Impact of Climate Changes on Pollution Levels in Europe

Final Report

NATO Project CLG 980505

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Scientists from five European Countries participated in the work on this project. The countries are:

***Bulgaria, Denmark, Hungary, Romania and Ukraine*.**

The work on this project started in June 2004 and is finishing in June 2006. In this time the participants in the project documented their research on the topic in 52 scientific publications (listed in Appendix 1 in this final report). More than other 15 publications are in print.

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Contents

Abstract

The impact of climate changes on the pollution levels in Europe is the major topic of this report. However, it is highly desirable to carry out such a study together with the investigation of the relationship between

(a) the impact of the climate changes on the European pollution levels

and

(b) the changes of the pollution levels that are due to a combination of the warming effect with some other factors.

In the latter case it was important to compare the changes of the European pollution levels that are caused by climatic changes with changes that are created by other factors (different emissions, inter-annual variability of meteorological conditions, etc.). Such an extensive comparison has successfully been accomplished by designing **four categories** of scenarios:

- traditional scenarios,
- climatic scenarios,
- scenarios with variations of the human-made (anthropogenic) emissions,
- scenarios in which the biogenic emissions were varied.

The total number of scenarios used during the work on this project was 14. It was necessary to run these scenarios on a long-time period in order to capture climatic variation. A time-period of 16 years was actually used.

The task of running 14 scenarios over a time-period of 16 years is extremely time-consuming. The storage requirements are also enormous. Therefore the task of running so many scenarios over so long time-period could be successfully solved only if several requirements are simultaneously satisfied:

- fast but sufficiently accurate numerical methods are to be implemented in the model,
- the cache memories of the modern computers have to be efficiently utilized,
- codes which can be run in parallel have to be developed and used,
- reliable and robust splitting procedures have to be implemented.

The solution of the four sub-tasks, which are listed above, will not be discussed in detail in this report. However, **the efficient solution of all these sub-tasks was crucial for the success of the whole project.** Some details about the success in the efforts to resolve these sub-tasks can be found in the papers published by the participants in the NATO Project CLG 980505 (a list of all papers published by the participants during the work on this project is given in Appendix 1 of this report; the major topics discussed in the publications are listed in Appendix 2, a short description of the particular tool used in this study, the large-scale air pollution model UNI-DEM, is presented in Appendix 3).

The results, which are presented in this report, show clearly that although the concentrations of the major pollutants do not depend too much on the climatic changes, some quantities, which are related to high pollution levels (first and

foremost, some quantities that are related to high ozone levels) and which can cause different damages **might be increased substantially as a result of the warming trends** in the future climate. It is carefully explained what is the reason for this phenomenon. Moreover, it is also emphasized that the results presented in this report indicate that some additional measures might be necessary in order to avoid exceedance of critical levels of some harmful pollutants. Many critical levels are established either by the authorities in the European Union or by the authorities in different European countries. Exceeded critical levels can cause damaging health effects (at least, for some groups of human beings), losses of crops, reduced biomasses from the forests, destruction of certain eco-systems, etc. It must be stressed here that year 2010 is crucial, because many measures are becoming obligatory in the European Union after this year.

The results of the emission scenarios indicate that such scenarios **should be run over a long period of years in order to make the conclusions more reliable.** Running such scenarios only for one year might provide some information about the sensitivity of the pollution levels to reductions of emissions. However, if the purpose is to find out by how much the emissions are to be reduced in order to prevent exceedance of critical levels, then the inter-annual variations of the pollution levels as a result of variation of meteorological conditions **will not** allow us to draw clear conclusions by running the emissions scenarios only for a single year. Long-term runs, at least over a period of 20-30 years, are needed in order to make it possible to decide what measures are to be taken in the efforts to reduce to a sufficiently low level the risk that a given critical level will be exceeded.

1. Introduction

Scenario SRES A2, taken from the IPCC report on climate changes (see Houghton et al. 2001), was used in this study in order to prepare a long sequence of air pollution scenarios for investigating the impact of predicted climatic changes on the pollution levels in Denmark and Europe. These scenarios were run over a period of sixteen consecutive years by applying **UNI-DEM** (the Unified Danish Eulerian Model). The most important features used in the development of UNI-DEM are described in detail in Zlatev (1995) and in Zlatev and Dimov (2006). Different studies performed by using UNI-DEM are discussed for example in Ambelas Skjøth et al. (2000), Bastrup-Birk et al. (1997), Geernaert and Zlatev (2004), Harrison et al. (1994), Havasi and Zlatev (2002), Zlatev et al. (2001) and Zlatev and Syrakov (2004a, 2004b). The major features of UNI-DEM are outlined in Appendix 3.

The variation of the concentration levels of potentially dangerous air pollutants during the period **from 1989 to 2004** is studied by applying different scenarios, which are based on

- the introduction of climatic changes,
- using a long time-interval in order to study the sensitivity of the model results to inter-annual variations of the meteorological conditions,
- different variations of the human-made (anthropogenic) emissions,
- increasing the biogenic emissions

as well as (and this is perhaps the most important factor)

- **different combinations** of the four factors from the previous items, i.e. different combinations of climatic changes, inter-annual variations of the meteorological conditions, variations of the human-made (anthropogenic) emissions and variations of the biogenic emissions.

The interplay of these four important factors as well as their combined impact on the formation of the **concentration levels** of different pollutants in different parts of Europe will be one of major aims of this study.

It should be stressed here, however, that the concentration levels **are not** the most important quantities when damaging effects from high air pollution levels are to be studied. Several other quantities, which are much more directly related to damages on plants, animals, eco-systems and human health, are much more important. Such quantities are discussed in several directives of the EC. Critical levels for such quantities, which are related to ozone pollution, are given in European Parliament (2002). It will be shown that even **relatively small changes** of the concentration levels may cause **considerable changes** of some of the related quantities (which in some situations will lead to exceeded critical levels and, thus, there will be a danger for damaging effects on some groups of recipients).

It should also be stressed that in many studies, including here studies that are intended to be used by policy-makers, the conclusions are normally taken by using simple scenarios based **only** on the variations of the human-made (anthropogenic) emissions (performed with meteorological data for a given single year). The results from such studies have (or, at least, may have) a limited value because two important issues:

- the considerably large inter-annual variation of the pollution levels

and

- the influence of the biogenic emissions

are, more or less, neglected when (a) the climatic changes, (b) the inter-annual variety of the meteorological conditions and/or (c) the biogenic emissions are not taken into account.

Different arguments are used to justify the decision to neglect these three factors (i.e. the climatic changes, the inter-annual variations of the meteorological conditions and/or the influence of the biogenic emissions) in air pollution studies. The results that will be given in the next sections **will show** very clearly that it is worthwhile (and perhaps also necessary) to develop and use a long sequence of scenarios, including scenarios related to climatic changes, inter-annual meteorological variety and biogenic emissions. Nevertheless, we feel that it is necessary to illustrate by one example the usefulness of including biogenic emissions in air pollution studies. It is often argued that the biogenic emissions are much lower than the corresponding human-made (anthropogenic) emissions (see, for example, Simpson et al, 1995, where the human-made and biogenic emissions are compared for year 1989). This statement is, of course, true when human-made (anthropogenic) and biogenic emissions for 1989 are compared (see Table 4 in Simpson et al., 1995). However, in some of the scenarios, which are proposed and used in Amann et al. (1999), it is assumed that the human-made (anthropogenic) emissions are reduced by quite large factors (up to 90%). It is obvious that the relative part of the biogenic emissions is becoming considerable for such scenarios and, thus, it is highly desirable, if not necessary, to take them into account.

2. Basic Scenario

The Basic Scenario was run over the period of sixteen years (from 1989 to 2004) by using meteorological data and emission data prepared partly by EMEP (European Monitoring and Evaluation Programme) and partly in NERI (National Environmental Research Institute, Roskilde, Denmark). The Basic Scenario was used

- to verify the model results

and

- to study the sensitivity of the model results to different changes of several essential parameters:
    - inter-annual meteorological conditions,
    - human-made (anthropogenic) and biogenic emissions

    and

    - climatic changes.

3. Constant meteorology versus constant anthropogenic emissions

Two traditional scenarios were prepared and used. In the first scenario constant meteorology (the meteorological data for 1989) was used. In the second of these two scenarios the human-made (anthropogenic) emissions for 1989 were used during the whole period (from 1989 to 2004).

When the first of these two scenarios, **Scenario Constant Meteorology**, is used, the trend showing reductions of the pollution levels is preserved, but the annual variability of the pollution levels disappears.

When the second scenario, **Scenario Constant Emissions**, is used, the annual variability of the pollution levels is preserved, but the trend showing reductions of the pollution levels disappears. The reductions of the European pollution levels are caused by the fact, which was mentioned in the previous sections, that the human-made (anthropogenic) emissions in Europe were reduced very considerably during the last two decades.

The main conclusion from the runs with these two scenarios (results from these runs will be given and discussed in Section 8) is that it is necessary to carry out calculations on **a long time-period** in order to be able to draw more useful and more reliable conclusions.

4. Climatic scenarios

The predictions about the increase of the annual temperatures in Europe according to the **IPCC SRES A2 Scenario** as well as several other conclusions, which are related to the climatic changes in Europe and which are discussed in Houghton et al. (2001), were used to prepare three climatic scenarios.

4.1. Climate Scenario 1

The predicted, by the **IPCC SRES A2 Scenario**, annual changes of the temperature were used to produce this climatic scenario. Resulting from this scenario changes of the temperature in Europe are shown in Fig. 4.1. Consider any cell of the grid used to create the plot shown in Fig. 4.1 and assume that this cell is located in a region in Fig. 4.1 where the increase of the temperature is in the interval [a,b]. The temperature at the chosen cell at a time n (where n is in the interval from 1989 to 2004) is increased by an amount $a + c(n)$, where $c(n)$ is randomly generated in the interval [0,b-a]. The mathematical expectation of the increase of the annual mean of the temperature at any cell of the space domain is (b-a)/2.

Only temperatures are varied in this scenario and **the mean value of the annual change** of the temperature at a given point will tend to be the same as that prescribed by the **IPCC SRES A2 Scenario** for each year of the chosen interval (from 1989 to 2004).

4.2. Climate Scenario 2

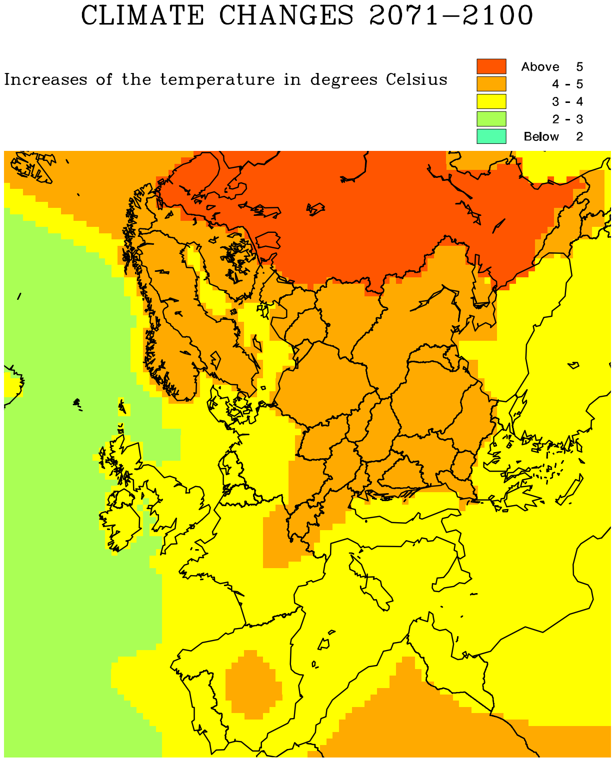
The extreme cases will become even stronger in the future climate; see Table 9.6 on p. 575 in Houghton et al. (2001). It is expected that:

- there will be higher maximum temperatures and more hot days in the land areas,
- there will be higher minimum temperatures, fewer cold days and fewer frost days in nearly all land areas

and

- the diurnal temperature range will be reduced over land areas.

We increased the temperatures during the night with a factor larger than the factor by which the daytime temperatures were increased. In this way the second and the third requirements are satisfied. The first requirement is satisfied as follows. During the summer periods the daytime temperatures are increased by a larger amount in hot days. All these changes are carried out only over land. Furthermore, the temperatures were varied in such a way that their annual means remained the same, at all cells, as those in the first climatic scenario. We also reduced the cloud covers over land during the summer periods.



<u>Figure 4.1</u>

Future changes of the temperatures in Europe and its surroundings according to Scenario SRES A2 from Houghton et al. (2001).

4.3. Climate Scenario 3

It is also expected, see Table 9.6 on p. 575 in Houghton et al. (2001), that:

- there will be more intense precipitation events

and

- there will be increased summer drying and associated risk of drought.

We increased the precipitation events during winter (both over land and over water). During summer, the precipitation events in the continental parts of Europe were reduced. Similar changes in the humidity data were made. The cloud covers during winter were increased, while the same cloud covers as in the second climatic scenario were applied in the third climatic scenario during summer.

Again, as in the previous two climatic scenarios, the mathematical expectation of the annual means of the temperatures is the same as the predictions made in the **SRES A2 Scenario**.

5. Scenarios related to human-made (anthropogenic) emissions

Several scenarios in which the human-made (anthropogenic) emissions are varied were prepared and run in the period 1989-2004. Two such emission scenarios:

- **Scenario 2010**

and

- **the MFR Scenario**; MFR stands for "maximum feasible reductions"

were run for all years (from 1989 to 2004). These scenarios are described and discussed in Amann et al. (1999). The reduction factors listed in Amann et al. (1999) were used to obtain reduced emissions for these two scenarios and the scenarios, which were obtained in this way, were run by using meteorological data for all years from 1989 to 2004. This means that the inter-annual variation of the meteorology conditions is preserved the same as in The Basic Scenario, while the emissions do not vary from one year to another.

Some information about the size of reductions (related to the 1990 emissions) can be seen in Table 1, where the reduction factors are given for several European countries and for Europe as a whole. The reduction factors listed in Table 1 show clearly that the predicted 2010 emissions (Scenario 2010) are very considerable in comparison with 1990. It will be shown in Section 8 (see Table 5) that the real reductions achieved in some countries (first and foremost, in some countries in Eastern and Central Europe) are even bigger in the middle of 90s. The reductions of the emissions of the hypothetical MFR Scenario are much bigger than the reductions of the emissions in Scenario 2010.

Table 1:

Reduction factors used in Amann et al. (1999) to obtain emissions for Scenario 2010 and the MFR Scenario. The emissions are obtained by multiplying the corresponding 1990 emissions with the reduction factors. The abbreviation REF is used in Amann et al. (1999) for Scenario 2010.

	Scenario 2010				Scenario MFR			
Country	SO2	NOx	VOC	NH3	SO2	NOx	VOC	NH3
Germany	0.11	0.44	0.36	0.75	0.06	0.23	0.21	0.47
Denmark	0.49	0.47	0.47	0.94	0.10	0.18	0.27	0.58
Bulgaria	0.46	0.84	0.97	0.89	0.07	0.17	0.19	0.61
Hungary	0.60	0.90	0.78	0.86	0.31	0.23	0.25	0.60
Romania	0.45	0.88	0.00	0.96	0.07	0.19	0.25	0.70
Ukraine	0.40	0.76	0.73	0.89	0.10	0.17	0.14	0.66
Europe	0.38	0.62	0.63	0.88	0.10	0.20	0.25	0.58

The emissions obtained in this way and used in Scenario 2010 and the MFR Scenario, were also used to derive two additional emission scenarios,

- **Scenario Climate 2010**

and

- **Scenario Climate MFR**.

These two scenarios are formed as a combination of

- the meteorological conditions derived from Climate Scenario 3

and

- the predicted human-made (anthropogenic) emissions from Scenario 2010 and Scenario MFR.

The latter two scenarios, which are combinations of emission scenarios with climatic scenarios, were also run over the whole period from 1989 to 2004.

5.1. Variation of the anthropogenic emissions in the studied period

It was mentioned several times in the previous sections that the human-made (anthropogenic) emissions in Europe have been reduced after 1989. In some parts of Europe the reductions are rather considerable (this is especially true for the $\mathbf{SO_2}$ emissions).

As a rule, the major reductions took place **in the beginning** of the 90s. The variations of the European human-made (anthropogenic) emissions (the $\mathbf{SO_2}$ emissions, the $\mathbf{NO_x}$ emissions, the **VOC** emissions, the **CO** emissions and the $\mathbf{NH_3}$ emissions) in the studied period (the period from 1989 to 2004) are shown

- in Fig. 5.1 (for the whole of Europe)

and

- in Fig. 5.2 – Fig. 5.6 (for the five countries participating in the NATO Project CLG 980505 on the *"Impact of Climatic Changes on Pollution Levels in Europe"*).

It is seen that the human-made (anthropogenic) emissions in countries in Eastern and Central Europe are showing a slight trend of increasing after the middle of 90s.

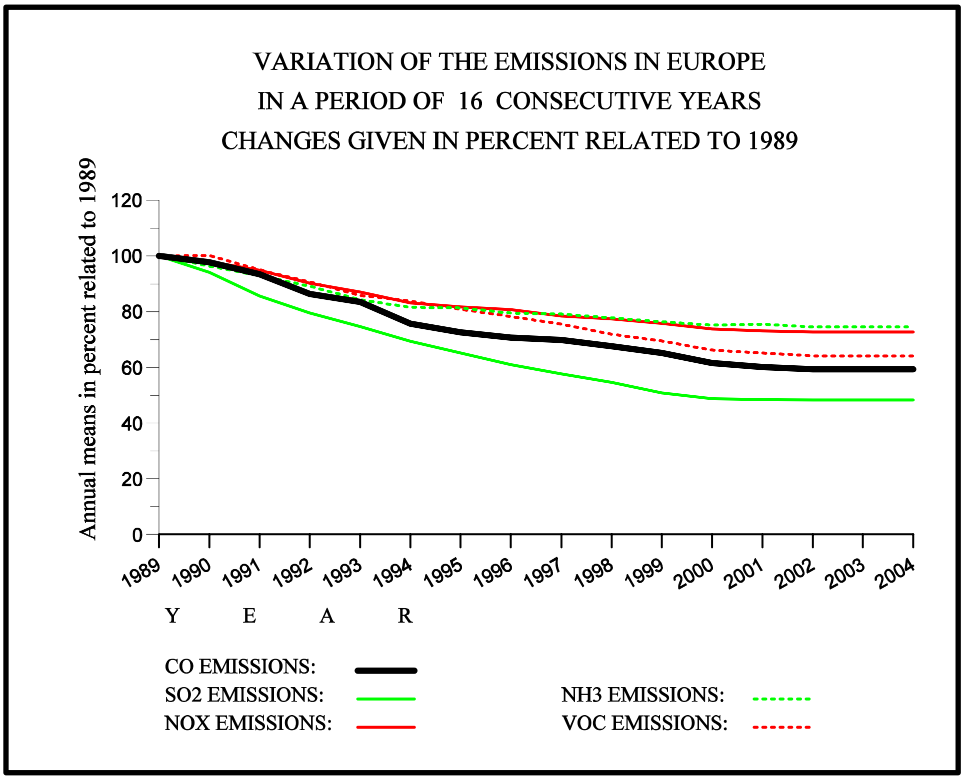


Figure 5.1

Variation of the European human-made (anthropogenic) emissions in the period 1989-2004.

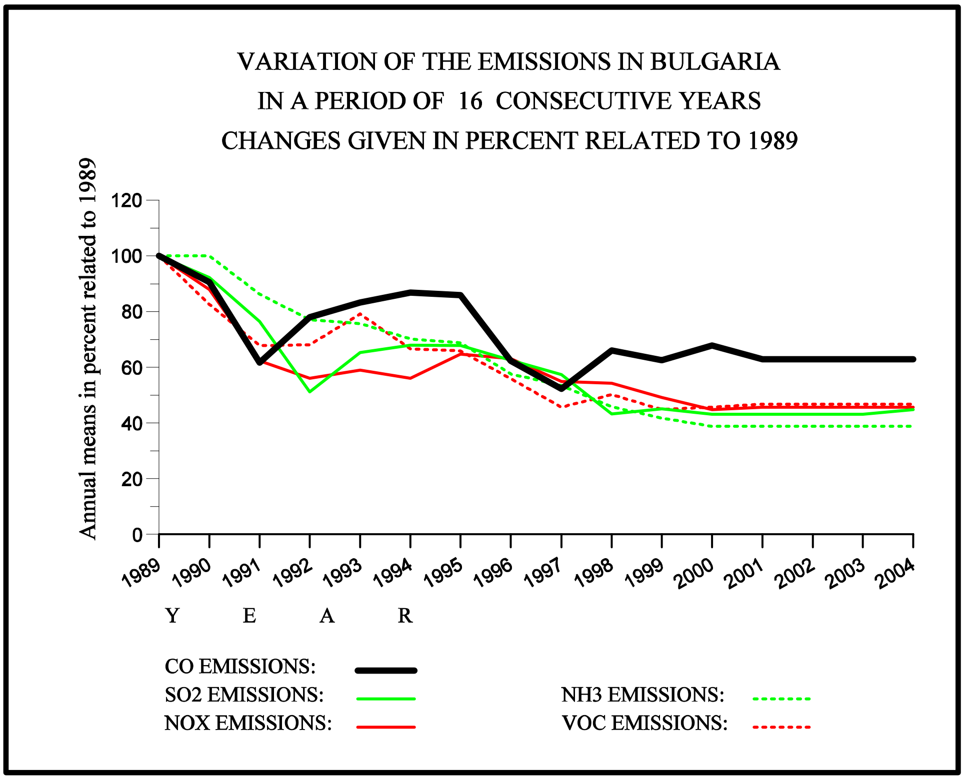


Figure 5.2

Variation of the Bulgarian human-made (anthropogenic) emissions in the period 1989-2004.

