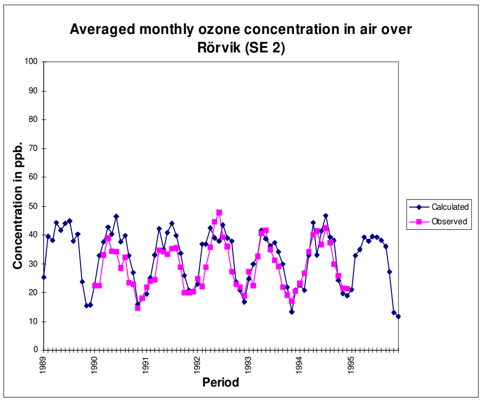

Figure 6. Comparison of averaged monthly calculated and measured ozone concentrations at Rörvik (Sweden) over a seven year period.

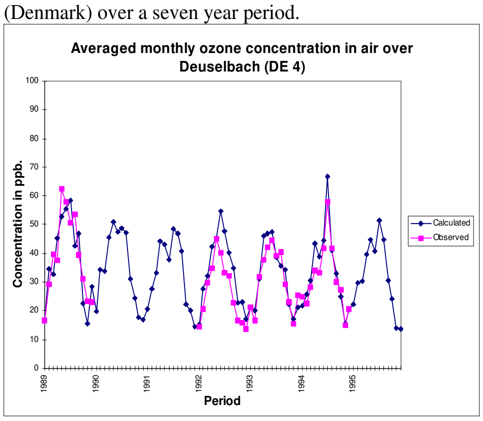

Figure 7. Comparison of averaged monthly calculated and measured ozone concentrations at Deuselbach (Germany) over a seven year period.

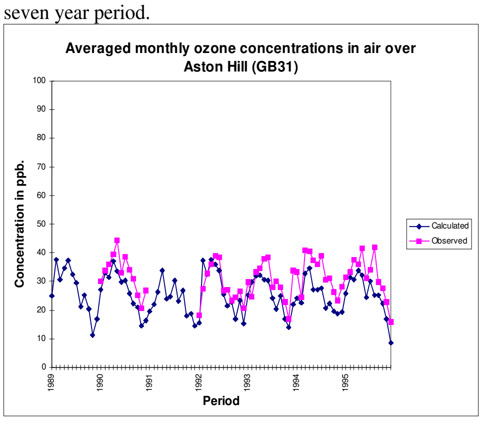

Figure 8. Comparison of averaged monthly calculated and measured ozone concentrations at Aston Hill (Great Britain) over a seven year period.

3.3 Results, Achievements and Benefits

Results obtained by using the Danish Eulerian Model in the EUROAIR Project. The improved version of the Danish Eulerian Model has been applied in a comprehensive study of different pollution issues concerning France. A long series of scenarios were run to study the following issues:

1. different pollution levels in France in a nine-year time period (1989-1997),
2. exceedance of critical levels in certain parts of France,
3. the changes of the air pollution levels in France in the period 1989-1997 as a results of the emission changes in France and in its surrounding countries in this period,
4. the effects of systematic reductions of French emissions on the concentrations and/or the deposition of corresponding emissions,
5. the contribution from foreign emission sources to the concentrations and the depositions in the French area,
6. the representation of the French pollution levels as functions of the variation of the French emissions.

The output data (several Gbytes) was handled by fast graphical subroutines in order to represent it in a form which is easily understandable also for non-specialists. Several thousand plots have been produced (i) to represent graphically levels of concentrations and depositions of the most important pollutants on yearly, seasonal and monthly basis, (ii) to compare levels of concentrations and depositions for different years, for different emission scenarios and for different meteorological conditions and (iii) to draw curves giving temporal variations of concentrations and depositions at given grid-points.

Achievements and conclusions. It is impossible to discuss all achievements and conclusions in this report. Therefore only the main conclusions are listed and shortly discussed below (some more results can be found by using the WEB home pages for the EUROAIR Project):

1. While it is true that the pollution levels in France are in general lower than the correspondent levels in some of the surrounding countries, it is also true that some critical levels are exceeded in France.

   The low pollution levels are mainly due to the fact that the French emissions are also low (excluding ammonia emissions in some Western regions in France), but the meteorological conditions (dominating winds from the Atlantic Ocean) also play some role. The low pollution levels in France are shown in Fig. 9 - Fig 12. This is for 1997, but similar patterns (the concentrations in France are lower than the concentrations in some of the surrounding countries) can be seen if other years are used (and also different seasons and months).

   On the other hand, there are some problems with high ozone concentrations. In the draft of the EU Ozone Directive from June 1998 the following situations are considered as harmful for human health: (i) days in which there were periods of eight or more successive hours with ozone concentrations greater than 60 ppb, (ii) days in which there were periods of one or more hours with ozone concentrations greater than 90 ppb, and (iii) days in which there were periods of one or more hours with ozone concentrations greater than 120 ppb. The population must be informed when (ii) is happening or will likely happen in the next one-two days. The situation where (iii) takes place is declared as alert; the population must be warned when (iii) is happening or will likely happen in the next one-two days. Our experiments show that the above three critical levels have been exceeded in some French regions nearly every year in the period 1989-1997 (the only exception is in fact 1996; in this year the critical level of 120 ppb have not been exceeded in France). Some results for 1997 are given in Fig. 13 - Fig. 15. Note that this was the year where the French authorities had to take special measures in an attempt to reduce the high pollution levels by temporal reductions of some emissions from the traffic (giving free tickets for the public transport and not allowing the use of some private cars).

High ozone concentrations are dangerous not only for human health, but also for crops; the yield could be reduced when a certain parameter, AOT40, exceeds the critical level of 3000 ppb.hours; this critical level is also taken from the draft of the EU Ozone Directive. It is seen from Fig. 16 that the critical levels is exceeded by a factor more than five in certain areas of France.