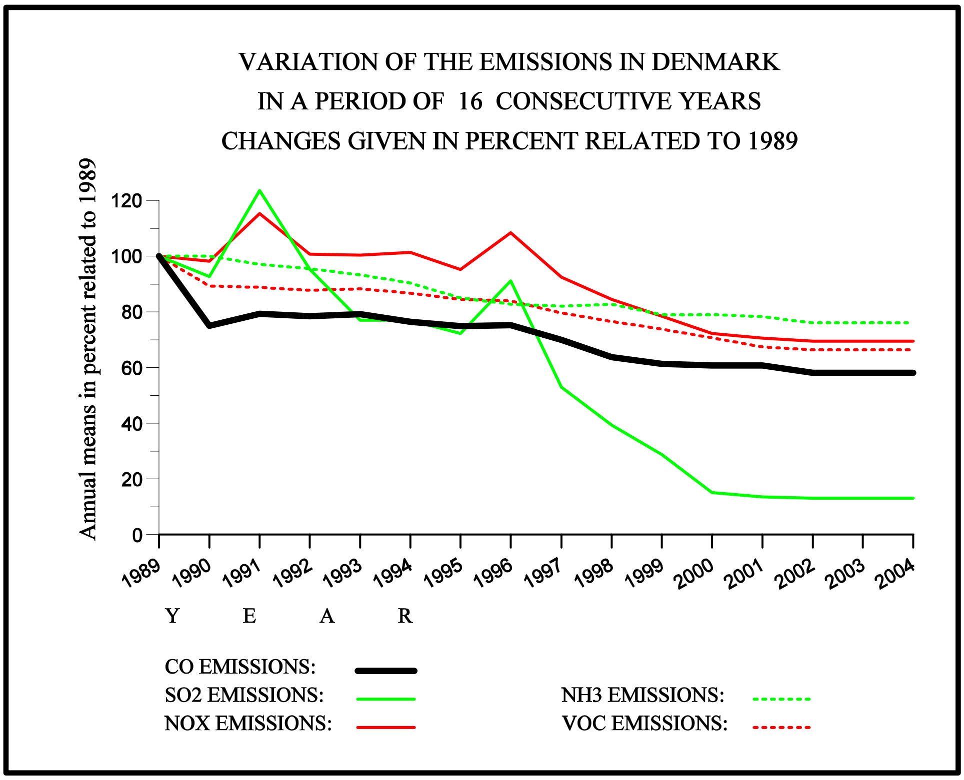


Figure 5.3

Variation of the Danish human-made (anthropogenic) emissions in the period 1989-2004.

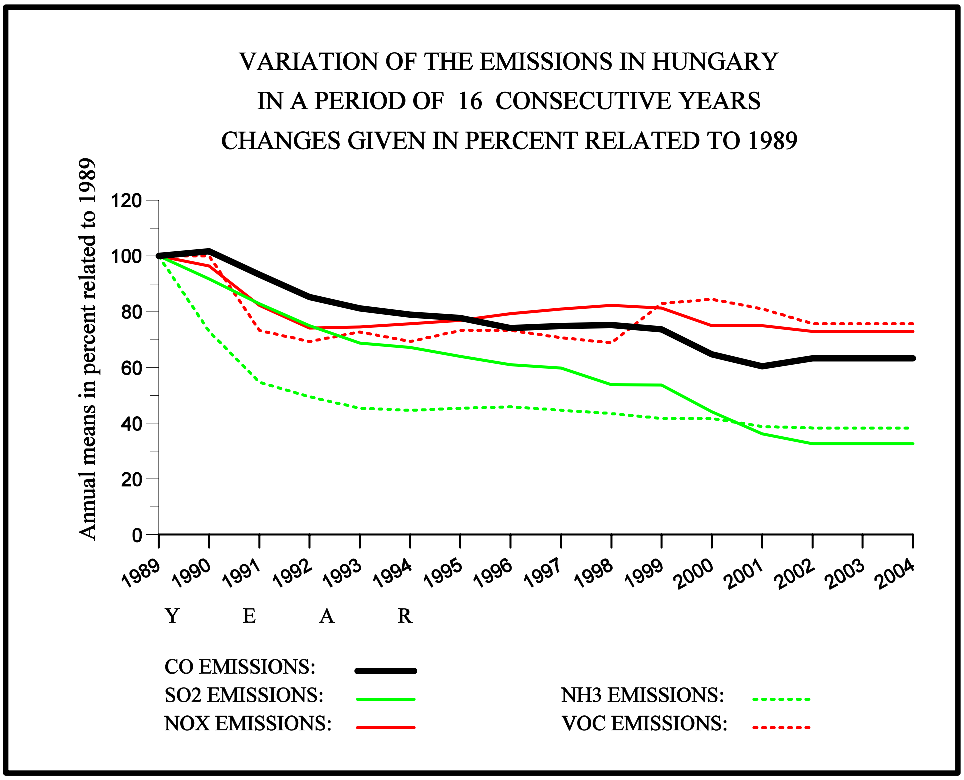


Figure 5.4

Variation of the Hungarian human-made (anthropogenic) emissions in the period 1989-2004.

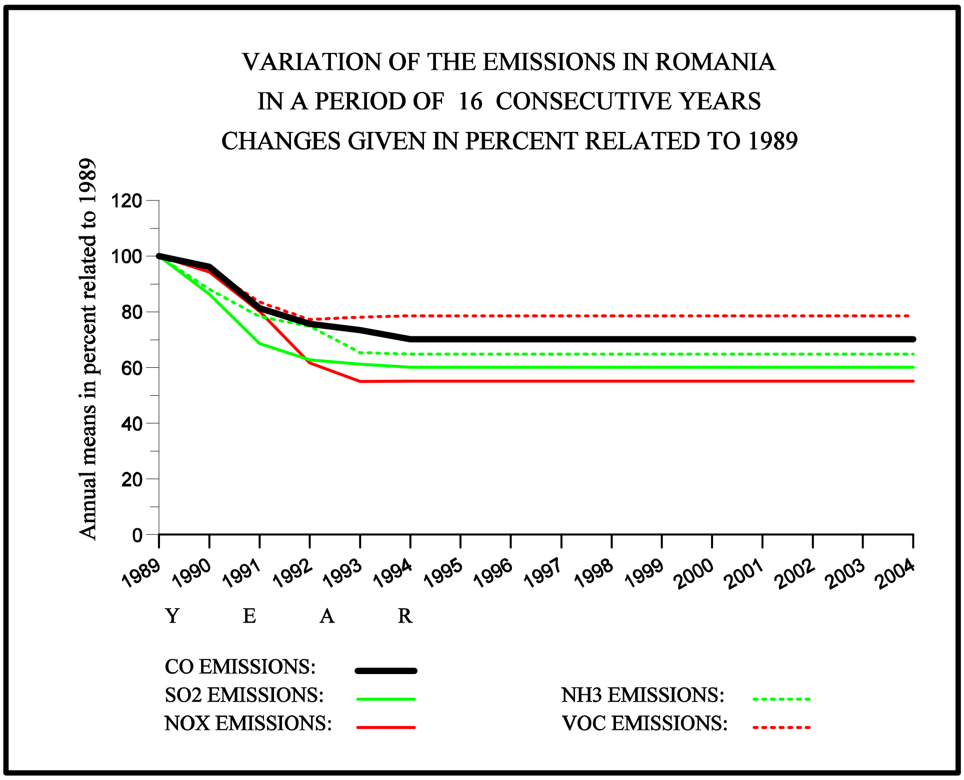


Figure 5.5

Variation of the Romanian human-made (anthropogenic) emissions in the period 1989-2004.

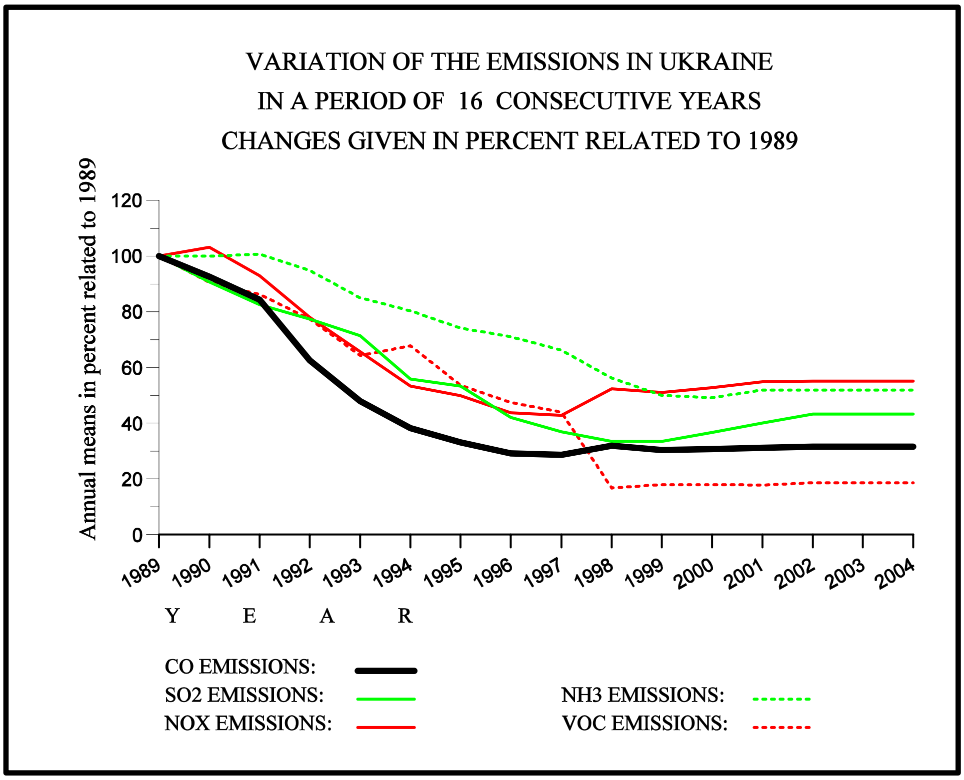


Figure 5.6

Variation of the Ukrainian human-made (anthropogenic) emissions in the period 1989-2004.

6. Scenarios related to biogenic emissions

The biogenic emissions in all scenarios that were discussed in the previous sections were prepared by using ideas described in Simpson et al. (1995) and Lübkert and Schöpp (1989). It is stated in Simpson et al. (1995) that the biogenic VOC emissions are in general much smaller than the corresponding human-made (anthropogenic) emissions. However, the human-made (anthropogenic) emissions were, as mentioned above, reduced very considerably during the last two decades. Moreover, some of the predictions and recommendations made in the Scenario 2010 and especially those made in the MFR Scenario (see Section 5) indicate that the human-made (anthropogenic) emissions will be further reduced and, moreover, the reductions for some countries in Europe are very considerable (up to about 90%). This is why the following three statements are certainly true:

- The relative part of the biogenic VOC emissions in Europe as a whole and in most of the European countries is steadily increasing. This can be deduced by studying the results related to emission reductions in Europe as a whole and in several countries of Europe, which are presented in Fig. 5.1 – Fig. 5.6).
- Furthermore, mainly the difference between the **annual means** of human-made (anthropogenic) and biogenic emissions is discussed in Simpson et al. (1995); see Table 5 in Simpson et al. (1995). However, **the major part of the biogenic emissions is emitted in the summer months.** The monthly variation of the biogenic emissions is discussed in Geernaert and Zlatev, 2004; see also Table 2 and compare the figures given there with the corresponding figures in Table 3. The annual variations and the pronounced summer maximum of the biogenic emissions implies that for some studies (especially studies related to high ozone levels) it is much more appropriate to compare the difference between human-made (anthropogenic) and biogenic VOC emissions during the summer months. **This difference is considerably smaller than the annual difference.**
- Finally, many scientists claim that the biogenic emissions are greatly underestimated (see, for example, Bouchet et al, 1999a, 1999b).

This short discussion shows that it is very important to investigate the influence of the biogenic emissions on pollution levels related to the expected future changes of the climate in Europe by using also some scenarios for biogenic emissions.

7. Summarizing the information about the selected scenarios

The scenarios, which were selected and run in this study, are listed in Table 4. Short information about the major parameters that were used to create the scenarios is also given in Table 4.

Table 2:

Temporal variations of the biogenic emissions from forests and from crops. Units: (1000 tonnes)/year

Month	Forests	In percent	Crops	In percent
January	265	2.3 %	0.606	0.38 %
February	260	2.3 %	0.716	0.45 %
March	327	2.8 %	1.150	0.72 %
April	605	5.2 %	4.450	2.80 %
May	1411	12.3 %	20.800	13.10 %
June	2130	18.5 %	38.200	24.00 %
July	2341	20.3 %	43.900	27.60 %
August	1989	17.3 %	32.100	20.20 %
September	1015	8.8 %	11.300	7.10 %
October	658	5.7 %	3.800	2.40 %
November	295	2.6 %	1.130	0.71 %
December	217	1.9 %	0.672	0.42 %
1995	11513		159.00	

Table 3:

Anthropogenic emissions of NO_x and VOC's in Europe. Values for 1990, 1995 and 1998 are taken from EMEP (see EMEP, 1999) and predictions for 2010 are obtained by using the factors given in Amann et al. (1999).

Year	NOx emis. in (1000 tonnes)/year	VOC emis. in (1000 tonnes)/ year
1990	28040	26751
1995	23369	21766
1998	21186	19854
2010	14979	13799

Table 4:

List of the scenarios used in this study

Scenario	Meteorology	Anthropogenic emissions	Biogenic emissions
Basic	EMEP and NERI	EMEP and NERI	Basic
Constant meteorology	Meteorology for 1989	as in the Basic Scenario	as in the Basic Scenario
Constant emissions	as in the Basic Scenario	Emissions for 1989	as in the Basic Scenario
Climate 1	Increased temperatures	as in the Basic Scenario	as in the Basic Scenario
Climate 2	as in Climate 1 + diurnal and seasonal variations	as in the Basic Scenario	as in the Basic Scenario
Climate 3	as in Climate 2 + new humidity and precipitation	as in the Basic Scenario	as in the Basic Scenario
2010	as in the Basic Scenario	Using IIASA factors	as in the Basic Scenario
MFR	as in the Basic Scenario	Using IIASA factors	as in the Basic Scenario
Climate 2010	as in Climate 3	as in Scenario 2010	as in the Basic Scenario
Climate MFR	as in Climate 3	as in Scenario MFR	as in the Basic Scenario
Biogenic Bassic	as in the Basic Scenario	as in the Basic Scenario	Increased
Biogenic Climate 3	as in Climate 3	as in the Basic Scenario	as in Biogenic Basic
Biogenic 2010	as in Climate 3	as in Scenario 2010	As in Biogenic Basic
Biogenic MFR	as in Climate 3	as in Scenario MFR	as in Biogenic Basic

Remarks related to Table 4:

1. Basic biogenic emissions are produced by applying ideas proposed in Simpson et al. (1995) and Lübkert and Schöpp (1989) as described in Geernaert and Zlatev (2004).
2. Increased biogenic emissions are produced by applying ideas from Anastasi et al. (1991).

8. Results from runs with the selected scenarios

Each of the six scenarios was run on powerful supercomputers over a time-period of ten years. This is a huge computational task that was handled by using an efficient parallel code. The computers, which were actually used, were SUN parallel computers. Up to 32 processors were applied in these runs (see more details in Alexandrov et al., 2004).

8.1. Validation of the results

Results obtained by using UNI-DEM have been compared with measurements in many studies; see, for example, Abdalmogith et al. (2006), Bastrup-Birk et al. (1997), Harrison et al. (1994), Havasi and Zlatev (2002), Zlatev et al. (2001). UNI-DEM has recently participated in two intercomparions of European large-scale models; Hass et al. (2004) and Roemer et al. (2004). Nevertherless, some comparisons with measurements are also given in this report.

The Basic Scenario is used in this section to validate the results by comparing them with measurements taken at Danish sites. The sites are Tange, Keldsnor and Anholt for all species excepting ozone. Ozone concentrations are measured in Ulfborg and Frederiksborg. The locations of these five sites are shown in Fig. 8.1.

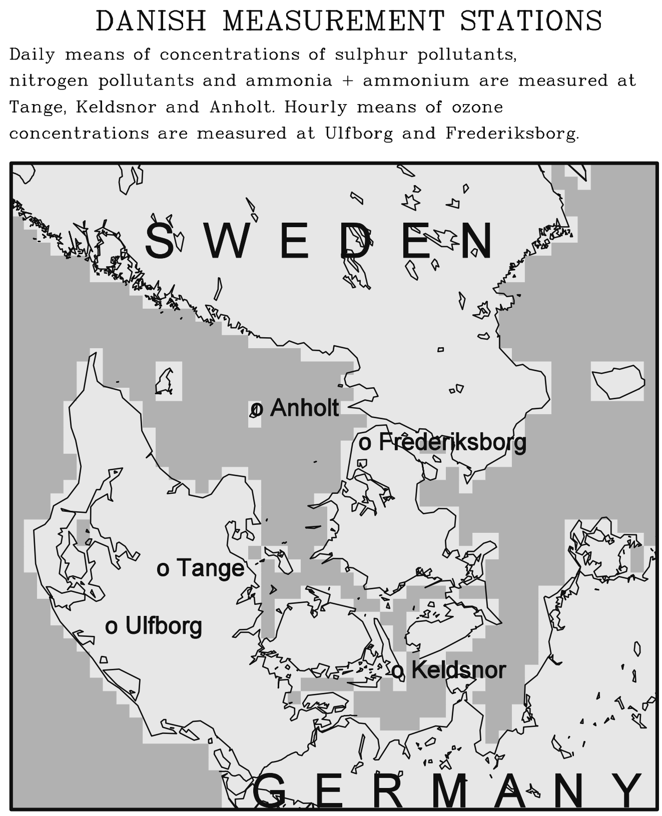


Figure 8.1

Locations of the Danish measurement stations, which are included in the EMEP network.

It should be mentioned here that all these stations belong to the EMEP network of measurement stations. Measurement data obtained at the Danish sites as well as measurement data from many other European stations can be downloaded, free of charge, from the EMEP Home Web-page (2006).

The curves representing the temporal variations of the annual means of the concentrations (measured and calculated by the model) for the major pollutants ($\mathbf{SO_2}$, $\mathbf{SO_4^=}$, $\mathbf{NO_2}$, $\mathbf{HNO_3} + \mathbf{NO_3^-}$, $\mathbf{NH_3} + \mathbf{NH_4^+}$ and $\mathbf{O_3}$) as well as for four quantities related to high ozone concentrations:

- AOT40 values for crops (the abbreviation AOT40C will be used for these values),
- AOT40 values for forest trees (the abbreviation AOT40C will be used for these values),
- numbers of days in which the averaged 8-hour ozone concentrations exceed at least once the limit of 60 ppb (such days will be called “bad days”)

and

- averaged daily ozone maxima,

are given in Fig. 8.2. Critical values for AOT40 values and “bad days” are defined in European Parliament (2002). Some investigations related to these quantities are reported in Havasi and Zlatev, 2002, and Zlatev et al., 2001).

Curves representing the temporal variation of the averaged concentrations over the 950 Danish 10 km x 10 km surface cells are also given in the plots of Fig. 8.2.

Annual averaged concentrations are compared in Fig 8.2.a – Fig. 8.2.f. Averaged quantities, related to ozone concentrations, taken over a period of three months (from May 1 to July 31) are compared in Fig. 8.2.g. Averaged quantities, also related to ozone concentrations, over the so-called extended summer period, the period from April 1 to September 30, are compared in Fig. 8.2.h –Fig. 8.2.j.