2. The emissions in many European countries were reduced considerably in the period from 1989 to 1997 (the VOC emissions in the former German Democratic Republic were reduced by a factor of about three). Of course, this caused in general some reductions of the pollution levels in France. However, the changes are different in the different regions of France and/or for the different pollutants. For some pollutants there was even slight increase of the pollution levels in the regions close to the Spanish border, which is caused by the fact that some emissions were increased in Spain (the fact that the French emissions close to the Spanish border have been increased is illustrated in Fig. 17).

   It has been pointed out that the monthly mean values of the ozone concentrations seem to be quite insensitive to changes of the emissions. A careful study of the output data indicates that this is not true for some critical values for the ozone concentrations. Compare Fig. 15 (showing the numbers of days in which the critical level of 120 ppb is exceeded in 1997) with Fig. 18 (showing the numbers of days in which the critical level of 120 ppb is exceeded in 1989). It is clearly seen that the critical levels were more often exceeded in 1989 in which the emissions are greater.

   Many scenarios with reductions of emissions have been performed. The results indicate that when the French emissions are reduced with $p\%$, the reduction of the concentrations and the depositions in France is in general much less than $p\%$. This has been fully checked for $p = 10\%, 20\%, 30\%, 40\%$ and partially for some other values of p. If, for example, the French emissions are reduced by 20%, then the sulphate concentrations in most of the regions in France are reduced by only 4% to 6%; see Fig. 19. This shows clearly that common actions with the surrounding countries are to be taken if greater reductions are needed.

   Indeed, if **all** French emissions are set to zero, then again the sulphate concentrations in most of the regions of France are rather high; between 50% and 65% of the level when the French emissions are not reduced (see Fig. 20). This shows that the contribution of foreign emission sources to the concentrations and depositions of some pollutants in France is rather considerable.

3. The concentrations and depositions in France have been studied as functions of the changes of the French emissions. The relationships, see Fig. 21, seem to be close to linear (also for pollutants that participate in many chemical reactions; such as NO_2 and ozone). This was not precisely what should be expected, because many of the chemical reactions are non-linear. The fact that large parts of the concentrations and depositions of some pollutants are caused by transboundary transport (and, thus, do not depend on the French emissions) can be an explanation of this close to linear relationship. Some non-linear effects can be seen for the relationship between ozone concentrations and the French emissions; see Fig. 21.

Benefits. A very comprehensive study, concerning (i) the French pollution levels and (ii) different relationships between these levels and emissions, has been performed with an improved version of the Danish Eulerian model especially developed during the work on the EUROAIR Project. Similar studies can be carried out for other European regions. The benefits from this study can be summarized as follows:

1. It has been shown that some critical levels for ozone, which are related to human health, are often exceeded in France. This leads to the necessity to take some preventive measures when this happens (as a matter of fact, an attempt to do this has taken place in Paris in 1997). This can be done by (i) predicting the appearance of such episodes by using air pollution forecasts and (ii) finding an optimal solution telling us where and by how much some emission sources should be reduced (note the important fact that reductions may be needed not only in the regions where the episodes are going to take place, but also in some other neighboring regions).

2. It has been shown that some critical levels for ozone (the AOT40 levels), which are related to the yield from crops, have been exceeded every year during the period from 1989 to 1997. Moreover, the critical levels have been exceeded in some parts of France by a factor greater than five (see again Fig. 16 and note also that some of the model results have been confirmed by results from measurements). Therefore, it is necessary now to perform the following actions:

   - to estimate the price l of loses of crops due to the exceeded ozone levels,
   - to find optimal solution for the measures which have to be taken in order to avoid loses of crops

   and

   - to evaluate the price g of performing the optimal measures, which will eliminate the loses of crops.

   Then comparing l and g one should be able to decide if it is worthwhile to perform the needed measures or it is more worthwhile to accept the loses of crops (because the measures are too expensive). It may be best to accept some compromise (to reduce the loses to some level which could be achieved by some cheap measures, so that the net result will be some gain).

3. It has been shown that the transboundary transport is very important also for large countries as France (it was commonly accepted that this is true for little countries as Denmark). This means that it will be rather expensive if one country alone tries to solve its air pollution problems (because large reductions of its own emissions lead to small changes of some pollution levels). Therefore, it is necessary to take some common actions (involving probably all European countries). Optimal solution must be found during these common actions (such solution may lead to great savings).

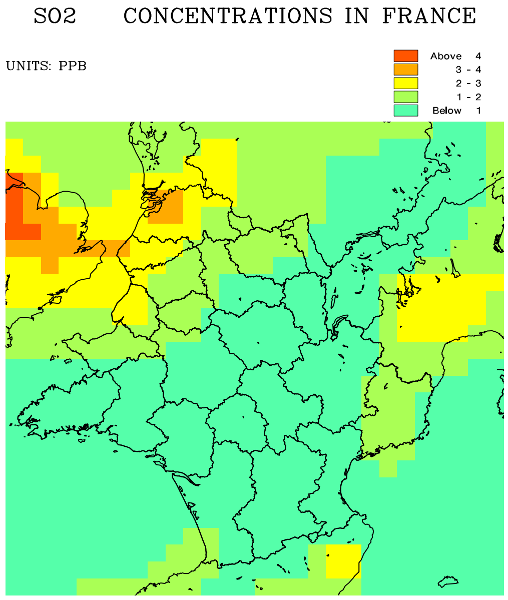

Figure 9
Sulphur di-oxide concentrations in 1997

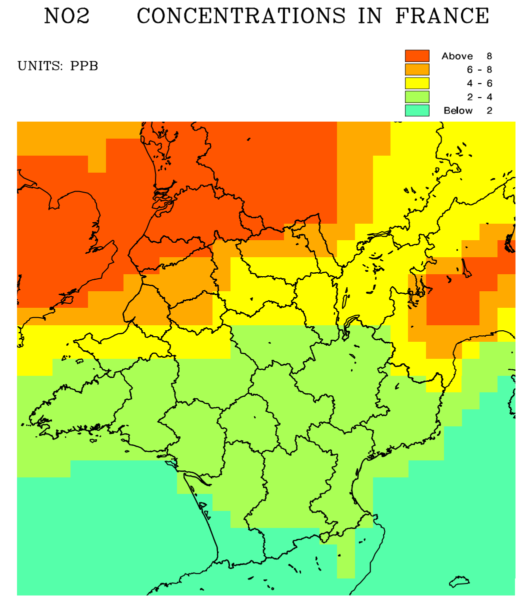

Figure 10
Nitrogen di-oxide concentrations in 1997

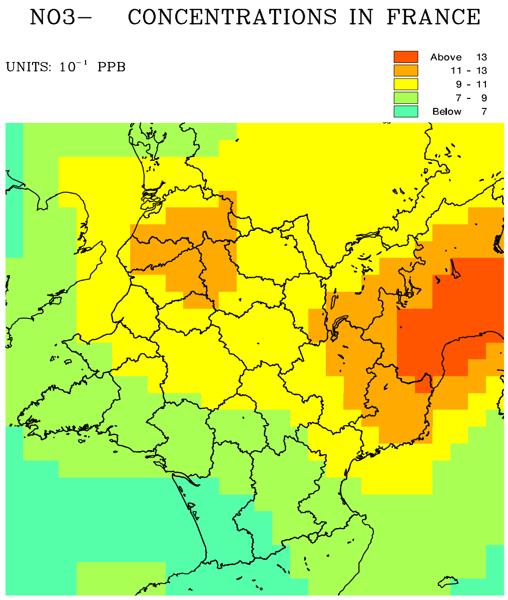

Figure 11
Nitrate concentrations in 1997

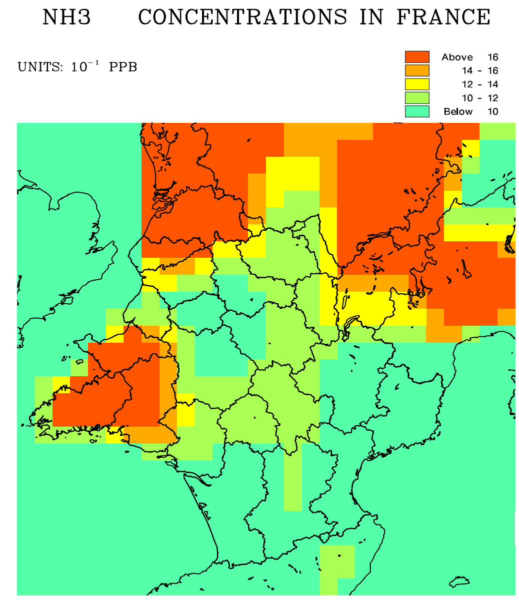

Figure 12
Ammonia concentrations in 1997

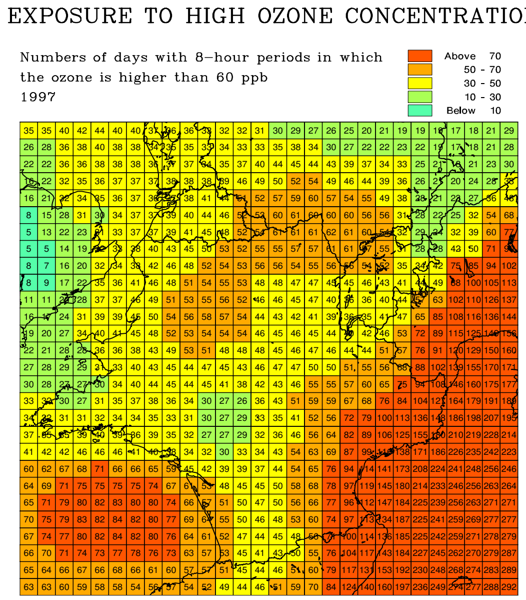

Figure 13
Numbers of days in which the ozone levels are higher than 60 ppb in at least 8 successive hours

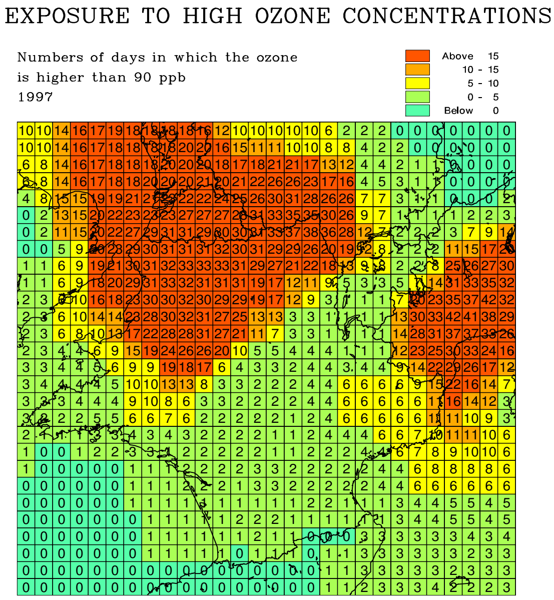

Figure 14
Numbers of days in which the ozone levels are higher than 90 ppb in at least one hour

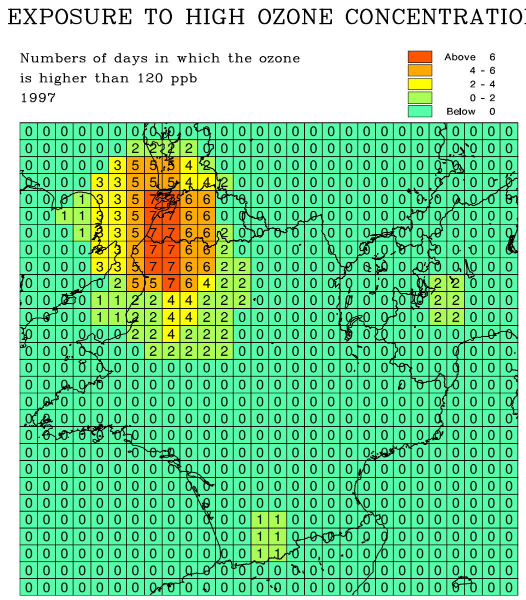

Figure 15
Numbers of days in which the ozone levels are higher than 120 ppb in at least one hour