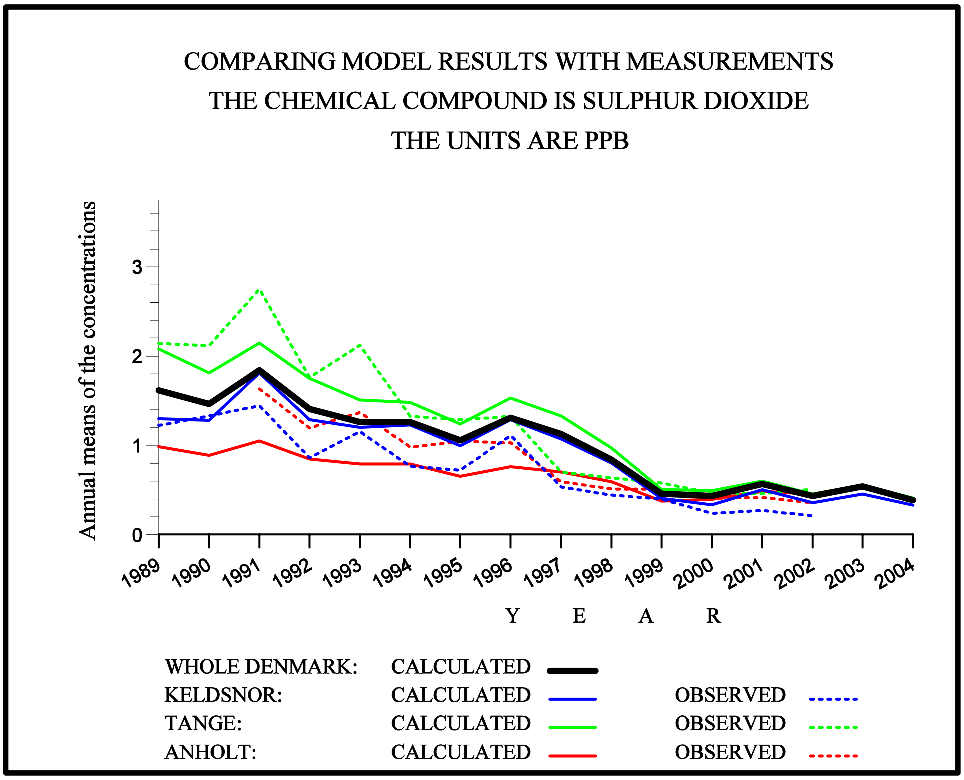


Figure 8.2.a

Comparison of annual means of SO_2 *concentrations.*

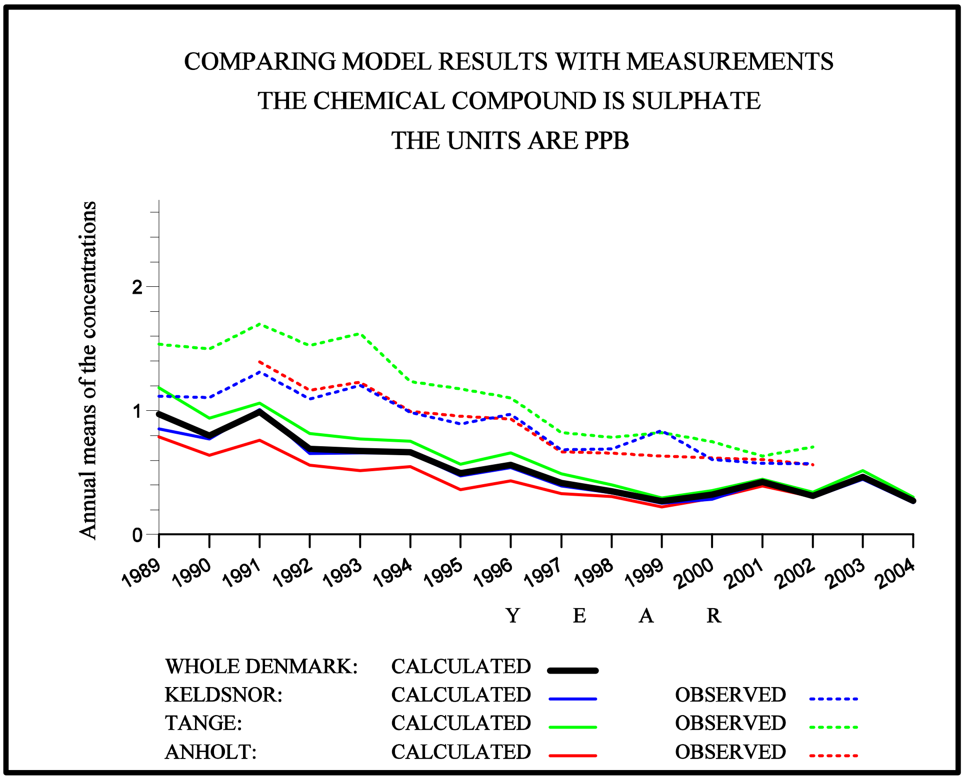


Figure 8.2.b

Comparison of annual means of $SO_4^=$ *concentrations.*

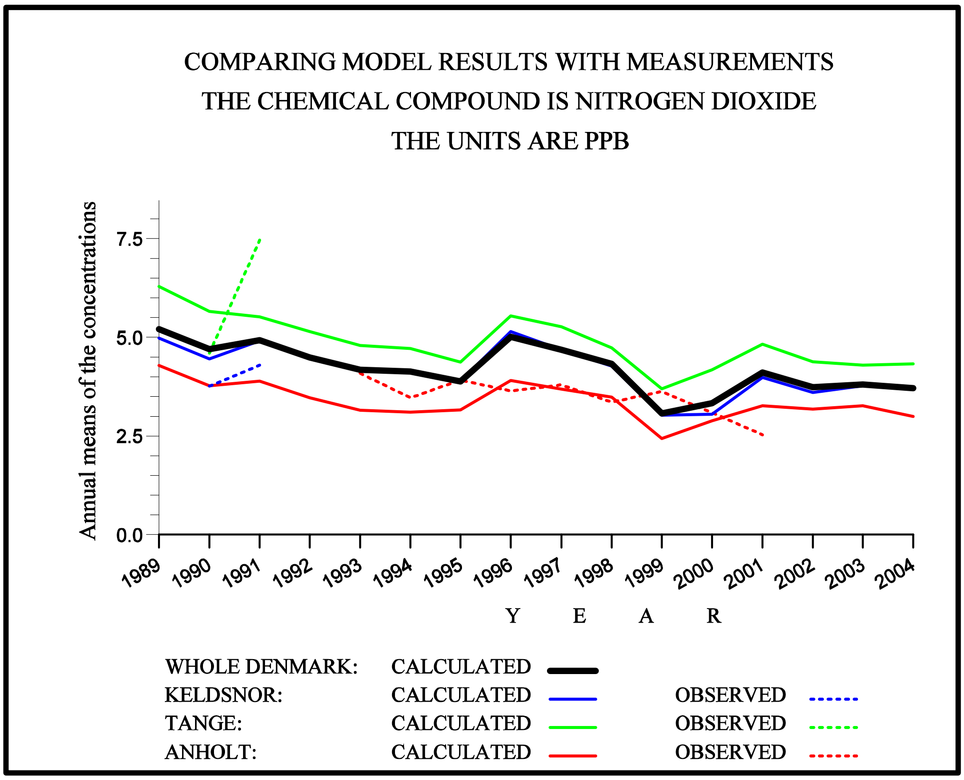


Figure 8.2.c

Comparison of annual means of $\mathbf{NO_2}$ *concentrations.*

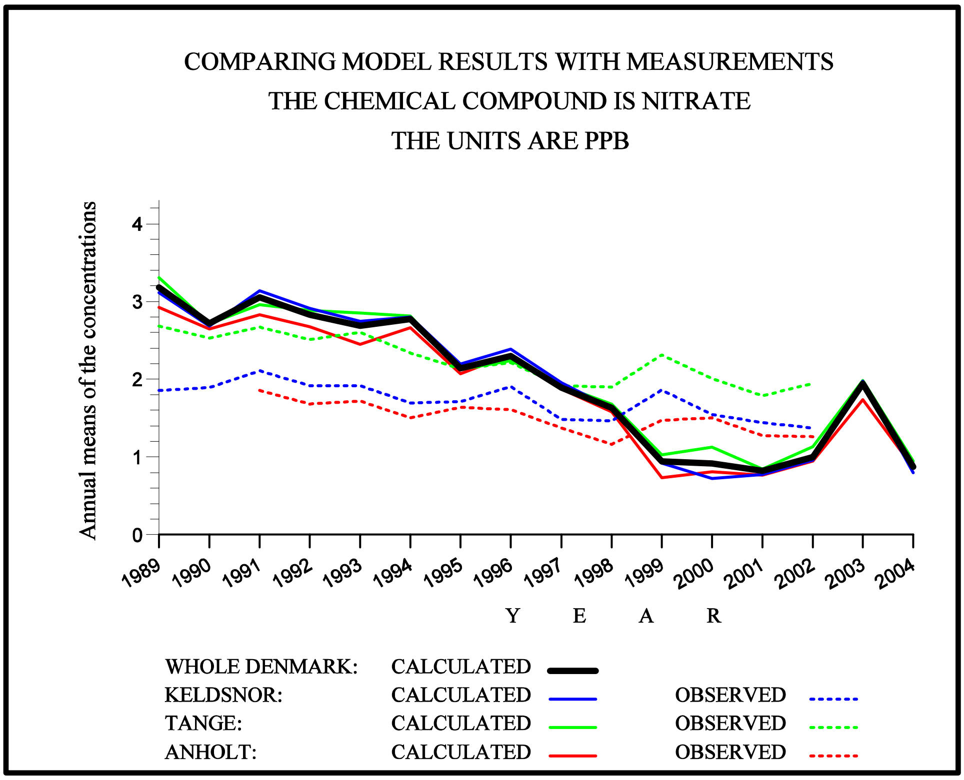


Figure 8.2.d

Comparison of annual means of $\mathbf{HNO_3 + NO_3^-}$ *concentrations.*

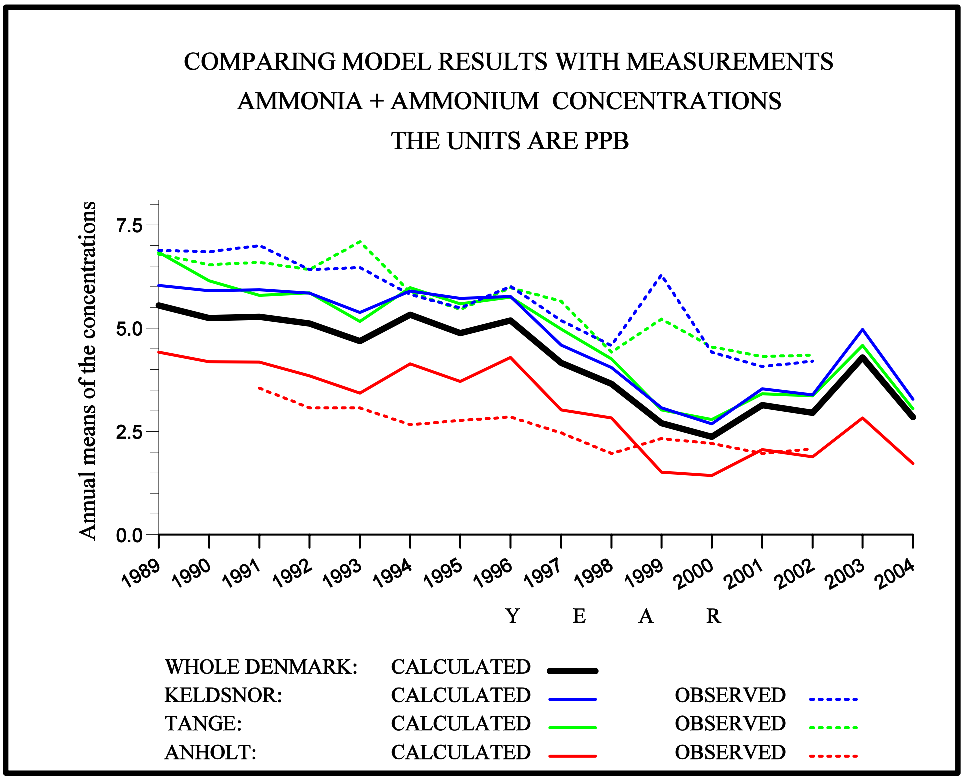


Figure 8.2.e

Comparison of annual means of $NH_3 + NH_4^+$ *concentrations.*

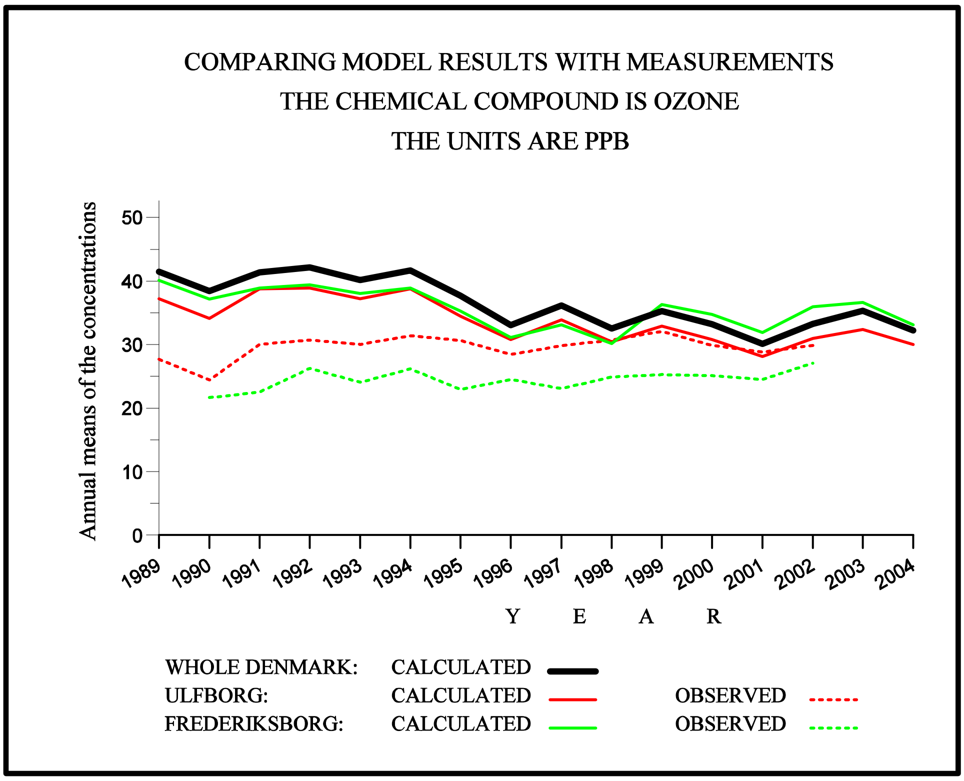


Figure 8.2.f

Comparison of annual means of O_3 *concentrations.*

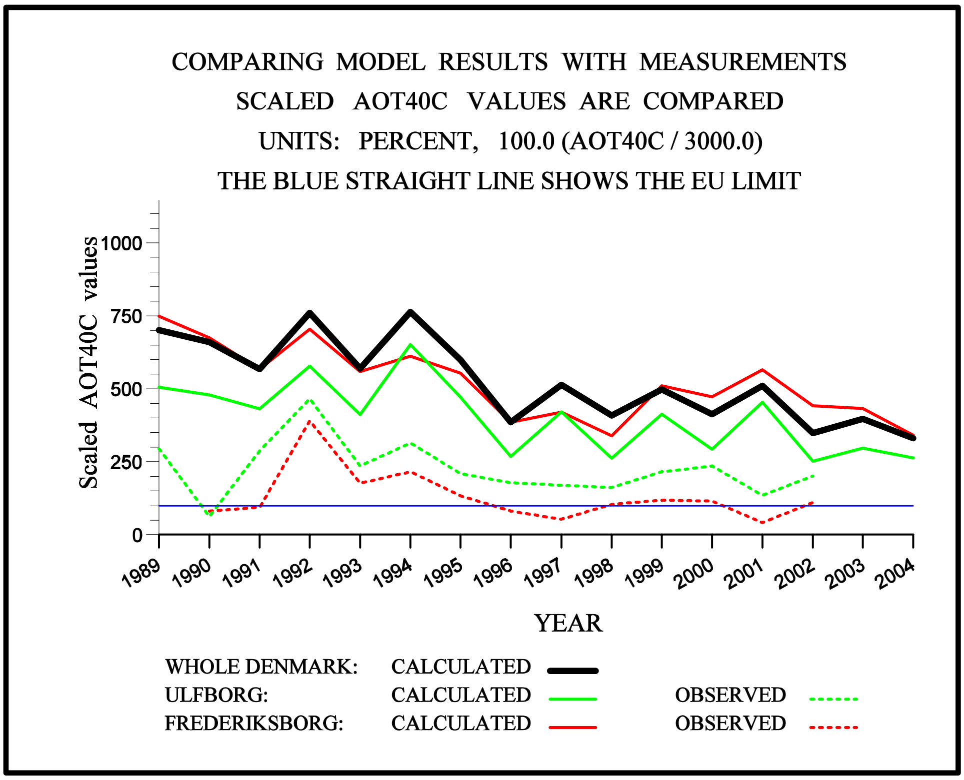


Figure 8.2.g

Comparison of **AOT40C** *(AOT40 for crops) values.*

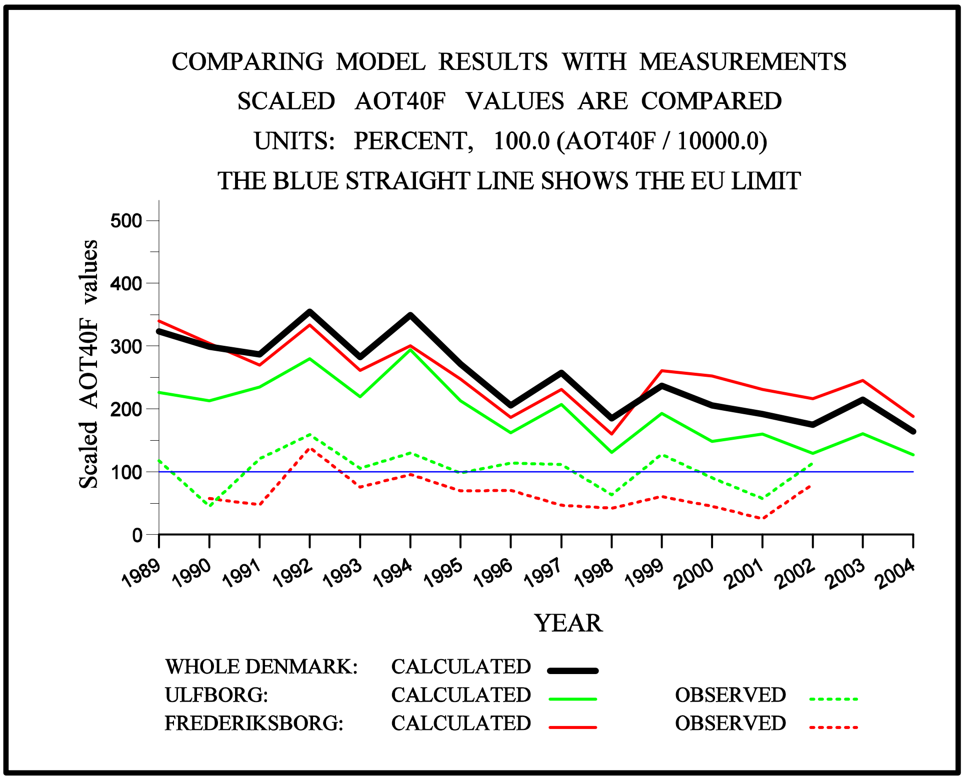


Figure 8.2.h

Comparison of **AOT40F** *(AOT40 for forest trees) values.*

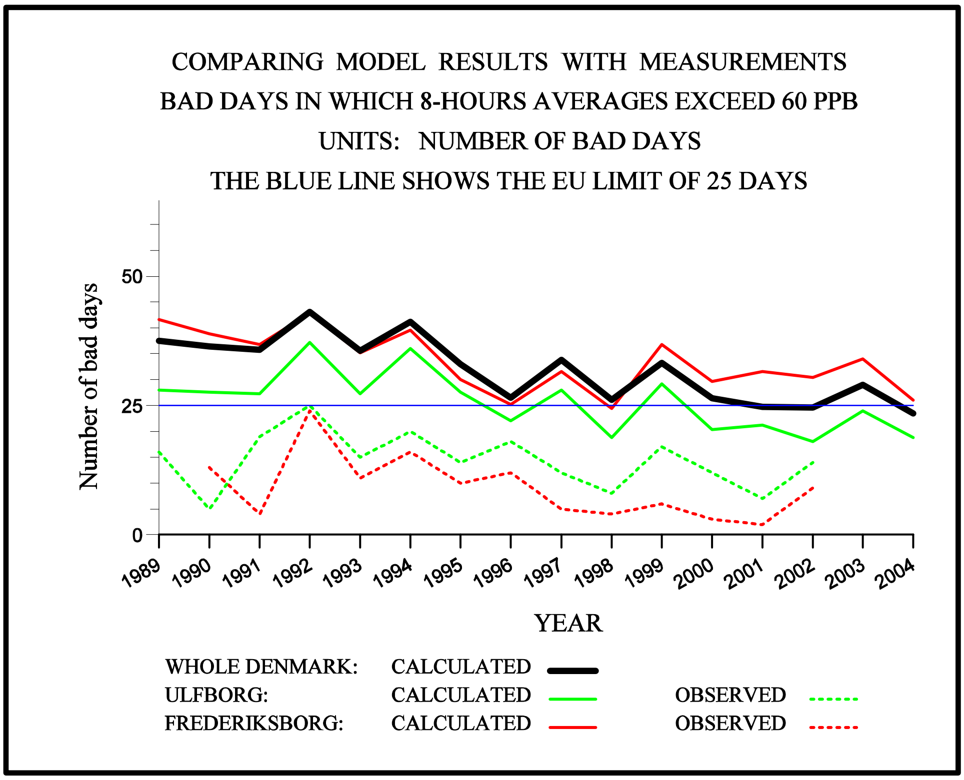


Figure 8.2.i

Comparison of numbers of days in which the 8-hour averaged ozone concentrations exceed at least once the EU limit of 60 ppb.