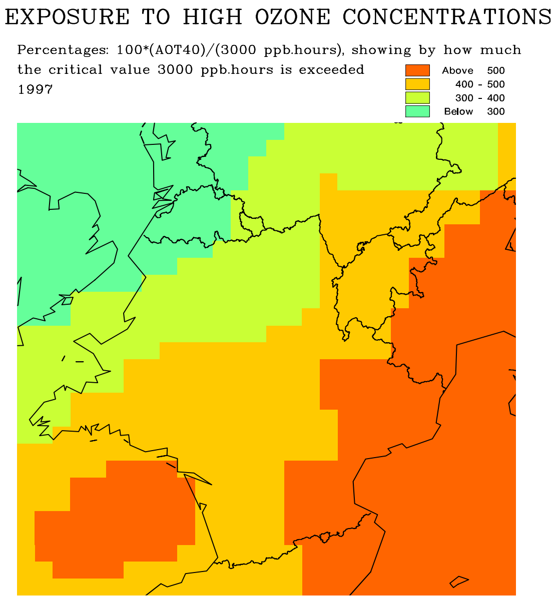

Figure 16
Exceedances of ozone critical levels for crops in percent

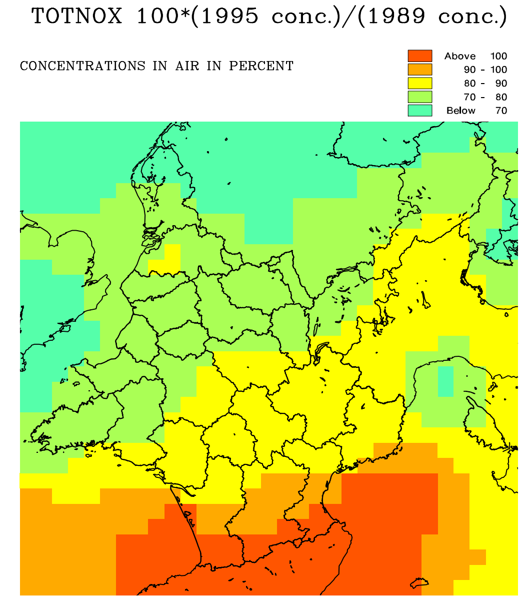

Figure 17
NO_x concentration changes in the period 1989-1995

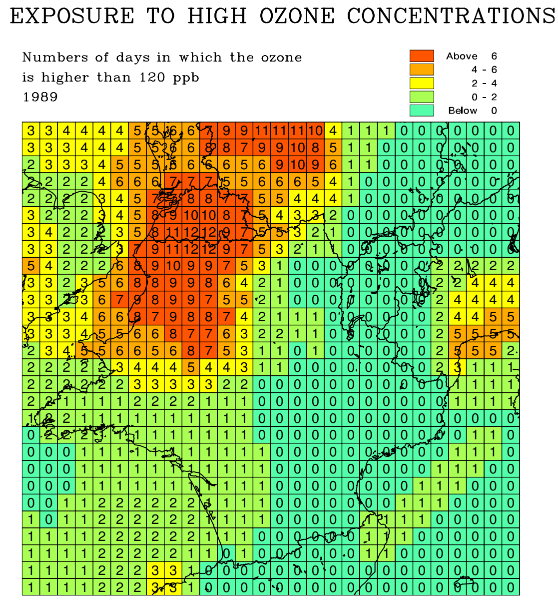

Figure 18
Numbers of days in 1989 in which the ozone levels are higher than 120 ppb in at least one hour

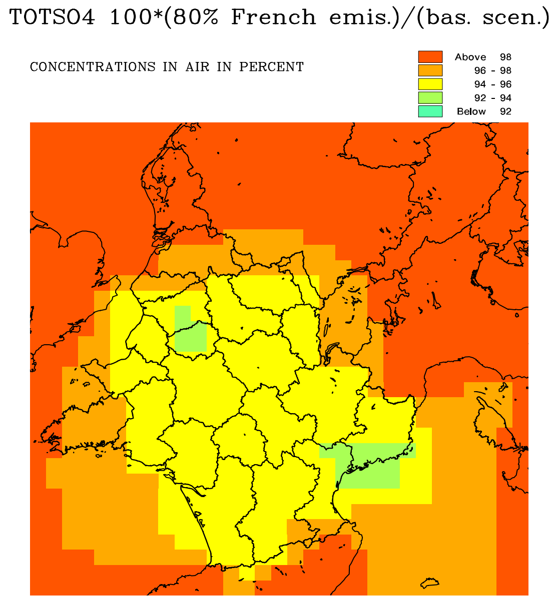

Figure 19
Changes of SO_4 concentrations caused by a 20% reduction of the 1995 French emissions

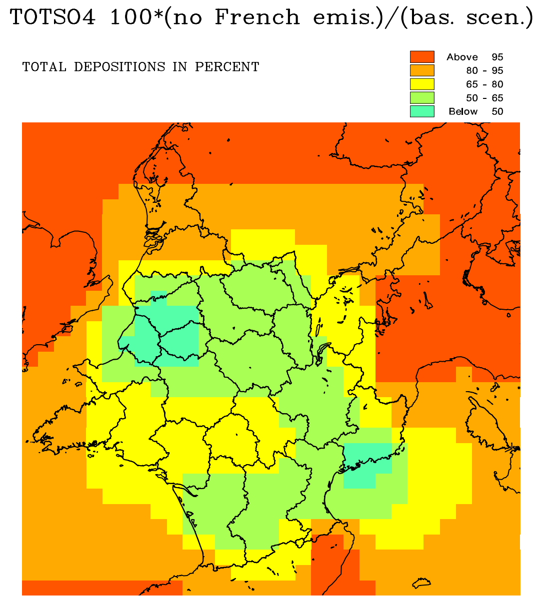

Figure 20
Changes of SO_4 depositions caused by setting the 1995 French emissions to zero

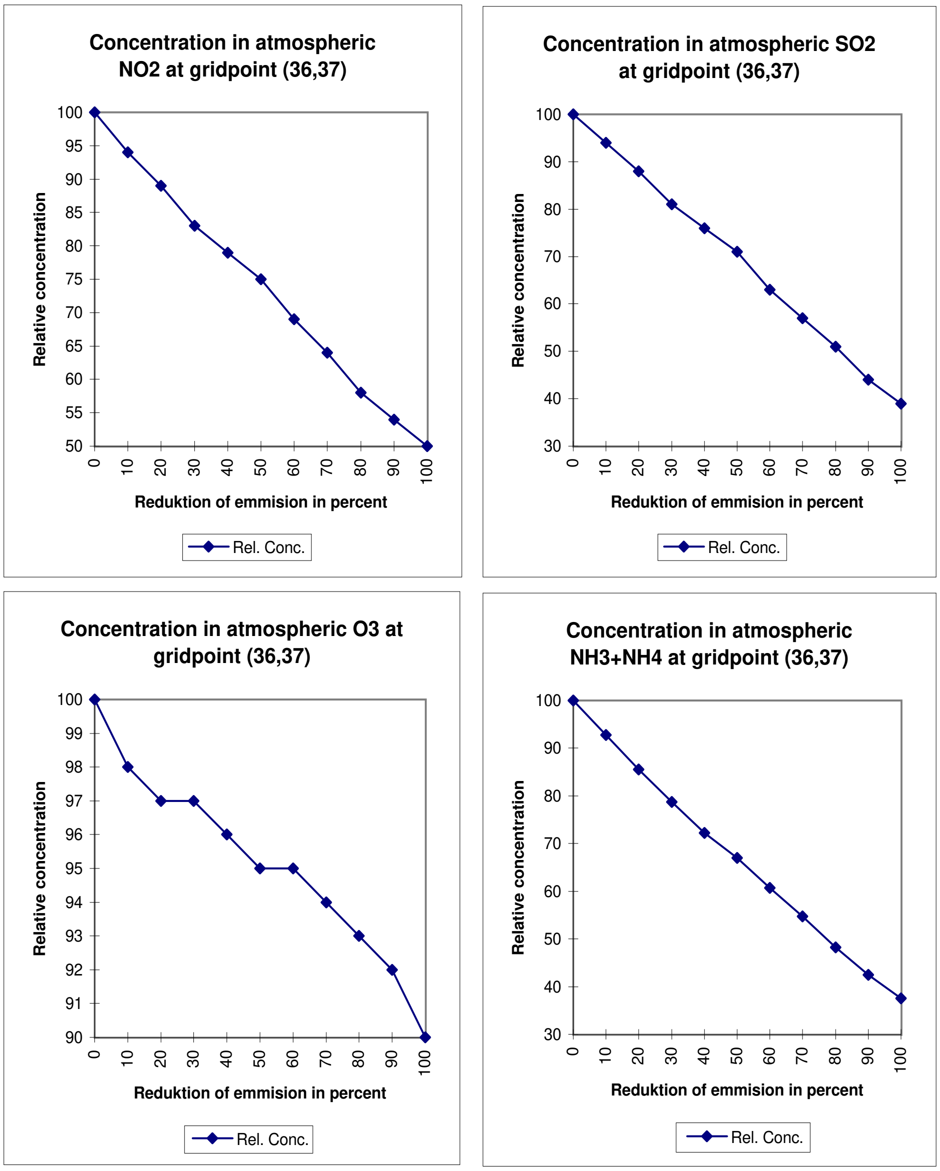

Figure 21

Variations (in percent) of concentrations at a grid-point in North-Western France for different emission scenarios

3.4 Dissemination

The main target audience that was addressed. Specialists which are working with environmental problems (both from governmental institutions and from non-governmental organizations), scientists studying effects from air pollution and decision makers have been contacted and informed of the work on the EUROAIR Project. Most of the contacts were made at different workshops.

List of external events. The participants in the EUROAIR Project participated in many meetings related to environmental modelling and presented results related to the work carried out within the EUROAIR Project. Many discussions with leading specialists in this area, which took place at all these meetings, helped us very much in our work on the EUROAIR Project. A list of the meeting is given below.

1. **The First GLOREAM Workshop.** The First GLOREAM Workshop was held in Aachen (Germany) from September 10 to September 12, 1997. GLOREAM stands for Global and Regional Air Pollution Modelling. The participants from the NERI team (Zahari Zlatev, Jørgen Brandt and Annemarie Bastrup-Birk presented three contributions at this Workshop, which were published in the proceedings. Zahari Zlatev, who is a member the Steering Committee of GLOREAM, participated in a meeting of this committee.
2. **Environmental Management Modeling and Simulation Workshop.** The Environmental Management Modeling and Simulation Workshop was held in Albuquerque (USA) from September 22 to September 25, 1997. Zahari Zlatev participated in the discussions of the modelling group. He presented also a poster with results obtained with the Danish Eulerian Model. Also informal discussions with American specialists about management issues related to air pollution modelling took place.
3. **Symposium on Regional Weather Prediction on Parallel Computer Environment.** The Symposium on Regional Weather Prediction on Parallel Computer Environment was held in Athens (Greece) from October 15 to October 18, 1997. Zahari Zlatev was invited to present a paper there (which will be published in the proceedings of the meeting). Closer connections were established with Prof. George Kallos and his group from the University of Athens. Some plans for future cooperative work with this group were discussed during this meeting.
4. **Fourth European PVM/MPI Users' Group Meeting.** The Fourth European PVM/MPI Users' Group Meeting was held in Krakow (Poland) from November 3 to November 5, 1997. Zahari Zlatev has been an invited speaker at this meeting (and the organizers paid all expenses). The HPCN issues related to the Danish Eulerian Model were discussed in the talk and in many informal conversations after the talk.
5. **EUROTRAC Workshop.** The EUROTRAC Workshop was held in Garmisch-Partenkirchen (Germany) from March 23 to March 27, 1998. EUROTRAC is a common European project for studying transport and chemical transformations in the troposphere. Two posters were presented by the group from NERI (and will be published in the proceedings). Zahari Zlatev participated in a meeting of the Steering Committee of GLOREAM which has been held during the EUROTRAC Workshop (GLOREAM is a part of EUROTRAC).
6. **The EGS 23rd Assembly**. The European Geophysical Society (EGS) XXIII Assembly was held in Nice, France, from April 20 to April 24, 1998. Jørgen Brandt was the co-convener and chairman and gave a presentation at the session: "OA11, Mesoscale Transport of Air Pollution Including Land/Sea Areas".
7. **NATO ARW on Large Scale Computations in Air Pollution Modelling.** The NERI team organized an ARW (Advanced Research Workshop) on "Large Scale Computations in Air Pollution Modelling". This workshop is sponsored by NATO (through their scientific programmes; grant ENVIR.ARW.971731) and was held in Sofia (July 6-10 1998). Results from the EUROAIR project were reported at this meeting. Many distinguished specialists from the field of environmental modelling attended the meeting in Sofia and discussed the problems arising in this field. Zahari Zlatev is a director of the ARW. There is an WEB home page for this meeting; its address is