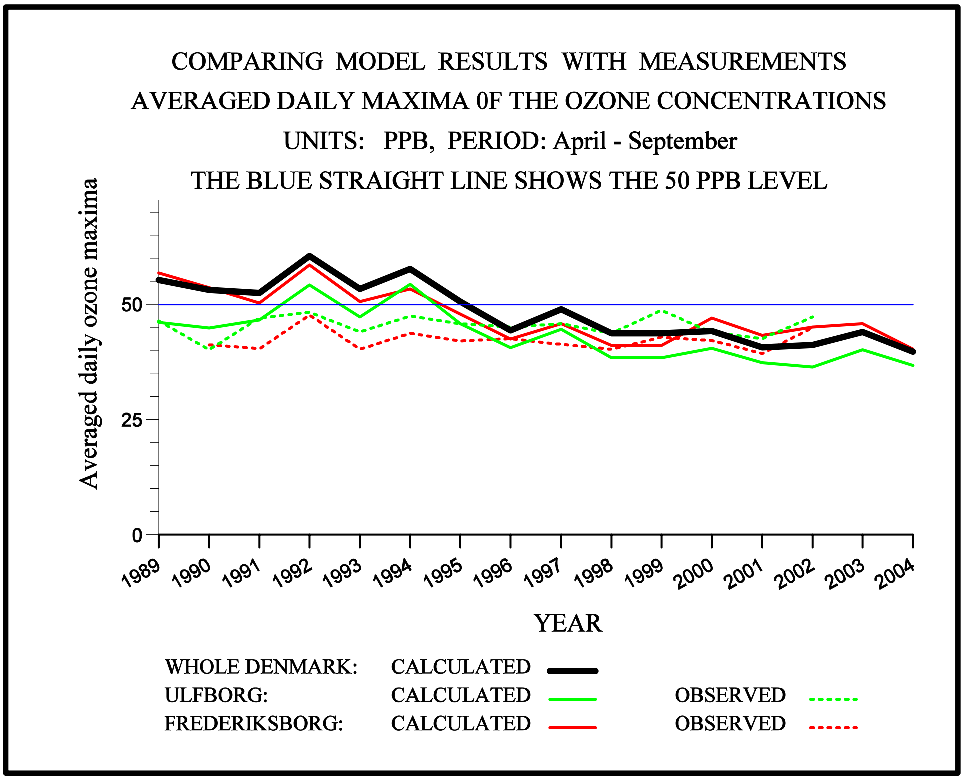


Figure 8.2.j

Comparison of averaged daily maxima of ozone concentrations.

The comparison of model results with measurements is not very easy. The stations do not measure regularly. Sometimes, measurements for many years are missing (see the upper plot in Fig. 8.2.c). Even if the station measures for all years (from 1989 until 2004) measurements for many days are sometimes missing. This fact causes great problems when AOT40 values calculated by the model have to be compared with the corresponding quantities obtained by using measurements. The AOT40 values are normally calculated by using the formula

$$(1) \qquad \mathbf{AOT40} = \sum_{i=1}^{N} \mathbf{max}(\mathbf{c_i} - \mathbf{40,0}),$$

where $\mathbf{N}$ is the number of day-time hours in the period under consideration (for crops this period contains the months May, June and July, while the period from April to September is used for forest trees), $\mathbf{c_i}$ is the calculated by some model or measured at some station ozone concentration. With a model we are able to calculate $\mathbf{c_i}$ for all values $\mathbf{i}$, $\mathbf{i = 1, 2, \dots, N}$. However, when many measurements at the stations under consideration are missing, then one should expect the AOT40 values that are measured at the EMEP stations to be considerably less than the calculated by the model AOT40 values. From Fig. 8.2.g and Fig. 8.2.h it is seen that precisely this happens in our comparisons, because many measurements are missing (some more details are given in Table 1 in Zlatev et al., 2001).

Missing measurements cause similar problems also when numbers of days in which the 8-hour averaged ozone exceed at least once the limit of 60 ppb. It should also be emphasized that some of the quantities that are related to high ozone concentrations (AOT40 values for crops and forest trees and numbers of days in which the averaged eight-hour ozone concentrations exceed at least once the limit of 60 ppb) are **very sensitive to small errors**; see Geernaert and Zlatev (2004) and Zlatev et al. (2001).

The missing measurements do not cause great problems when the averaged daily ozone maxima are compared. In this case we can use the number of measurements at a given station in order to obtain the averaged value at the measurement station at consideration. This is why the results of the comparison of calculated by the model and measured averaged daily ozone maxima gives much better results than the results of the corresponding comparisons for AOT40 values and for averaged 8-hour ozone concentrations that exceed at least once the limit of 60 ppb (compare Fig. 8.2.j with Fig. 8.2.g - Fig. 8.2.i).

After this general discussion of the difficulties, which appear when model results and measurements are compared, we are prepared to draw conclusions from the comparison between measurements and model results in our study. We shall start with specific conclusions related to each of the pollutants and finish the discussion in this sub-section with general conclusions.

8.1.1. Specific conclusions drawn from the comparison with measurements

- The comparison of calculated and measured **sulphur dioxide** (see Fig. 8.2.a) shows that the following statements are true.

  (a) There is a very clear trend of decreasing of the sulphur dioxide pollution levels in Denmark (both for the measurements and for the model results). Of course, this should be expected, because the sulphur dioxide emissions were decreased very considerably in the period under consideration.

  (b) The agreement between measurements and model results become much better at the end of the period. It is not very clear what the reason for this improvement is. There are two possibilities: either the quality of the sulphur dioxide measurements was improved at the end of the period or the quality of the input data used in the model (measurement data and emission data) was improved. Of course, also a combination of these two possibilities may be the reason for the better agreement of measurements and model results at the end of the studied period.

- The comparison of calculated and measured **sulphate** (see Fig. 8.2.b) shows that the following statements are true.

  (a) Again there is a trend of decreasing of the pollution levels in Denmark (both for the measurements and for the model results). However, the rate of reduction is not so pronounced as that for the sulphur dioxide. This is probably due to the fact that sulphate is a secondary pollutant, which is created during the transport and, therefore, long-range transport effects may play a more considerable role for the sulphate pollution levels in Denmark.

  (b) The measurements are consistently higher than the model results. It is not very clear what is the reason for underestimating the sulphate concentrations by the model. There are at least two possibilities: either the involved chemical rate constants are not very accurate or the deposition rates are too small.

  (c) The agreement between measurements and model results becomes slightly better at the end of the period. The reasons for this behaviour are the same as those for the sulphur dioxide (see above).

- The comparison of calculated and measured **nitrogen dioxide** (see Fig. 8.2.c) shows that the following statements are true.

  (a) There is a trend of decreasing of the nitrogen dioxide pollution levels in Denmark (both for the measurements and for the model results). However, this trend is not so pronounced as that trend of reduction of the sulphur dioxide pollution levels. This is not a big surprise, because the reduction of the nitrogen dioxide emissions in Denmark is much smaller than the reduction of the sulphur dioxide emissions (see Fig. 4.3).

  (b) Only measurements at Anholt are available on a long time-period. There is a rather good agreement between these measurements and the model results. There is also a slight trend of improvement of the agreement at the end of the period.

- The comparison of calculated and measured **nitrate** (in fact the sum of $\mathbf{HNO_3}$ and $\mathbf{NO_3^-}$ is considered; see Fig. 8.2.d) shows that the following statements are true.

  (a) There is a slight trend of decreasing of the pollution levels in Denmark (both for the measurements and for the model results). The trend is more pronounced for the model results.

  (b) There are no big differences of the model results obtained at the measurement sites while the differences of the measurements are bigger (the lowest concentrations are found at Anholt, which can be considered as a remote rural site).

  (c) It is difficult to see an improvement of the agreement between measurements and model results at the end of the period (as for the previous cases).

- The comparison of calculated and measured **ammonia-ammonium** (the sum is used in the comparisons; see Fig. 8.2.e) shows that the following statements are true.

  (a) There is a trend of decreasing of the pollution levels in Denmark (both for the measurements and for the model results).

  (b) Both the model results and the measurements at Anholt are considerably lower than the model results and the measurements at the other sites (including the averaged model results for the whole of Denmark).

  (c) It is difficult to see an improvement of the agreement between measurements and model results at the end of the period (as in Fig. 8.2.a – Fig. 8.2.c).

- The comparison of calculated and measured **ozone** (see Fig. 8.2.f) shows that the following statements are true.

  (a) There is a very slight trend of decreasing of the calculated by the model ozone concentrations. The situation is opposite for the measured ozone concentrations (these are slightly increasing).

  (b) The agreement of measurements and model results is much better at Ulfborg than in Frederiksborg. It should be noted here that Ulfborg can be considered as a remote rural site, while Frederiksborg is rather close to big city Copenhagen, the capital of Denmark.

  (c) There is a very clear trend of improvement of the agreement between measurements and model results at the end of the period (the agreement at Ulfborg is becoming very good after 1995).

- The comparison of calculated and measured **AOT40C** (AOT40 values for crops; see Fig. 8.2.g) shows that the following statements are true.

  (a) There is a very slight trend of decreasing of the calculated by the model AOT40C values. It is difficult to see such a trend for measured AOT40C values. However, there is no trend of increasing as in the case for measured ozone concentrations in Fig. 8.2.f.

  (b) The measured AOT40C values are considerably smaller than the calculated by the model AOT40C values. This should be expected according to the analysis made above in connection with formula (1).

  (c) The differences between measured and calculated AOT40C values are becoming smaller at the end of the time-period, but the calculated results are still considerably larger than the measurements.

  (d) The inter-annual variations of the AOT40C values are rather considerable. The reason for this is the fact that the AOT40C values are accumulated in a rather small period (only three months, from May 1 to July 31). The meteorological conditions in such a short time-interval can vary very much from one year to another year.

- The comparison of calculated and measured **AOT40F** (AOT40 values for forest trees; see Fig. 8.2.h) shows that the following statements are true.

  (a) The behaviour is quite similar to the behaviour of measured and calculated AOT40C values. This is, of course, not a big surprise because the same rules are used in the preparation of the AOT40F values as the rules used to prepare AOT40F values. Only the period is increased (from the three months for the AOT40C values to the six months used for the AOT40F values).

  (b) The AOT40F values (both measured and calculated by the model) are considerably smaller than the corresponding AOT40C values. This is also not a big surprise. The AOT40F values are calculated for a period of six months (from April 1 to September 30) by using the same rules as these used to calculate the AOT40C values over a period of three months (May, June, July). The AOT40C values are scaled by using a critical value of 3000 ppb.hours, while the AOT40F values are scaled by a factor of 10000 (the critical value for the AOT40F values). Taking this into account and using also the fact that the ozone concentrations in April and September are usually smaller than the ozone concentrations in May, June, July, it is clear that one should expect the AOT40F values will be smaller (by a factor larger than two) than the corresponding AOT40C values. Comparing the results in Fig. 8.2.h with the results in Fig. 8.2.g, it is seen that the AOT40F values are indeed smaller (by a factor larger than two) than the AOT40C values.

- The comparison of calculated and measured **numbers of "bad days"** (days in which the eight-hour averaged ozone concentrations exceed at least once the critical level of 60 ppb; see Fig. 8.2.i) shows that the following statements are true.

(a) There is a very slight trend of decreasing of the calculated by the model numbers of "bad days". It is difficult to see such a trend for measured numbers of "bad days". However, there is no trend of increasing as in the case for measured ozone concentrations in Fig. 8.2.f.

(b) The measured numbers of "bad days" are considerably smaller than the numbers of "bad days" that are calculated by the model. This should be expected, as in the previous two figures, using similar arguments as those made in the comparison of measured and calculated AOT40 values by using formula (1).

(c) The differences between measured and calculated numbers of "bad days" are becoming slightly smaller at the end of the time-period, but the calculated results are still considerably larger than the measurements.

(d) The inter-annual variations of the numbers of "bad days" are rather considerable. The reason for this is the fact that the numbers of "bad days" are accumulated in a rather small period (only six months, from April 1 to September 30). The meteorological conditions in such a short time-interval can vary very much from one year to another year.

- The comparison of calculated and measured **averaged daily maxima of the ozone concentrations** (over the extended summer period from April 1 to September 30; see Fig. 8.2.j) shows that the following statements are true.

(a) There is a very slight trend of decreasing of the calculated by the model averaged daily maxima of the ozone concentrations. It is difficult to see such a trend for measured daily maxima of the ozone concentrations. However, there is no trend of increasing as in the case for measured ozone concentrations in Fig. 8.2.f.

(b) The measured averaged daily ozone concentrations are very close to the calculated by the model averaged daily maxima of the ozone concentrations. The reasons for this behaviour were explained above; see the discussion after formula (1).

(c) The differences between measured and calculated averaged daily maxima of the ozone concentrations are becoming slightly smaller at the end of the time-period, and very close to each other.

(d) The inter-annual variations of the averaged daily ozone maxima of the ozone concentrations are considerable, but these are not as big as the variations observed in Fig. 8.2.g – Fig. 8.2.i.

8.1.2. General conclusion drawn from the comparison with measurements

The comparison of measurements and model results (as well as the specific conclusions listed above) indicate that the following conclusion is more or less true for all pollutants.

- It is clearly seen from the plots in Fig. 8.2 that the reductions in the European emissions in the period 1989 to 2004 do result in some reductions of the concentrations (both the measured and the calculated concentrations) of most of the pollutants in Denmark. An exception is the variation of the ozone concentrations. While the calculated by the model ozone concentrations show a slight trend of reduction, the ozone measurements at the two Danish stations show a slight trend of increasing. Note, however, that the model results are closer to the measurements at the end of the period.

8.2. Testing scenarios where the emissions and the meteorology are kept constant

The purpose with the experiments in which either the emissions or the meteorology is kept constant is to show that runs over a long time-period (a time-period of 16 years is actually used in our study, but the use of a longer period seems to be even more desirable). It is very important to understand the fact that if an emission scenario is prepared (let us call it Scenario A), then it is by far **not sufficient** to run this scenario for a given single year (say, year 1990). If the same emission scenario, Scenario A, is after that run by using meteorology from another year (say, year 2000), then the difference between the new and the old results can be very significant (which is clearly seen by studying the plots in this sub-section). This statement is especially true for the important quantities AOT40C (AOT40 for crops), AOT40F (AOT40 for forest trees) and the numbers of “bad days” (days in which the eight-hour averages of the ozone concentrations exceed at least once the limit of 60 ppb). Critical levels for the latter three quantities are given in the Ozone Directive (see European Parliament, 2002). It is quite clear that if some measures intended to keep these quantities below the critical levels are accepted by using an emission scenario, which is run for an arbitrarily chosen year, then the critical levels might be exceeded when meteorological conditions are not the same. This might lead to economical losses because the money spent to reduce the emissions according to the chosen scenario is not necessarily always giving the desired effect.

Results obtained when the emissions and the meteorological conditions are kept constant are presented in Fig. 8.3. It is immediately seen that the following conclusions can be drawn:

- The inter-annual variations of the pollution levels obtained when the Basic Scenario is run can be very significant.
- There is a trend of decreasing the pollution levels (due to the reductions of the European emissions in the studied period).
- If the meteorological conditions are kept constant, then the trend of decreasing is preserved, but the inter-annual variations are smoothed considerably.
- If the emissions are kept constant, then the inter-annual variations are preserved, but the decreasing trend disappears.

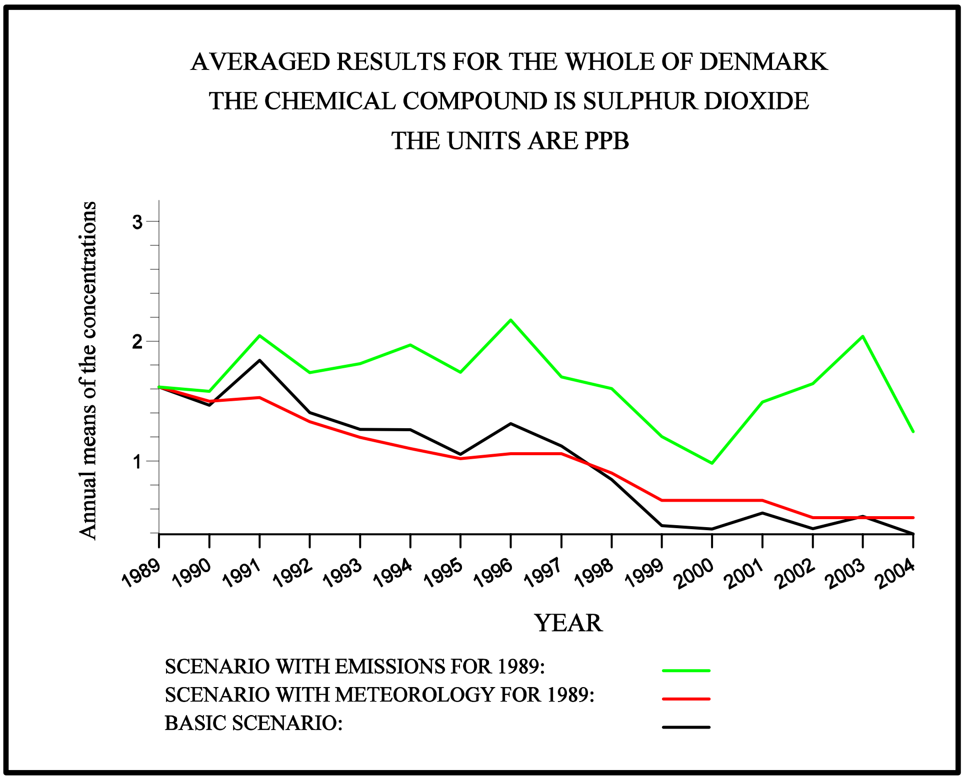


Figure 8.3.a

Averaged (over the Danish cells) annual means of SO_2 *concentrations obtained by three scenarios.*

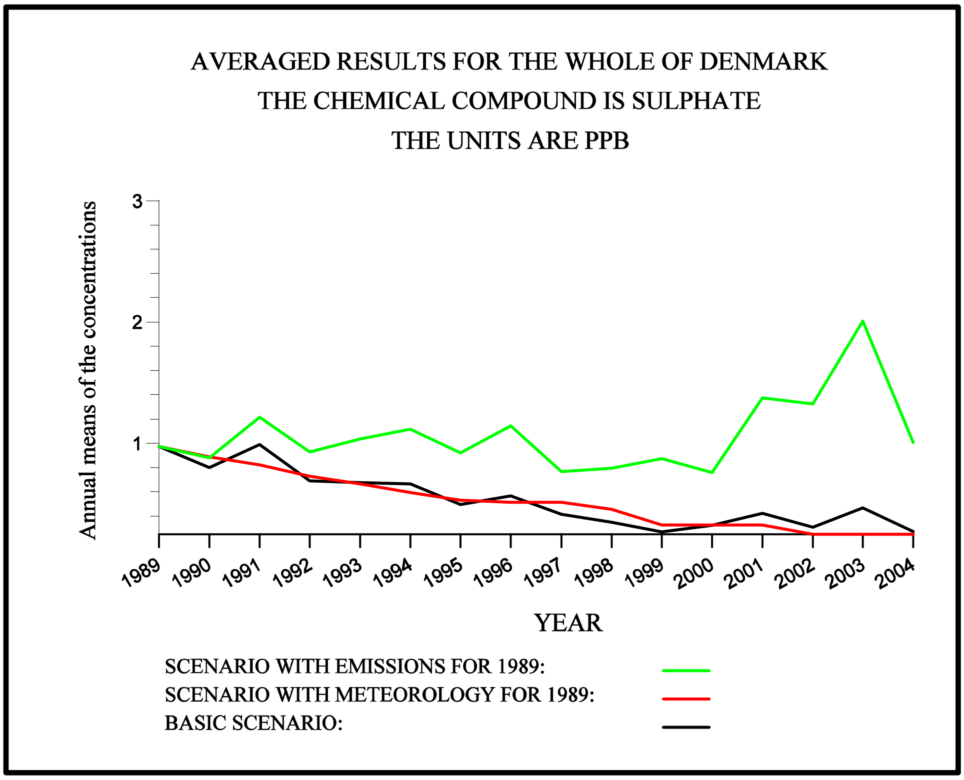


Figure 8.3.b

Averaged (over the Danish cells) annual means of $SO_4^{=}$ *concentrations obtained by three scenarios.*