   http://www.dmu.dk/atmosphericenvironment/natoarw
8. **Mini-symposium at a SIAM Meeting.** Zahari Zlatev has been invited to organize a mini-symposium on "High Performance Computing in Air Pollution Modelling" at the Annual SIAM Meeting which will be held from July 13 to July 17 1998 in Toronto (Canada). SIAM stands for Society for Industrial and Applied Mathematics. Scientists from Italy, Greece, the Netherlands and Denmark presented talks at this mini-symposium.

9. **4th Conference on Numerical Methods and Applications.** Zahari Zlatev has been an invited speaker and a member of the Organizing Committee at this meeting, which took place in Sofia (Bulgaria) from August 19 to August 23, 1998. Open problems connected to the numerical algorithms used in the Danish Eulerian Model have been discussed with several distinguished numerical analysts at this meeting.
10. **Fiftth European PVM/MPI Users' Group Meeting.** The Fourth European PVM/MPI Users' Group Meeting was held in Liverpool (England) from September 7 to September 9 1998. Zahari Zlatev has been an invited speaker at this meeting (and the organizers paid all expenses). The HPCN issues related to the Danish Eulerian Model were discussed in the talk and in many informal conversations after the talk.
11. **The Second GLOREAM Workshop.** The Second GLOREAM Workshop was held in Madrid (Spain) from September 15 to September 18, 1998. GLOREAM stands for Global and Regional Air Pollution Modelling. The participants from the NERI team (Zahari Zlatev and Jørgen Brandt presented two contributions at this WORKSHOP, which will published in the proceedings. Zahari Zlatev, who is a member the Steering Committee of GLOREAM, participated in a meeting of this committee. Several participants from the Nordic countries held a meeting on sensitivity tests with air pollution models in connection with a common project sponsored by NMR (the Nordic Council of Ministers); Zahari Zlatev is a coordinator of this project.
12. **23rd NATO/CCMS Meeting on Air Pollution Modelling and Its Applications.** This meeting was held in Varna (Bulgaria), from September 28 to October 2, 1998. Zahari Zlatev gave a talk and participated in a formal discussion about Long-range Transport of Air Pollution as well as in many informal discussions about the use of large scale air pollution models in different studies.
13. **International Conference on Air Pollution Modelling and Simulation.** This meeting has been held in Camps-sur-Marne (France) from October 26 to October 29, 1998. Zahari Zlatev and Jørgen Brandt presented two contributions at this conference. Zahari Zlatev was also a member of the Organizing Committee. Some of the best specialists in large scale environmental modelling are participating in this conference.

List of dissemination materials. During the work on the EUROAIR Project the following dissemination materials were produced:

1. Brochure about the EUROAIR Project.
2. Several simple videos demonstrating the distribution of high concentrations in Europe and parts of Europe (first and foremost, the distribution of high ozone concentrations).
3. WEB home pages for the EUROAIR Project http://www.dmu.dk/AtmosphericEnvironment/euroair.
4. An anonymous ftp (all deliverables and some related reports are available to interested specialists from this ftp).

List of publications. Results obtained during the work on the EUROAIR Project were used in many publications. Every time this happened the support from the EUROAIR Project has been acknowledged. A full list of such papers is given below.

1. **V. Alexandrov, A. Sameh, Y. Siddique and Z. Zlatev:** *"Numerical integration of chemical ODE problems arising in air pollution models".* Environmental Modelling and Assessment, **Vol. 2, 1997**), 365-377.
2. **C. Ambelas Skjøth, A. Bastrup-Birk, J. Brandt and Z. Zlatev:** *"Studying ozone episodes in Europe with the Danish Eulerian Model".* In: **"Air Pollution Modeling and Its Applications XXIII"**. Plenum Press, New York and London, to appear.
3. **A. Bastrup-Birk, J. Brandt, I. Uria and Z. Zlatev:** *"Studying cumulative ozone exposures in Europe during a seven-year period".* Journal of Geophysical Research, **Vol. 102, No. D20, 1997**, 23917-23935.
4. **A. Bastrup-Birk, J. Brandt and Z. Zlatev:** *"Long term calculations with the Danish Eulerian Model".* In: **"Global and Regional Atmospheric Modelling"** H. Hass and I. J. Ackermann, eds.), pp. 147-156. Proceedings from the First GLOREAM Workshop, Ford Research Centre, Aachen, Germany, 1998.
5. **A. Bastrup-Birk, J. Brandt and Z. Zlatev:** *"Modelling transport and dispersion from accidental releases".* In: **"Global and Regional Atmospheric Modelling"** (H. Hass and I. J. Ackermann, eds.), pp. 167-176. Proceedings from the First GLOREAM Workshop, Ford Research Centre, Aachen, Germany, 1998.