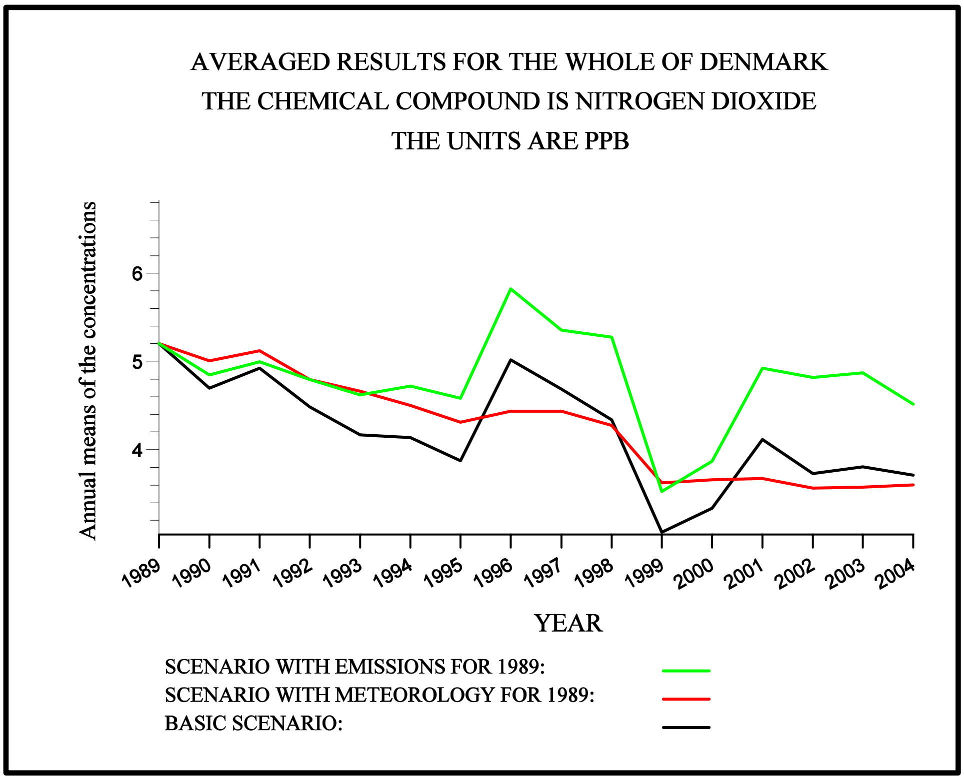


Figure 8.3.c

Averaged (over the Danish cells) annual means of NO_2 *concentrations obtained by three scenarios.*

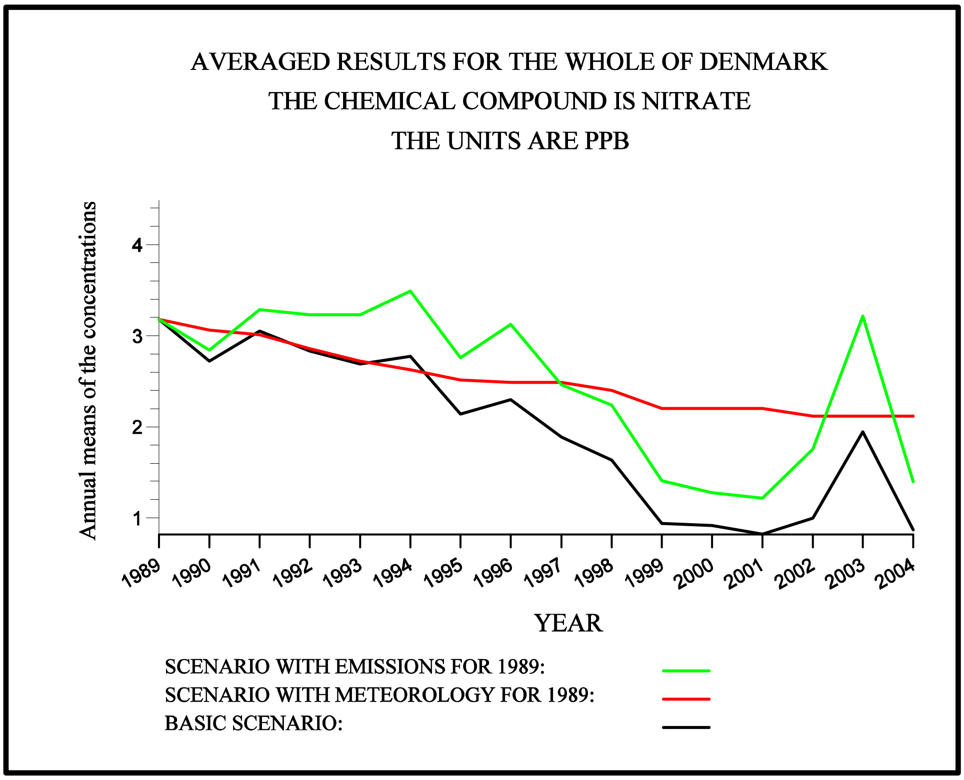


Figure 8.3.d

Averaged (over the Danish cells) annual means of $HNO_3 + NO_3^-$ *concentrations obtained by three scenarios.*

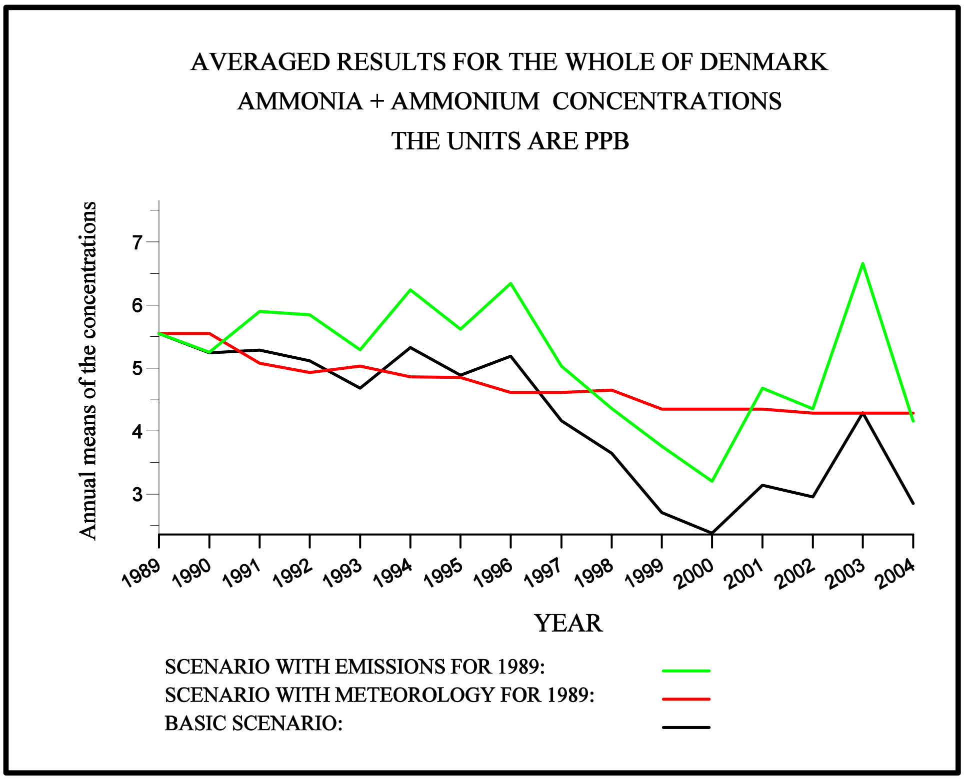


Figure 8.3.e

Averaged (over the Danish cells) annual means of $NH_3 + NH_4^+$ *concentrations obtained by three scenarios.*

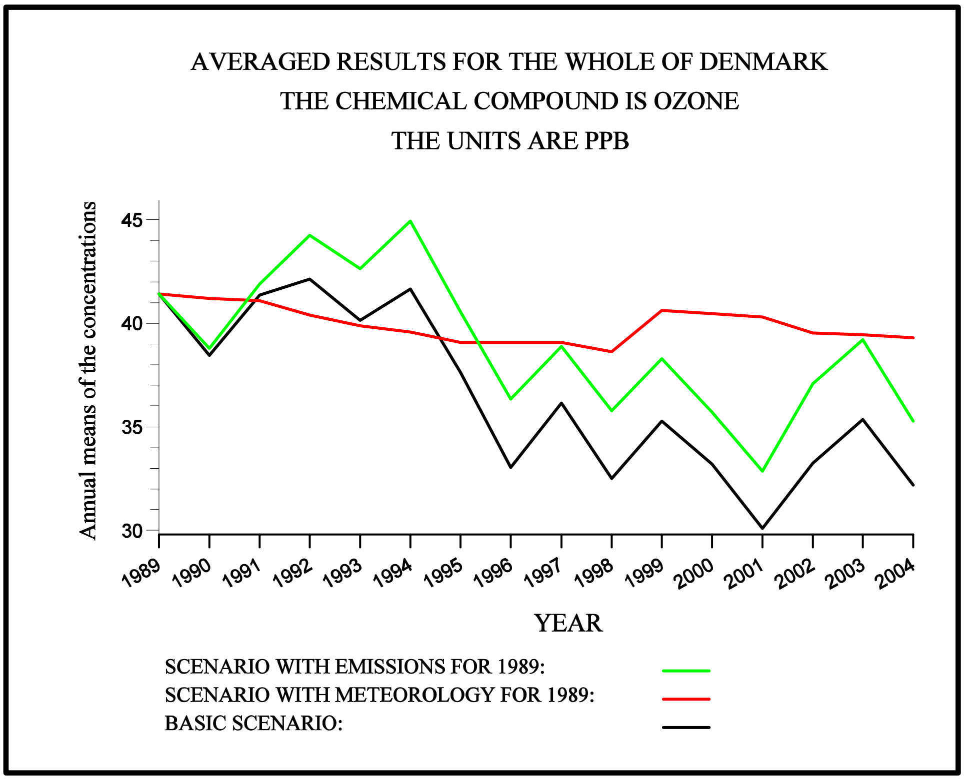


Figure 8.3.f

Averaged (over the Danish cells) annual means of O_3 *concentrations obtained by three scenarios.*

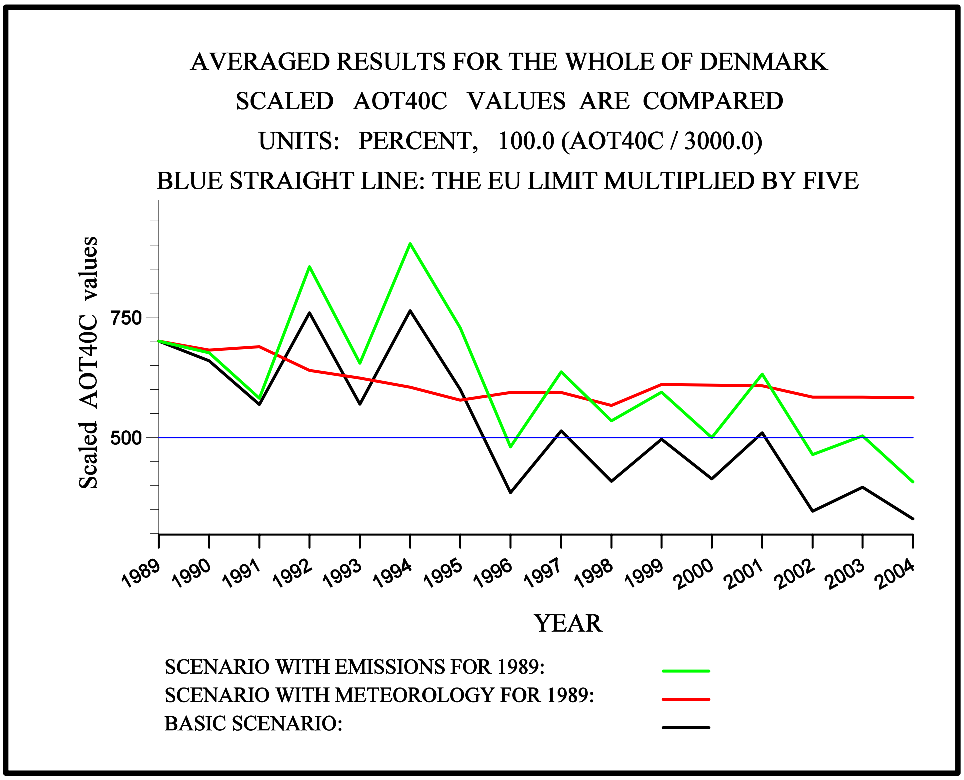


Figure 8.3.g

AOT40C *(AOT40 for crops) values obtained by three scenarios.*

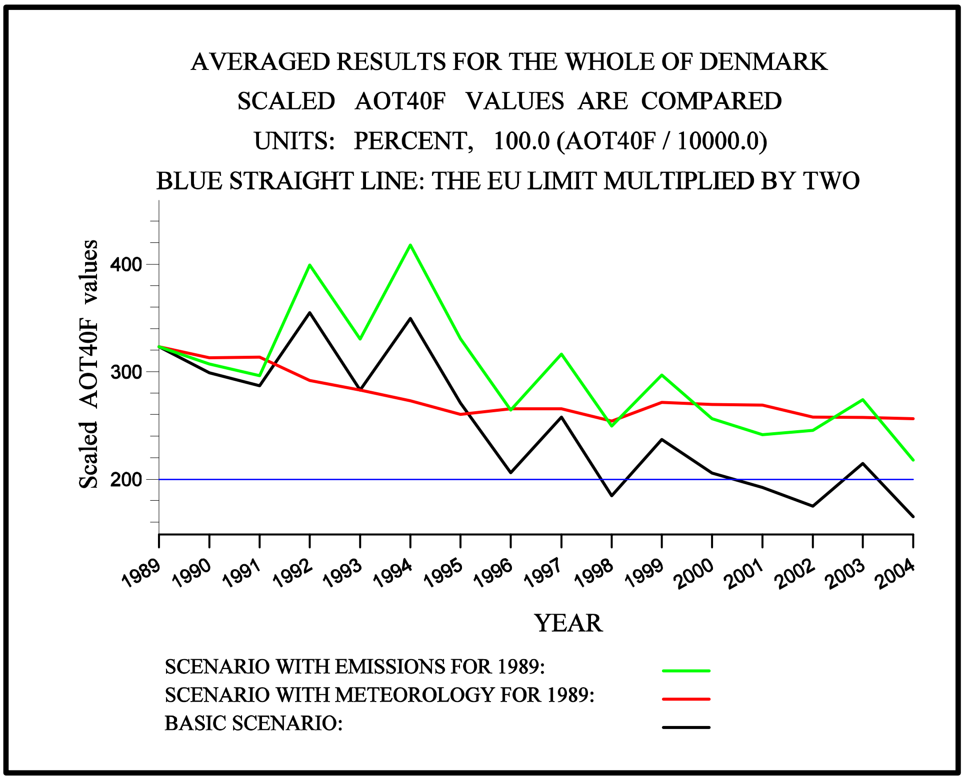


Figure 8.3.h

AOT40F *(AOT40 for forest trees) values obtained by three scenarios.*

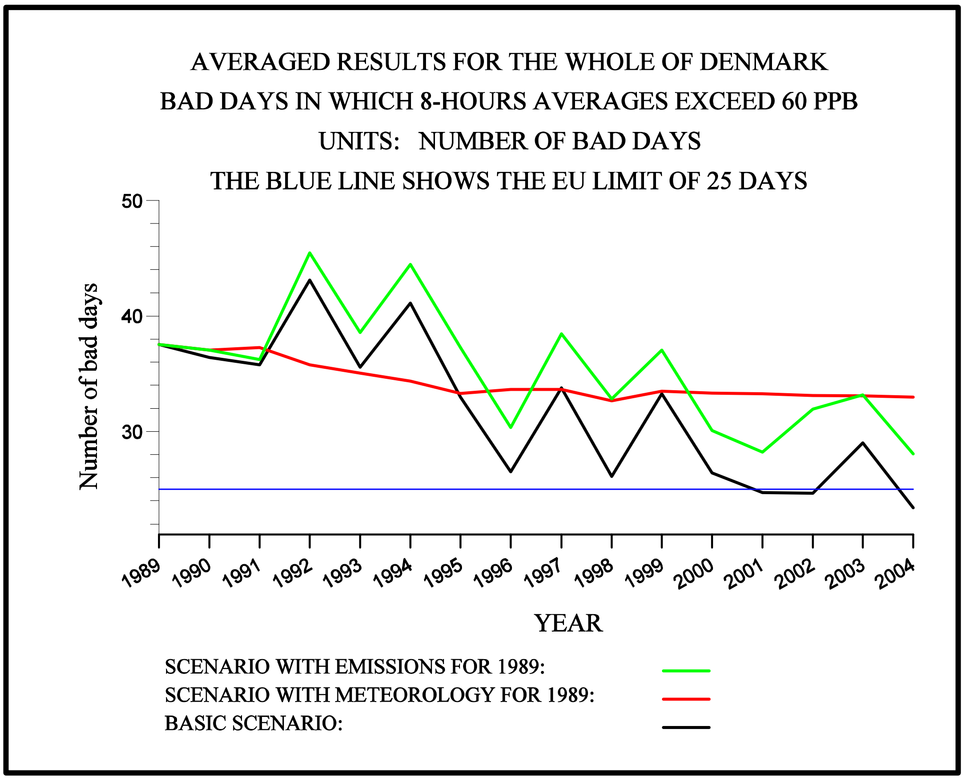


Figure 8.3.i

Comparison of numbers of days in which the 8-hour averaged ozone concentrations exceed at least once the EU limit of 60 ppb obtained by three scenarios.

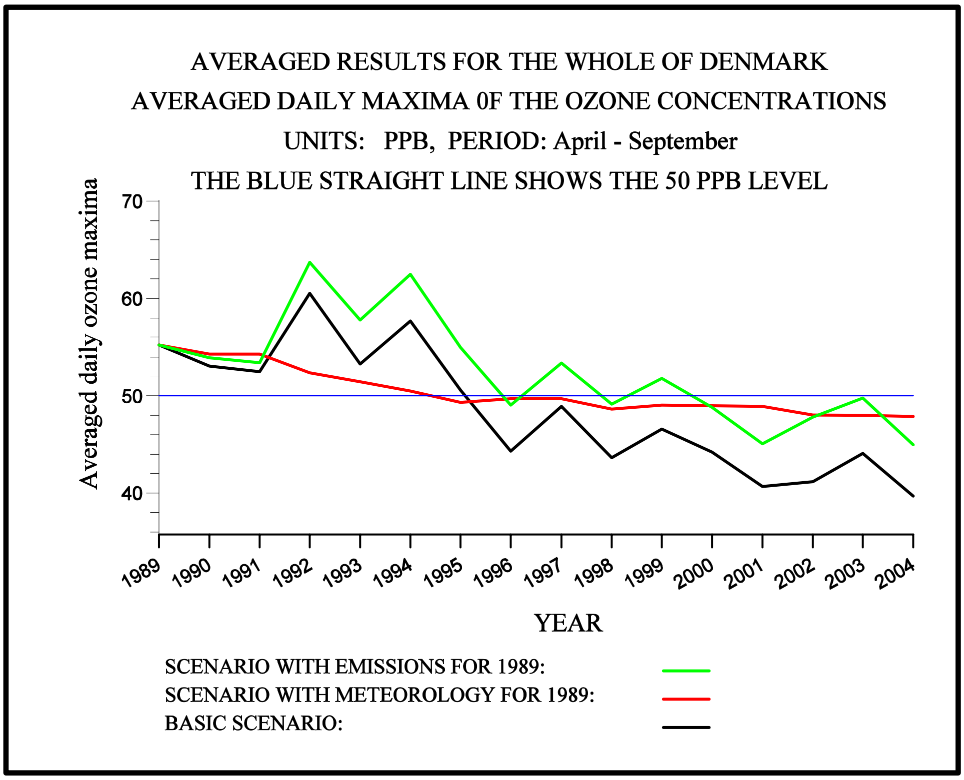


Figure 8.3.j

Averaged daily maxima of ozone concentrations obtained by three scenarios.

- Sometimes it is suggested to run the model for a period of several years and to take the mean value in the evaluation of the scenario tested. This is probably **not a good idea.** The inter-annual variations will be smoothed in this way (i.e. the results will be to a certain degree similar to the results obtained with the scenario with constant meteorology (see the red curves in Fig. 8.3). This might give an optimistic result that the reduction of the emissions proposed by the selected scenario is able to keep the pollution below the prescribed critical levels, while the truth might be that every second or third year the critical levels are exceeded. The results in Fig. 8.3 (especially the results in Fig. 8.3.g, Fig. 8.3.h and Fig. 8.3.i) show that one should be, at least, very careful when decisions, which based on the use of such approach (based on averaging the results obtained in several consecutive years), are to be taken.

8.3. Results obtained by using the climatic scenarios

The results obtained by using the Unified Danish Eulerian Model were validated by comparing results calculated with the Basic Scenario and measurement data. The need to run this model over a long time period was justified by comparing results obtained with the Basic Scenario with results obtained with scenarios where the emissions and the meteorological conditions are kept constant. In this way, the necessary preliminary work is completed and we are ready to start the investigation of the influence of the climate changes on pollution levels.

We shall first compare the temporal variations of the mean Danish concentrations of the major pollutants (averaged over the Danish cells of the grid) for the three climatic scenarios with the variation obtained when the Basic Scenario is used. After that we shall consider the changes of some quantities related to ozone levels for the whole of Europe. In the first case we shall consider the period of sixteen years, as in the previous sections, while results for a representative year (year 2004) will be used in the comparisons related to the second case.

8.3.1. Temporal variations of the concentrations.

The results obtained when the three climatic scenarios were run for 16 hypothetical years, each of them corresponding to one year in the period 1989 to 2004 (see Section 3), are compared with the corresponding results obtained by using the Basic Scenario in Fig. 8.4 for the same compounds as those used in the previous two sub-sections. The following major conclusions can be drawn from this comparison.

- The results obtained by the three climatic scenarios are very similar to these obtained by the Basic Scenario. For some pollutants, as for example $\mathbf{SO_2}$, it is very difficult to distinguish the different curves. The differences are slightly more considerable for ozone, but here the changes are also within a few percent.
- The annual Danish ozone concentrations are reduced when the three climatic scenarios are used (Fig. 8.4.f). The reductions are rather small.

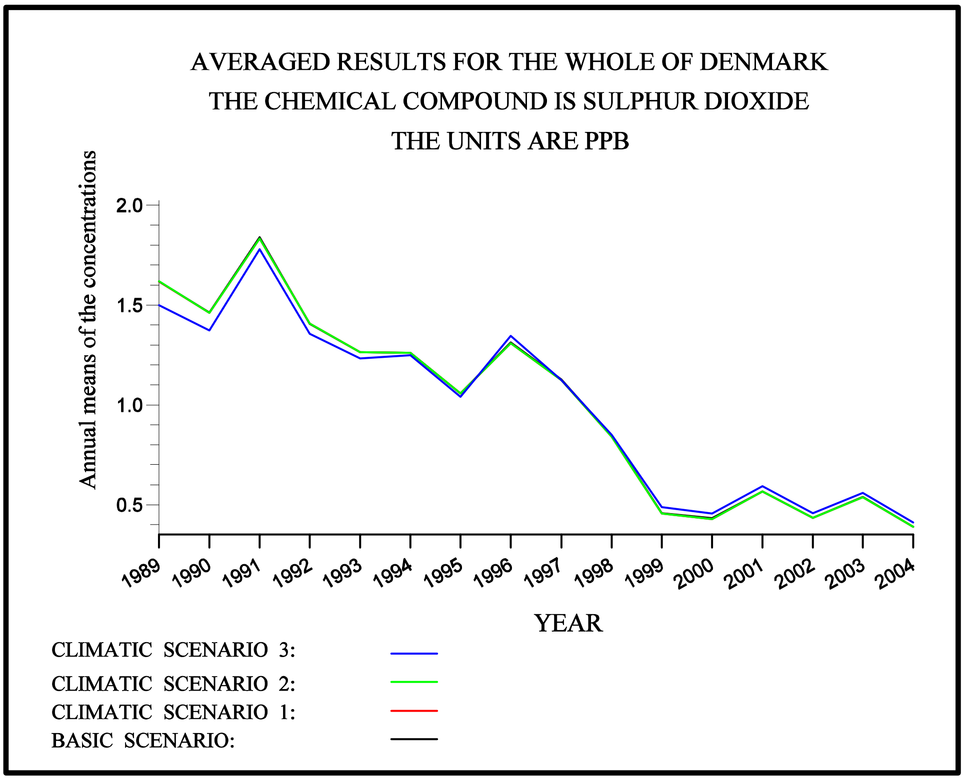


Figure 8.4.a

Comparison of concentrations (climatic scenarios vs the Basic Scenario).

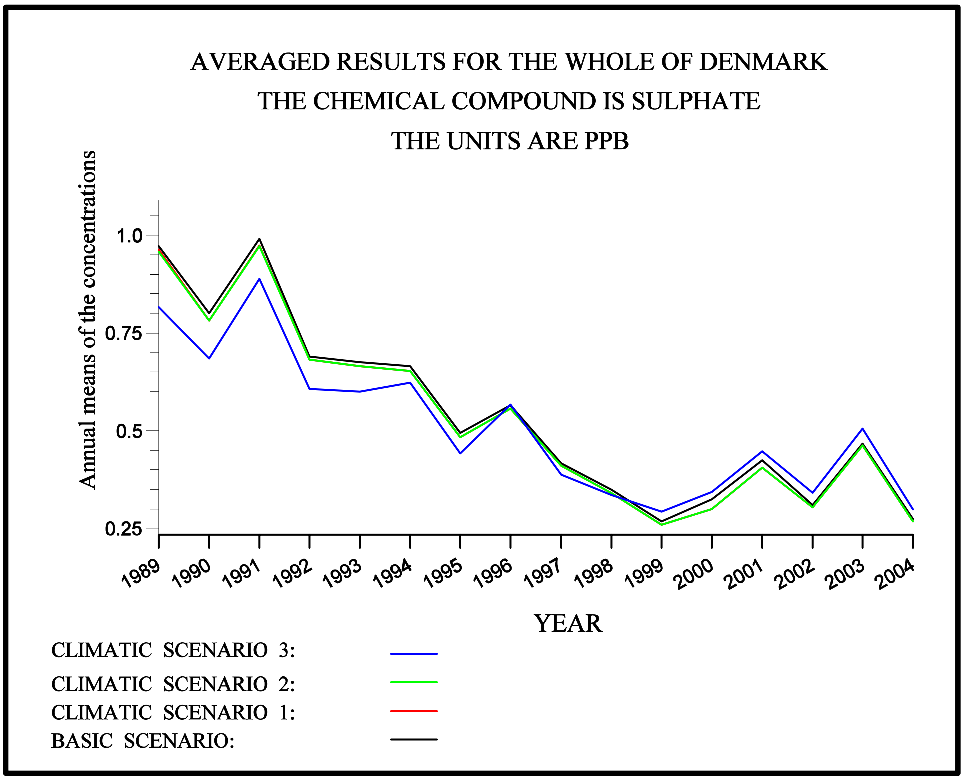


Figure 8.4.b

Comparison of concentrations (climatic scenarios versus the Basic Scenario).

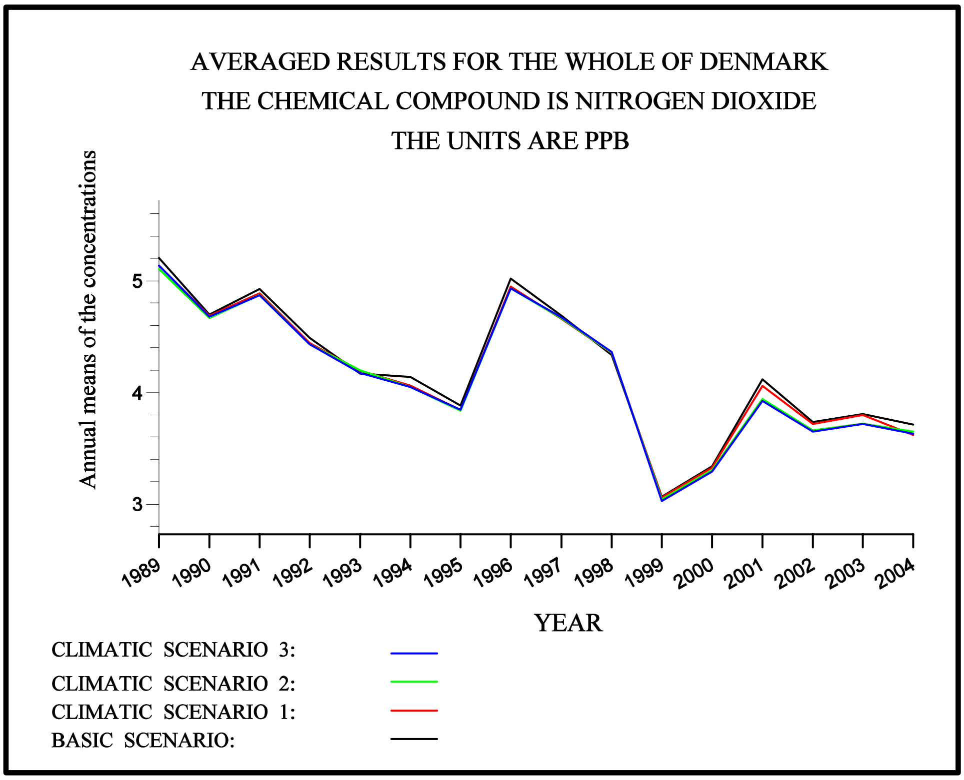


Figure 8.4.c

Comparison of concentrations (climatic scenarios versus the Basic Scenario).

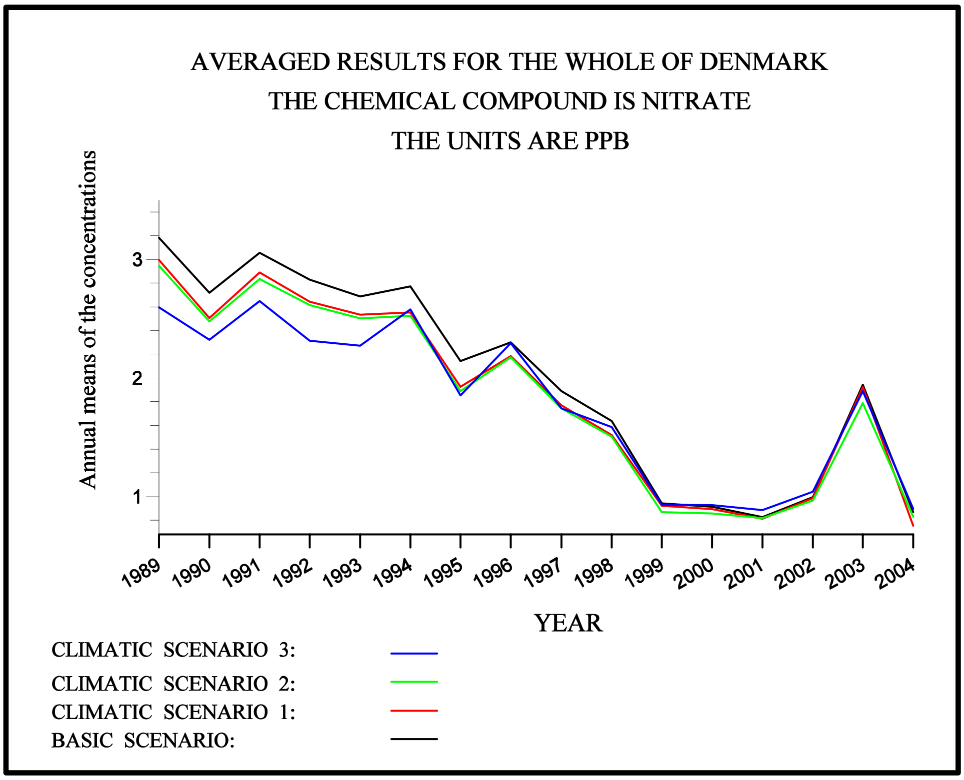


Figure 8.4.d

Comparison of concentrations (climatic scenarios versus the Basic Scenario).

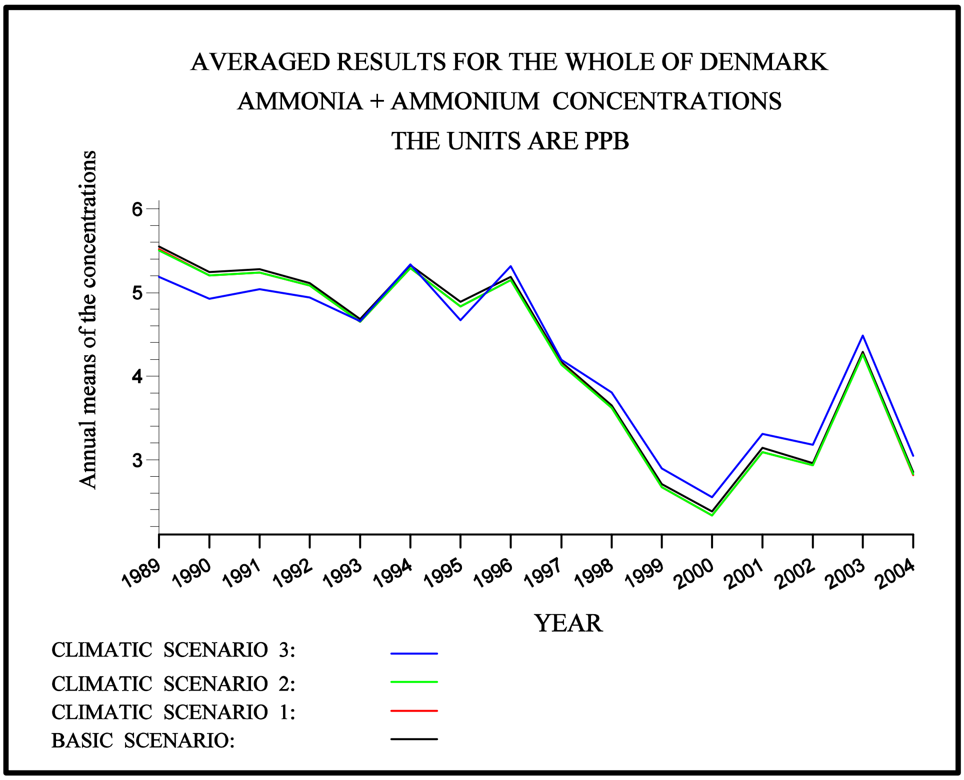


Figure 8.4.e

Comparison of concentrations (climatic scenarios versus the Basic Scenario).

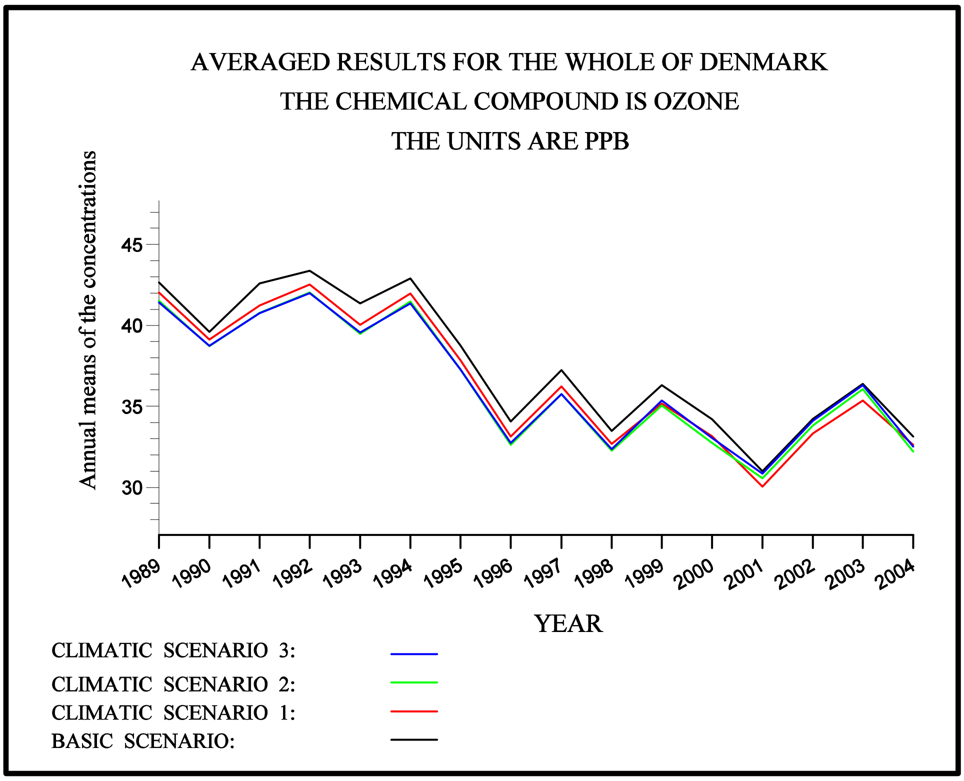


Figure 8.4.f

Comparison of concentrations (climatic scenarios versus the Basic Scenario).

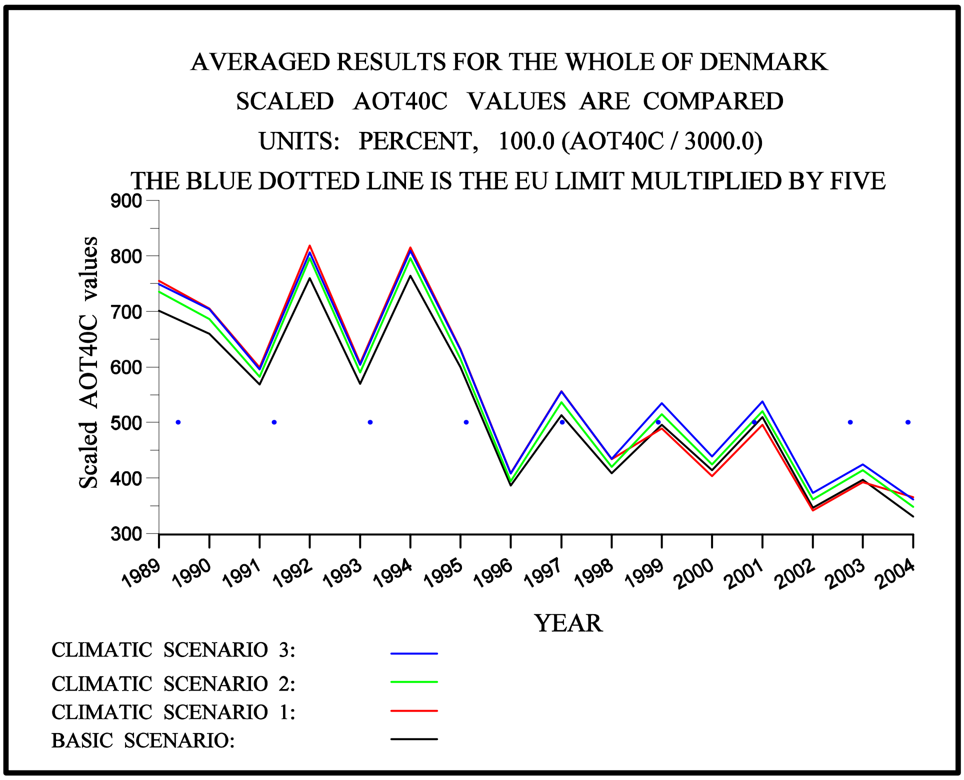


Figure 8.4.g

(AOT40 for crops) values (climatic scenarios versus the Basic Scenario).