6. **A. Bastrup-Birk, J. Brandt and Z. Zlatev:** *"Using partitioned ODE solvers in large air pollution models"*. Systems Analysis Modelling Simulation, **Vol. 32 (1998)**, pp. 3-17.

7. **A. Bastrup-Birk, J. Brandt and Z. Zlatev:** *"Modelling Atmospheric Transport, Dispersion, and Deposition on Short and Long Range - Validation Against ETEX-1, ETEX-2, and Chernobyl - a contribution to subproject GLOREAM"*. In **"Proceedings from the EUROTRAC-2 Symposium, March 23-27, 1998, Garmisch-Partenkirchen, Germany. Transport and Chemical Transformation of Pollutants in the Troposphere"**, pp. 4, to appear.

8. **A. Bastrup-Birk, J. Brandt and Z. Zlatev:** *"Studying Air Pollution Problems in Europe by Using the Danish Eulerian Model and TreGro (contribution to the EUROAIR EU-Project) - A contribution to subproject GLOREAM"*. In **"Proceedings from the EUROTRAC-2 Symposium, March 23-27, 1998, Garmisch-Partenkirchen, Germany. Transport and Chemical Transformation of Pollutants in the Troposphere"**, pp. 4, to appear.

9. **A. Bastrup-Birk, J. Brandt and Z. Zlatev:** *"Real time predictions of transport and dispersion from a nuclear accident"*. In: **"Large Scale Computations in Air Pollution Modelling"**. Kluwer Academic Publishers, Dordrecht, to appear.

10. **A. Bastrup-Birk, J. Brandt and Z. Zlatev:** *"Studying air pollution levels in Europe with the Danish Eulerian Model"*. In: **"Measuring and Modelling Integration on Environmental Processes"**. Computational Mechanics Publications, Southampton, to appear.

11. **C. Bendtsen and Z. Zlatev:** *"Running air pollution models on message passing machines"*. In: **"Parallel Virtual Machine and Message Passing Interface"** (M. Bubak, J. Dongarra and J. Wasniewski, eds.), pp. 417-426. Springer-Verlag, Berlin, **1997**.

12. **C. Bendtsen and Z. Zlatev:** *"Using the Message Passing Interface in Large Scale Air Pollution Models"*. Future Generation Computer Systems, to appear.

13. **J. Brandt, A. Bastrup-Birk, J. H. Christensen, T. Mikkelsen, S. Thykier-Nielsen and Z. Zlatev:** *"Testing the importance of accurate meteorological input fields and parameterizations in atmospheric transport modelling, using DREAM - validation against ETEX-1"*. Atmospheric Environment, to appear.

14. **J. Brandt, I. Dimov, K. Georgiev, I. Uria and Z. Zlatev:** *"Numerical algorithms for the three-dimensional version of the Danish Eulerian Model"*. In: **"Regional Modelling of Air Pollution in Europe"** (G. Geernaert, A. Walløe Hansen and Z. Zlatev, eds.), pp. 249-262. National Environmental Research Institute, Roskilde, Denmark, **1997**.

15. **J. Brandt and Z. Zlatev:** *"Studying long-range transport from accidental nuclear by mathematical models"*. In: **"Large-scale Scientific Computations in Engineering and Environmental Mathematics"**, Notes in Numerical Fluid Dynamics, Vol. 62 (M. Griebel, O. Iliev, S. Margenov and P. S. Vassilevski, eds.), pp. 136-144. Vieweg, Braunschweig, Wiesbaden, **1998**.

16. **J. Brandt and Z. Zlatev:** *"Efficient algorithms for the chemical part of large air pollution models"*. In: **"Large-scale Scientific Computations in Engineering and Environmental Mathematics"**, Notes in Numerical Fluid Dynamics, Vol. 62 (M. Griebel, O. Iliev, S. Margenov and P. S. Vassilevski, eds.), pp. 145-154. Vieweg, Braunschweig, Wiesbaden, **1998**.

17. **I. Dimov, K. Georgiev and Z. Zlatev:** *"Long-range transport of air pollutants and source receptor relations"*. In: **"Large-scale Scientific Computations in Engineering and Environmental Mathematics"**, Notes in Numerical Fluid Dynamics, Vol. 62 (M. Griebel, O. Iliev, S. Margenov and P. S. Vassilevski, eds.), pp. 155-166. Vieweg, Braunschweig, Wiesbaden, **1998**.

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19. **K. Georgiev and Z. Zlatev:** *"Running an advection-chemistry code on message passing computers"*. In: **"Recent Advances in Parallel Virtual Machine and Message Passing Interface".** (V. Alexandrov and J. Dongarra, eds.), pp. 354-363 Springer-Verlag, Berlin, **1998**.

Several other publications (based on talks given at different international meetings) will soon be published. We are preparing a paper devoted entirely on the results from the demonstration presented in the EUROAIR Project, which will appear in 1999.

List of a direct mail actions. Some results from the EUROAIR Project have been advertized by using the subscribers of the network for atmospheric dispersion (GT-ATMD@NIC.SURFNET.NL).