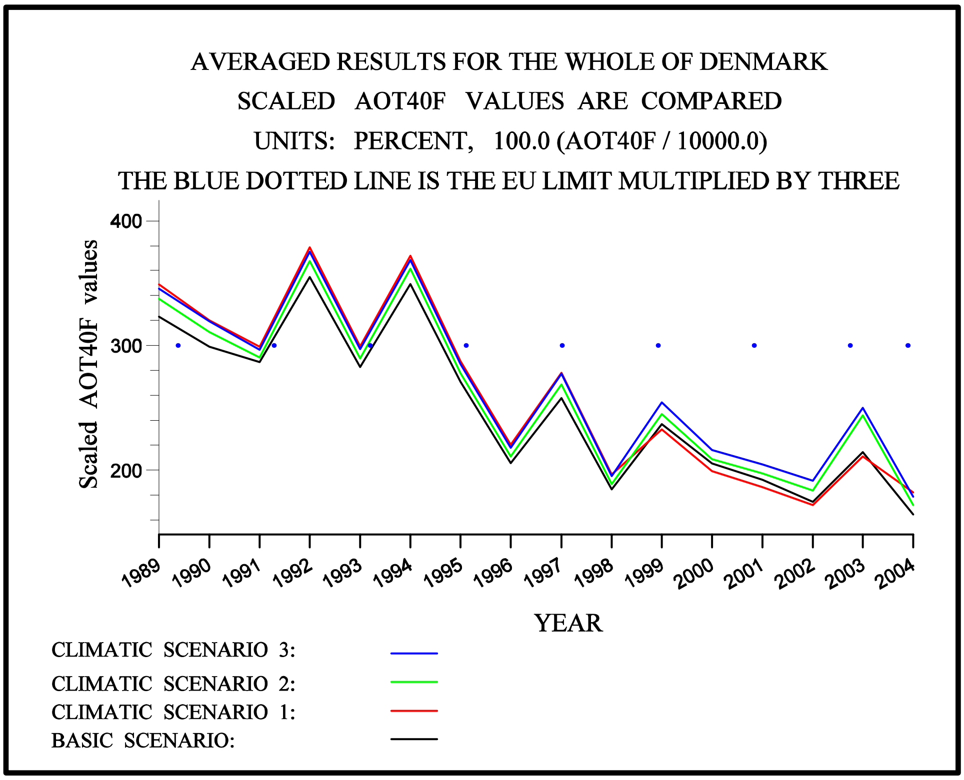


Figure 8.4.h

(AOT40 for forest trees) values (climatic scenarios versus the Basic Scenario).

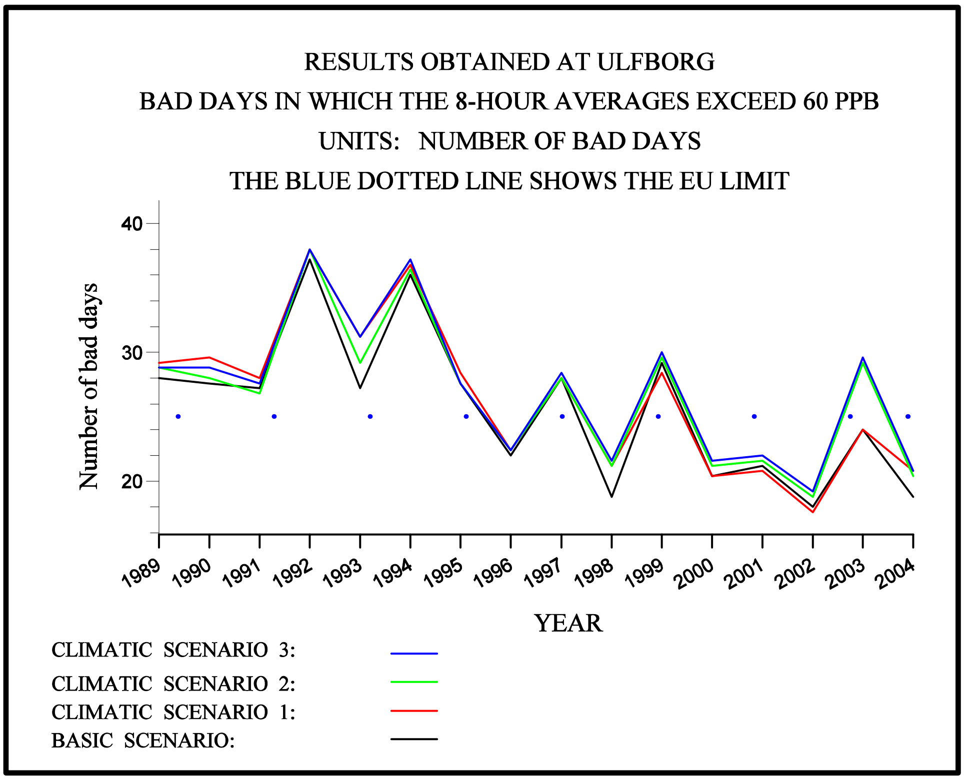


Figure 8.4.i

Comparison of numbers of days in which the 8-hour averaged ozone concentrations exceed at least once the EU limit of 60 ppb (climatic scenarios versus the Basic Scenario).

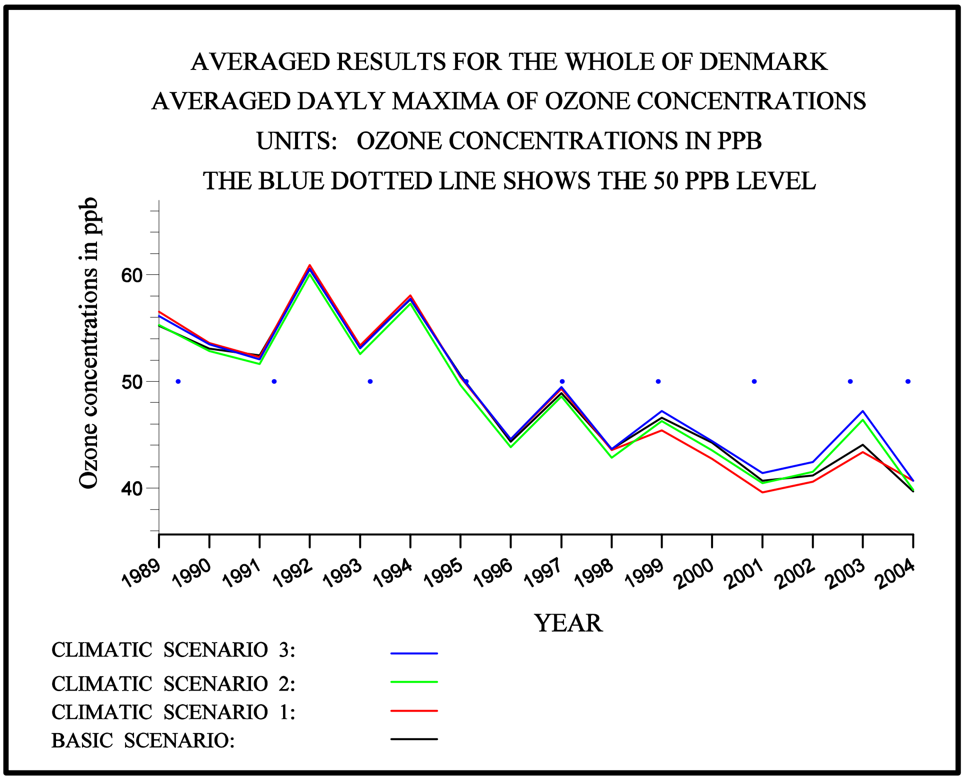


Figure 8.4.j

Averaged daily maxima of ozone concentrations (climatic scenarios versus the Basic Scenario).

- The quantities related to high ozone concentrations are slightly increased when the climatic scenarios are used (Fig. 8.4.g - Fig. 8.4.j). In the next subsection we shall show that the increase of these quantities when the climatic scenarios are used is rather considerable in some parts of Europe.

8.3.2. Changes in different parts of Europe

Changes in Denmark were studied until now. It is also interesting to investigate the changes in other parts of Europe. High ozone levels can cause damages to plants, animals and human health when these exceed certain critical levels. Therefore, we shall concentrate our attention to the quantities related to high ozone levels. We choose again the quantities studied in the previous sections:

- AOT40C values (causing damages to crops when the critical level of 3000 ppb.hours is exceeded),
- AOT40F values (causing damages to forest trees when the critical level of 10000 ppb.hours is exceeded),
- numbers of "bad" days in which the 8-hour average of the ozone concentrations exceeds at least once the critical value of 60 ppb (causing health damages for certain groups of humans; the number of "bad" days should not exceed 25 after year of 2010, the long-term aim is to reduce this number to zero in the European Union, see European Parliament, 2002)

and

- averaged daily maxima of ozone concentrations (over the period from April 1 to September 30).

Results obtained by the Basic Scenario for 2004 are given in Fig. 8.5. It is clearly seen that the EU limits on the AOT40C values, AOT40F values and numbers of “bad days” **are exceeded** in many areas of Europe. In some countries in the Mediterranean area and in Central Europe the exceedances are rather high.

Some results for 2004, obtained when the results obtained by using the Basic Scenario and Climatic Scenario 3 are compared in Fig. 8.6. In all plots of this figure the relative changes, in percent, of the considered ozone levels are presented (i.e. at each cell of the grid the result obtained by using Climatic Scenario 3 is divided by the results obtained by the Basic Scenario and the obtained ratio is multiplied by 100).

It is seen from Fig. 8.6 that the quantities related to high ozone concentrations are in general increased when Climatic Scenario 3 is used. For some parts of Europe the increases are rather considerable. Unfortunately, this is also true for some of the areas where the Basic Scenario is showing that the exceedances are already very large (compare Fig. 8.6 and Fig. 8.5).

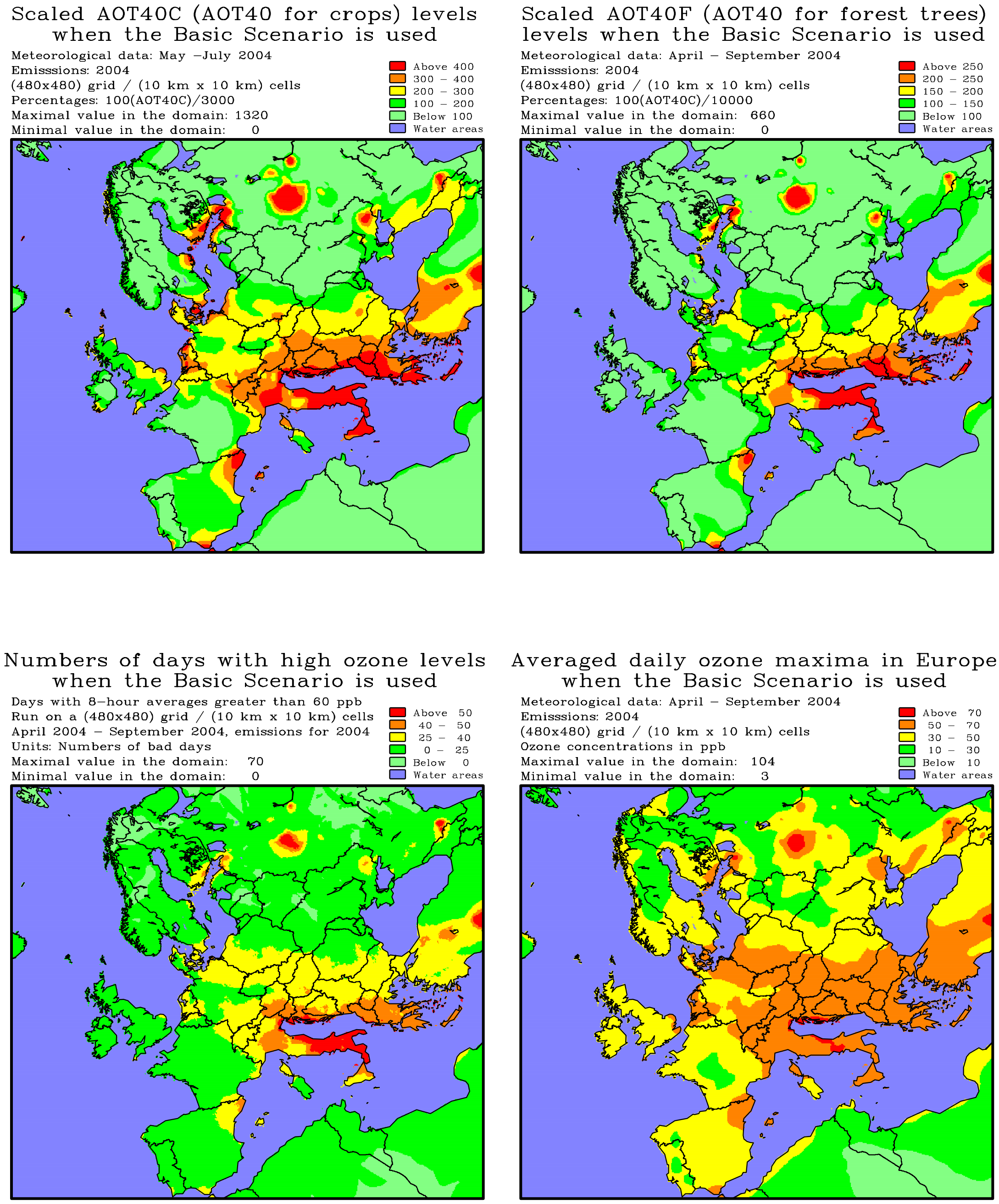


Figure 8.5

Distribution of different quantities related to high ozone concentrations in Europe. AOT40C (AOT40 for crops) levels are given on the upper left-hand-side plot. AOT40F (AOT40 for forest trees) levels are given on the upper right-hand-side plot. Both the AOT40C values and the AOT40F values are scaled by dividing them with the EU limit (3000 ppb.hours and 10000 ppb.hours, respectively) and multiplying the result by 100. In this way it is immediately seen by how much the EU limits are exceeded. The number of "bad" days (days in which the 8-hour averages of the ozone concentrations exceed at least once the EU limit of 60 ppb, the number of "bad" days should not exceed 25 after 2010 according to the EU Ozone Directive) are given in the lower left-hand-side plot. Averaged (over the extended summer period from April 1 to September 30) daily maxima of the ozone concentrations are given in the lower right-hand-side plot.

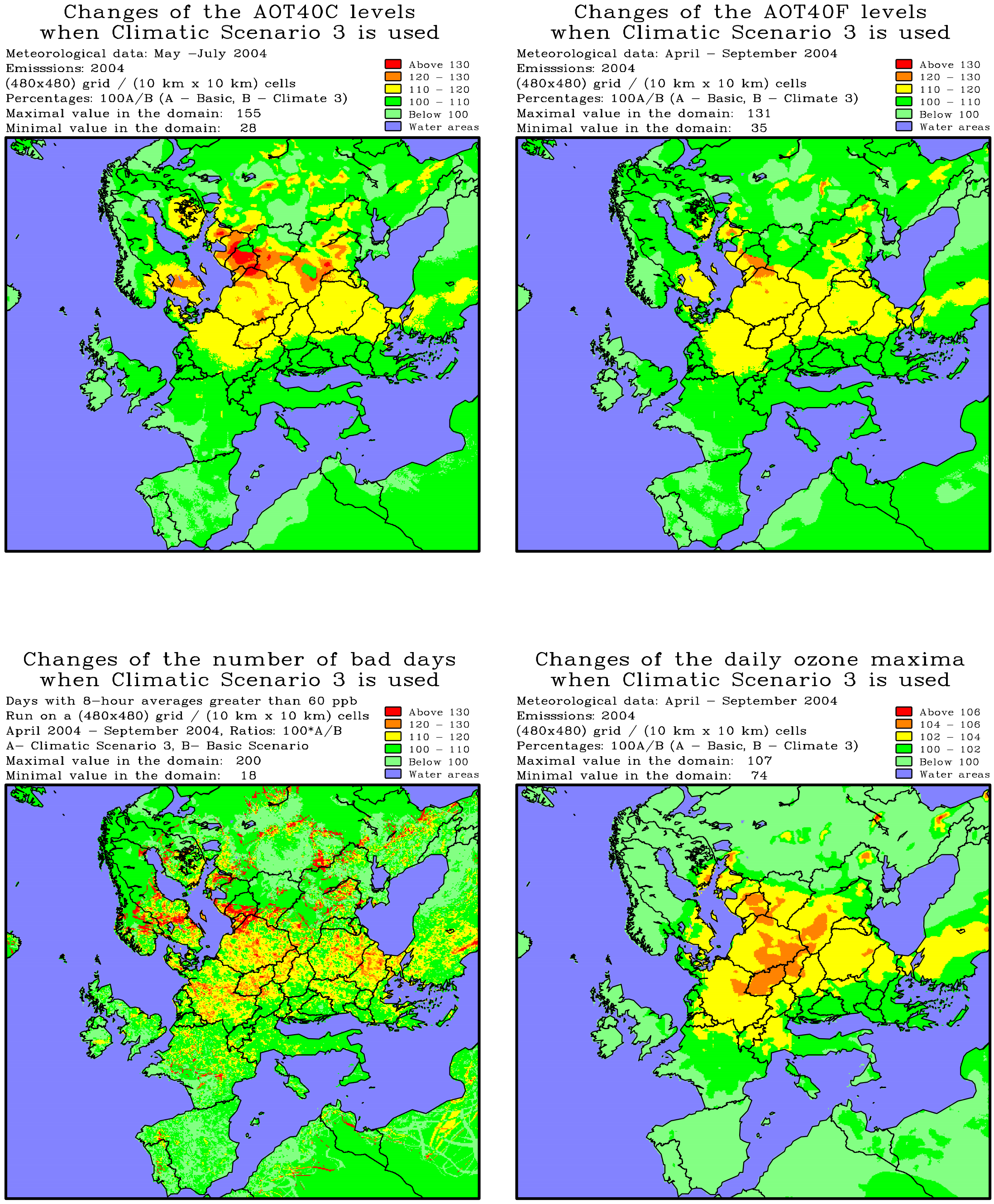


Figure 8.6

The changes in different part of Europe, obtained when Climatic Scenario 3 is used instead of the Basic Scenario, are shown in the four plots of this figure. The quantities shown are AOT40C (AOT40 for crops), AOT40F (AOT40 for forest trees), "bad days (days in which the 8-hour averages of the ozone concentrations exceed at least once the EU limit of 60 ppb) and averaged (over the extended summer period from April 1 to September 30) daily maxima of the ozone concentrations. At each grid-point the value obtained when the Climatic Scenario 3 is applied is divided by the value obtained when the Basic Scenario is used and the result is multiplied by 100 (i.e. the changes are obtained in percent).

The results shown in the right-hand-side lower plot of Fig. 8.6 show that the increase of the averaged daily maxima of the ozone concentrations due to the Climatic Scenario 3 are rather small, while the remaining plots in Fig. 8.6 indicate that the changes of some important quantities (which could cause damages on crops, forest trees and human health) can be considerable. The conclusion is that it might be insufficient to compare changes of concentrations. **It is also necessary to compare directly the quantities that characterize the danger for damaging effects.**

8.4. Results obtained by using scenarios related to anthropogenic emissions

As stated in Section 5, two human-made (anthropogenic) emission scenarios, Scenario 2010 and the MFR Scenario, were used in the experiments. The reduction factors that can be used to create emissions for these two scenarios are listed in Amann et al. (1999). We used these factors and the EMEP emissions for 1990 (see Vestreng et al., 2004). The emissions for several European countries and for the whole of Europe for selected years are given in Table 5. More details can be found in Amann et al. (1999) and Vestreng et al. (2005). It is necessary to emphasize here that the results in Table 5 for Denmark and Germany are typical for the countries in Western Europe (Scenario 2010 predicts in general lower emissions in these countries than the emissions in the period 1989-2004). The results for the remaining countries, which are shown in Table 5, are in general typical for the countries in Eastern Europe. Thus, **Scenario 2010 predicts (in general) reduced human-made (anthropogenic) emissions in Western Europe and increased human-made (anthropogenic) emissions in Eastern Europe (comparing with the emission levels after the middle of 90s).**

Two additional scenarios are used together with Scenario 2010 and Scenario MFR. In these two scenarios the same emissions as the emissions for Scenario 2010 and Scenario MFR are used but the climatic conditions from Scenario Climate 3 are used instead of the actual meteorological data for the period from 1989 to 2004. The new scenarios created with the climatic conditions from Scenario Climate 3 are called Climate Scenario 2010 and Climate Scenario MFR (see also Section 5).

Results obtained by using five scenarios (the Basic Scenario, Scenario 2010, the MFR Scenario, Climate Scenario 2010 and Climate Scenario MFR) will be presented and discussed in this section. Temporal variation of major pollutants is given in Fig. 8.7. The changes in different parts of Europe are presented in Fig. 8.9 – Fig. 8.12. The results presented in all these figures are commented below.

8.4.1. Temporal variations of the concentrations

Temporal variations of the major pollutants at the Danish measurement sites are given in Fig. 8.7.a – Fig. 8.7.j. Several conclusions can be drawn from the results presented in these figures.

- The MFR Scenario and the Climate MFR Scenario are always leading to big reductions of the pollution levels.
- The Climate MFR Scenario is as a rule giving larger concentrations than the MFR Scenario, but the difference is very small. The same is true for the relationship

between the concentrations obtained by using the Climate Scenario 2010 and Scenario 2010.