3.5 Conclusions

The main objective of the EUROAIR Project was to collect comprehensive information about the pollution levels and about the relationships between emission variations and pollution levels for a given region in Europe. It was necessary first to prepare a high performance version of the Danish Eulerian Model by which runs over a long time periods (many years) can be carried out. This task was solved together with specialists from UNI-C. It was also necessary to define clearly the problems which have to be solved (the region with its sub-regions, the time-period, the scenarios, the relationships which are of interest and so on). This task was solved together with specialists from INERIS and the particular region chosen was France (but this is not important; the same problems can be studied for other regions in Europe). The main part of the work on these two tasks has been done in the beginning of the project, but some adjustments were made after then. The next task was to perform systematic studies by using the updated model according to the requirements from the end-user and to prepare carefully the results so that other specialists can easily apply them in further investigations. All this work was fully completed. The main conclusions can be summarized as follows:

1. It has been shown that the need to make simplifying assumptions only in order to be able to run the code on computers can in many cases be avoided by applying efficiently different high speed computers. By the use of HPCN, we were, moreover, able to solve tasks which we could not solve when we started the work on this project. This caused another problem: huge output files had to be handled in order to represent the digital information (by using graphical programs) so that it becomes easily understandable also for non-specialists. Therefore new and faster visualization techniques had to be selected and used.
2. It has been shown that some concentrations in certain periods are very high and, therefore, harmful (according to the established critical levels) for human health. It is necessary to work further for predicting the occurrence of such periods (by calculating air pollution forecasts) and to take some preventive measures when such periods are likely to appear in the next two-three days.
3. Long exposures to high ozone concentrations (measured by using a special quantity called AOT40) could damage the plants (as, for example, forest trees and crops). It has been verified in this projects that the AOT40 values exceed several times the critical values (accepted in EU); both in France and in many other regions in Europe. This leads to some loses (in USA the loses due to long exposures to high ozone concentrations are estimated to be between one and two billion dollars). The challenging task is to evaluate the loses in Europe that are caused by long exposures of crops to high ozone concentrations. Then an evaluation is needed of the price that has to be paid by taking preventive measures in order to avoid the loses. Finally some cost-benefit analysis is to be used in order to find an optimal solution, by which the loses can be avoided or, at least, reduced as much as possible if it is not possible to avoid them completely. Such a comprehensive problem should be attacked together with economists and specialists in effects from high pollution levels (first and foremost, biologists).
4. Runs over long-time periods are needed in the attempts to study different trends in the development of the air pollution levels in a given region and to predict what will happen in the future. Runs over long time periods are usually performed by making many non-physical assumptions to simplify the models used and to make it possible to handle them on the computers available. More precise and more reliable information can be achieved if such assumptions are not made. It was shown that the improved during the EUROAIR Project version of the Danish Eulerian Model can be run over very long periods (in fact, now the main problem is not to run the model over long time-periods, but to get high quality input data for the model).
5. The question: how can the pollution levels be reduced to some acceptable levels in an optimal way is important. It is clear now that reducing the emissions in **all** European countries with the same amount is not an optimal solution. It may even be impossible to carry out such a decision in the real life. It is not clear how countries which have to develop their industry, their traffic systems, their agriculture can meet such a requirement. This is the case for many Eastern countries. However, it should be mentioned that even in countries as Spain and Norway some emissions have been slightly increased during the last years. On the other hand, one country cannot alone reduce its pollution to desirable levels by reducing only its own emissions. It has been shown in the EUROAIR Project that even in a large European country as France, considerable reductions of its own emissions lead to a very modest reduction of some pollution levels (it was known that this is the case for the small European countries; such as Denmark). Therefore common actions are needed and, moreover, optimal solutions (telling us clearly where and by how much to reduce the emissions) are to be found.

The list of conclusions can be continued. However, it is also important to emphasize some requirements which are to be met in order to make the comprehensive studies even more useful. The main such requirements are:

1. The problems with input data are becoming more and more important. Better meteorological data and, which is even more important, better emission data are necessary.
2. If and when the problems with the availability of high quality input data are resolved (the hope is that this will happen in the near future), then some improvements in the existing air pollution models will become necessary. Some mechanisms used at present are rather simple and their use is justified only by the fact that the uncertainties in the input data cause the dominating errors.
3. The time is coming now when large scale air pollution models (or at least the results from large scale air pollution models) should be incorporated in integrated studies, where also large economical models are used. Optimal solutions can only be achieved by such an integrated approach where the economical issues are directly taken into account when decisions are to be made.

3.6 Contact details

The EUROAIR Project (ESPRIT # 24618) was a demonstration activity within DANHIT TTN. The project started on September 1 1997. Its duration was 12 months. The work on this project has been carried out by specialists from UNI-C, NERI and INERIS.

The specialists from UNI-C (a regional TTN node) were engaged with the HPCN issues connected to the project (mainly by helping the specialists from NERI to increase the efficiency of the Danish Eulerian Model on parallel computers).

The specialists from INERIS (i) supplied information about the sub-regions in France and some other information concerning distribution of emission sources in France, (ii) participated in the preparation of a set of scenarios and a plan for carrying out the computations for determination of the pollution levels in France over a long time period as well as for the investigations of the relationship between French emissions and pollution levels in France and (iii) participated in the interpretation of the results.

The specialists from NERI (i) improved the existing model (the parallel issues together with specialists from UNI-C), (ii) performed all runs needed to prepare a comprehensive data base of results concerning the pollution in France and (iii) visualize the output results.

All three institutes participated actively both in the interpretation of the results and in their dissemination.

The total EU support for this project was 17 man-months. However, the results were considerably improved by the fact that the NERI team got some additional support for several related projects from NATO, NMR (the Nordic Council of Ministers) and the Danish Natural Sciences Research Council. The team from NERI was the whole time strongly supported by the Director of the Department for Atmospheric Environment (first and foremost, it should be mentioned that we got several powerful computers during the work on the EUROAIR Project; UNI-C also supported partly the NERI team to obtain a very powerful ONYX2 computer, which was extensively used to improve the visualizations and animations of the output data).

The WEB home pages are http://www.dmu.dk/AtmosphericEnvironment/EUROAIR

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Acknowledgements

Some work in designing the code for efficient runs on the IBM SP has been performed by K. Georgiev from the Bulgarian Academy of Sciences during his stay at the National Environmental Research Institute in October -December 1997. This stay was partly supported by a grant received from NATO (OUTS.CRG.960312).

A grant from the Danish Natural Sciences Research Council gave us access to all Danish supercomputers.

The emission data and the meteorological data were obtained from the Norwegian Meteorological Institute in Oslo. They were prepared within the EMEP Programme. The last update of the emissions in Europe was used. We should like to thank S. Mylona for sending us the newest emission data.

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