- The other two scenarios, Scenario 2010 and the Climate Scenario 2010 are also producing smaller concentrations in most of the cases.
- The difference between the concentrations produced by the Basic Scenario and any of the two scenarios (Scenario 2010 or the Climate Scenario 2010) are becoming smaller at the end of the time-interval. The reason for this can be explained as follows. The emissions used in the Basic Scenarios are becoming smaller at the end of the period, while the same emissions are used during the whole interval when the two emission scenarios are used. Therefore, there is no reduction trend when the latter scenarios are used, while there is a reduction trend when the Basic Scenario is used.
- The $\mathbf{SO_2}$ concentrations obtained by using Scenario 2010 and the Climate Scenario 2010 are becoming larger than the corresponding concentrations obtained when the Basic Scenario is run (see Fig. 8.7.a). The reason for this is the fact that the $\mathbf{SO_2}$ emissions for the Basic Scenario are becoming smaller than the emissions in Scenario 2010 in the end of the period from 1989 to 2004 (this can also be seen in Table 5). The same conclusion is valid for the sulphate concentrations in Denmark (see Fig. 8.7.b) and can be explained in the same way.
- The important quantities AOT40 values for crops, AOT40 values for forest trees and numbers of “bad days” (which could cause damages when the critical levels are exceeded) are reduced considerably in Denmark (see Fig. 8.7.g – Fig. 8.7.i). However, this is not true for the whole of Europe (this topic will be discussed in the next paragraph.
- The important quantity number of “bad days” (which might cause damages on human health when the EU critical level of 25 days per year is exceeded) is becoming less than the EU critical level (see Fig. 8.7.i). This is also true (with one exception, year 1994) when the Climate Scenario 2010 is used.

Table 5

Anthropogenic emissions in several European countries and in Europe as a whole. The emissions for 1990, 1995 and 2000 are taken from the recent EMEP report (see Vestreng et al., 2005). The predictions for 2010 are calculated by using the reduction factors given in Amann et al. (1999).

Country	Year	SO2	NOx	VOC	NH3
Germany	1990	5326	2846	3534	736
	1995	1937	2000	2248	611
	2000	636	1634	1697	607
	2010	586	1252	1272	552
Denmark	1990	177	283	229	133
	1995	136	273	201	114
	2000	28	208	172	105
	2010	87	133	108	125
Bulgaria	1990	2008	361	217	144
	1995	1476	266	173	99
	2000	982	184	120	56
	2010	924	303	210	128
Hungary	1990	1010	238	205	124
	1995	705	190	150	77
	2000	486	185	173	71
	2010	606	214	160	107
Romania	1990	1311	546	772	300
	1995	887	322	613	215
	2000	728	289	518	206
	2010	590	480	772	288
Ukraine	1990	2783	2828	1369	729
	1995	1639	531	811	540
	2000	1129	561	271	348
	2010	1113	2149	999	649
Europe	1990	46766	28346	28660	8594
	1995	32949	24323	24158	7333
	2000	25926	22672	20362	6871
	2010	17772	17575	18056	7563

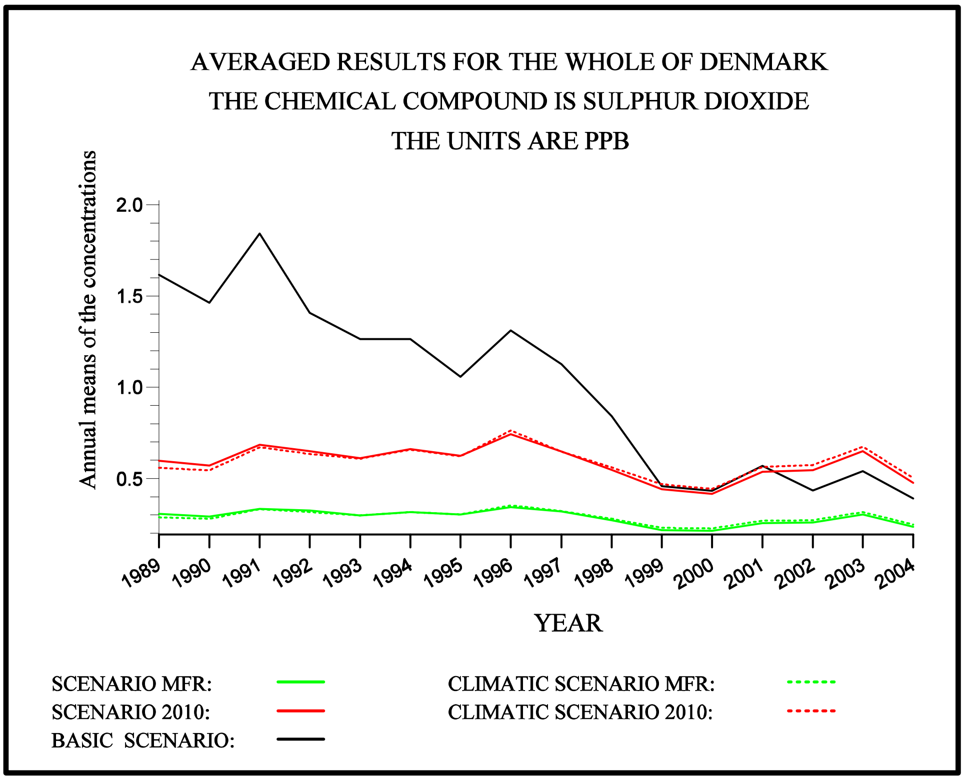


Figure 8.7.a

Variation of the annual means of the SO_2 *concentrations when different scenarios for human-made (anthropogenic) emissions are run.*

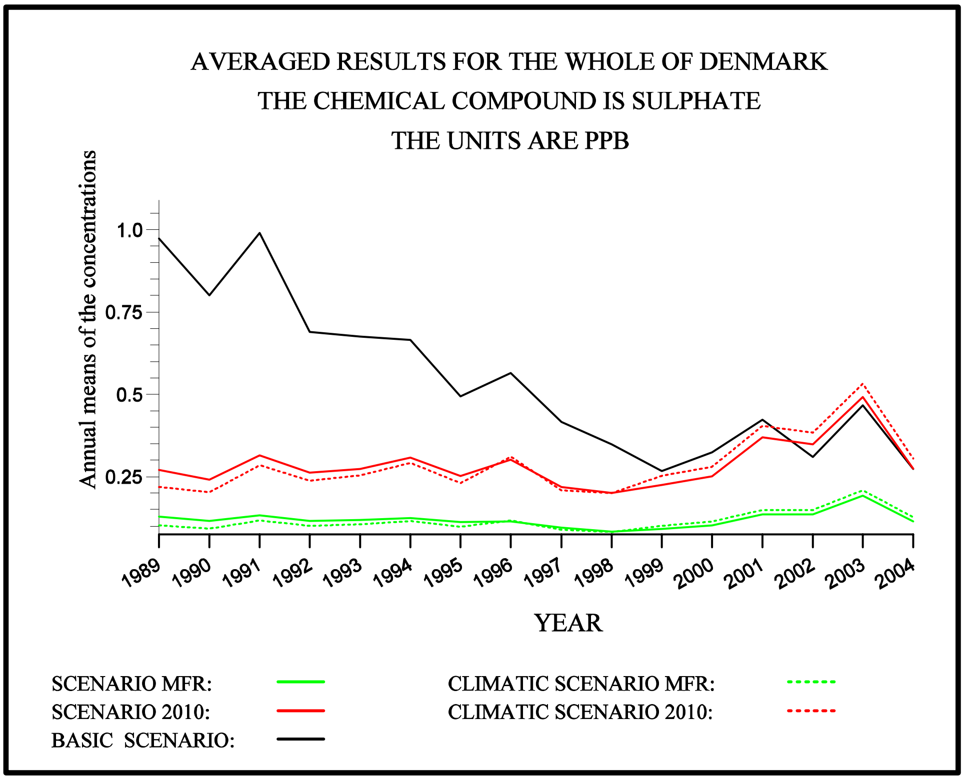


Figure 8.7.b

Variation of the annual means of the $SO_4^=$ *concentrations when different scenarios for human-made (anthropogenic) emissions are run.*

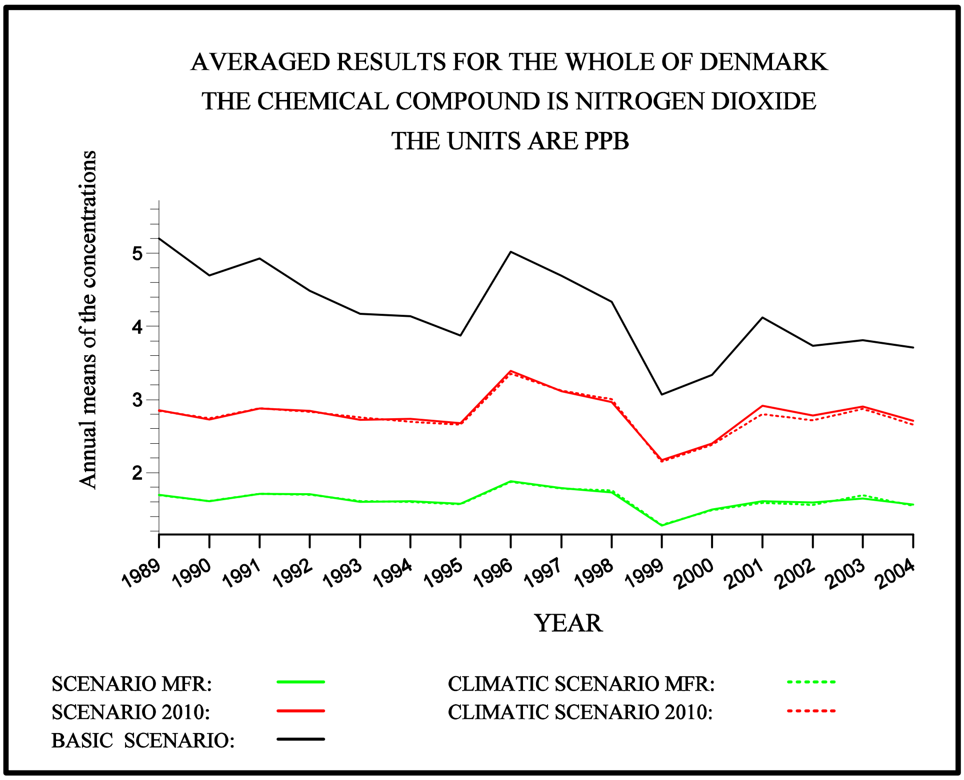


Figure 8.7.c

Variation of the annual means of the $\mathbf{NO_2}$ *concentrations when different scenarios for human-made (anthropogenic) emissions are run.*

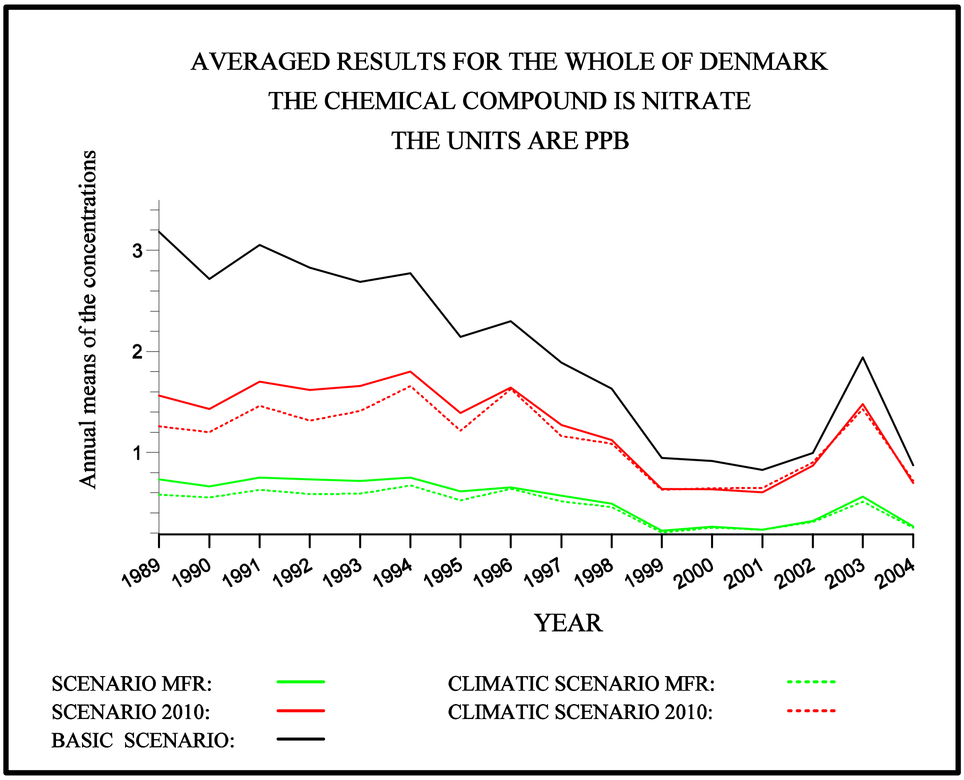


Figure 8.7.d

Variation of the annual means of the $\mathbf{HNO_3 + NO_3^-}$ *concentrations when different scenarios for human-made (anthropogenic) emissions are run.*

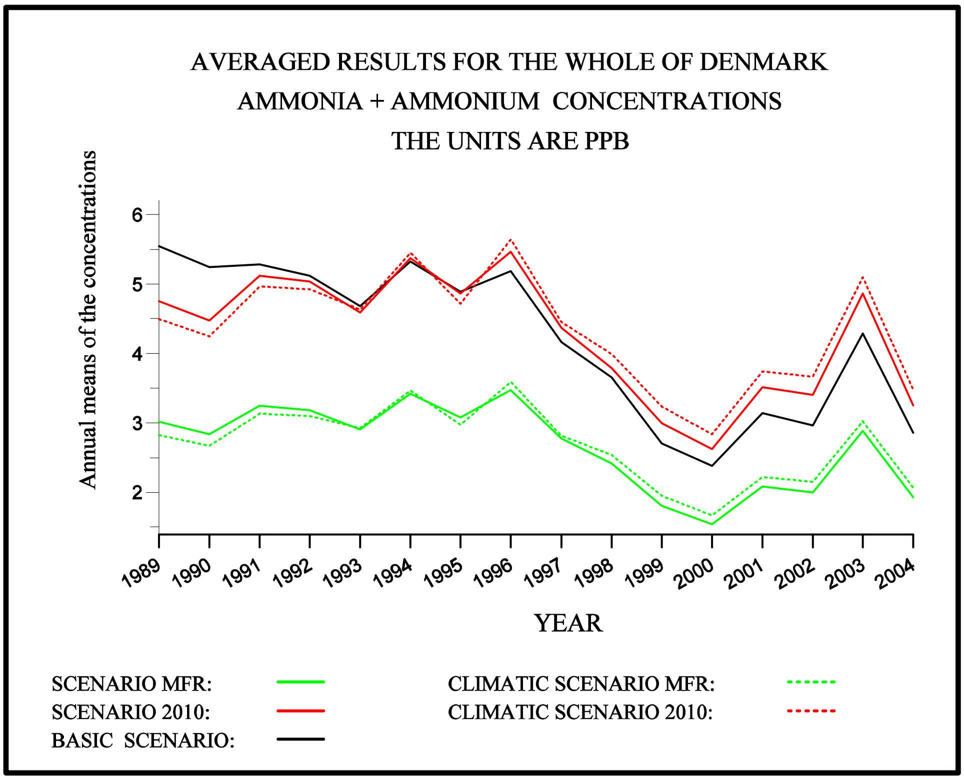


Figure 8.7.e

Variation of the annual means of the $\mathbf{NH_3 + NH_4^+}$ *concentrations when different scenarios for human-made (anthropogenic) emissions are run.*

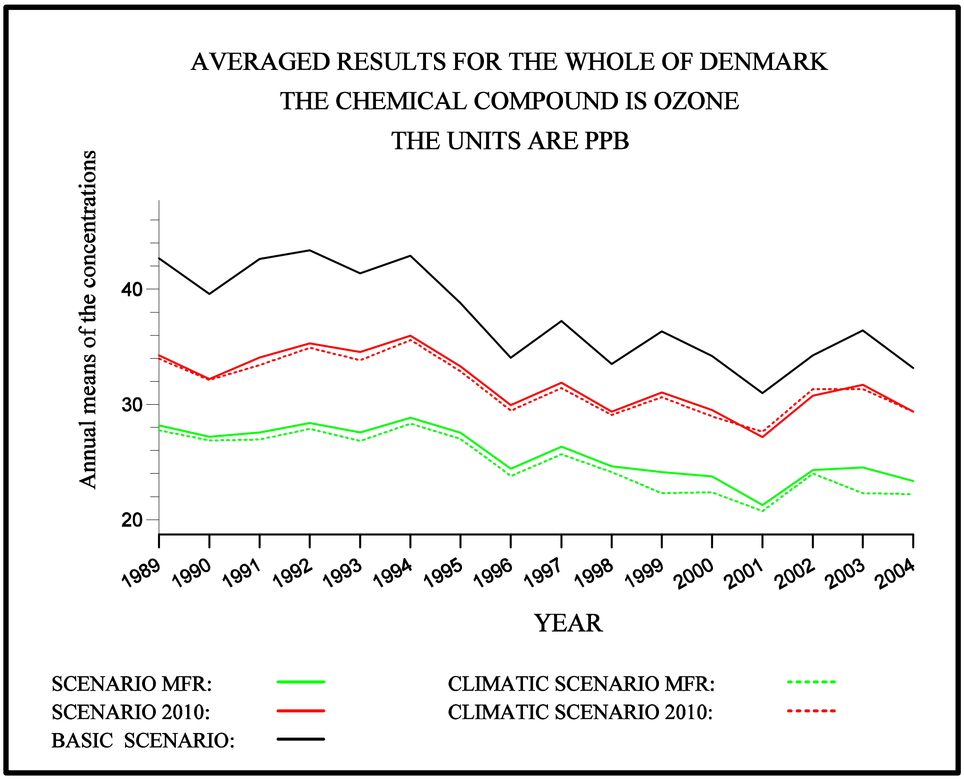


Figure 8.7.f

Variation of the annual means of the $\mathbf{O_3}$ *concentrations when different scenarios for human-made (anthropogenic) emissions are run.*

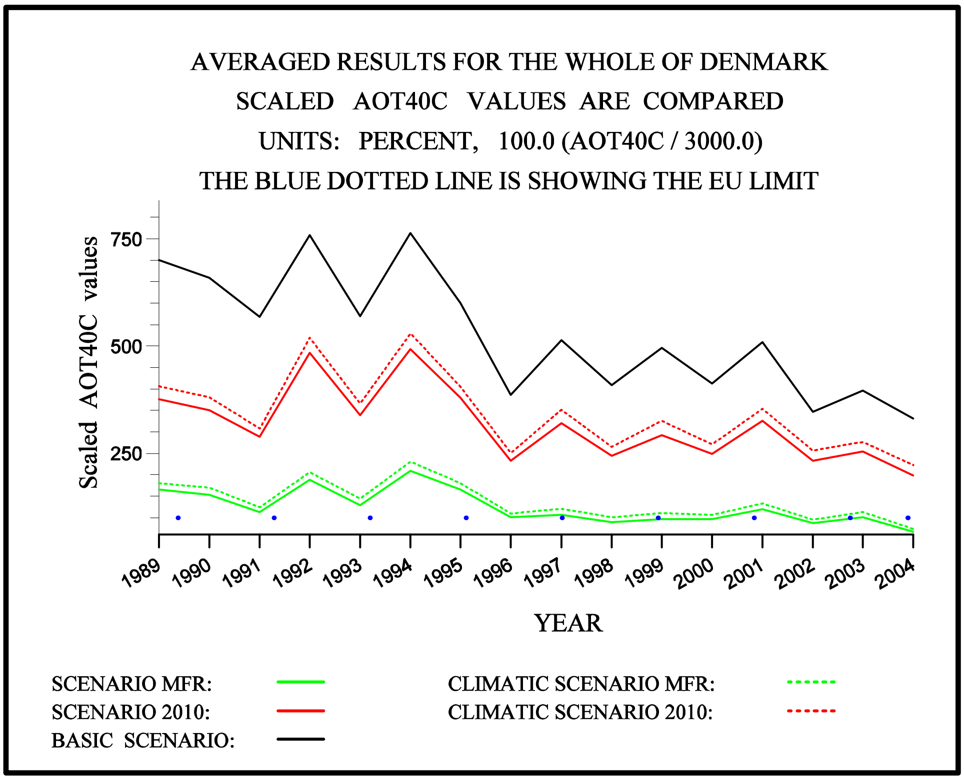


Figure 8.7.g

Variation of the scaled AOT40C (AOT40 for crops) values when different scenarios for human-made (anthropogenic) emissions are run.

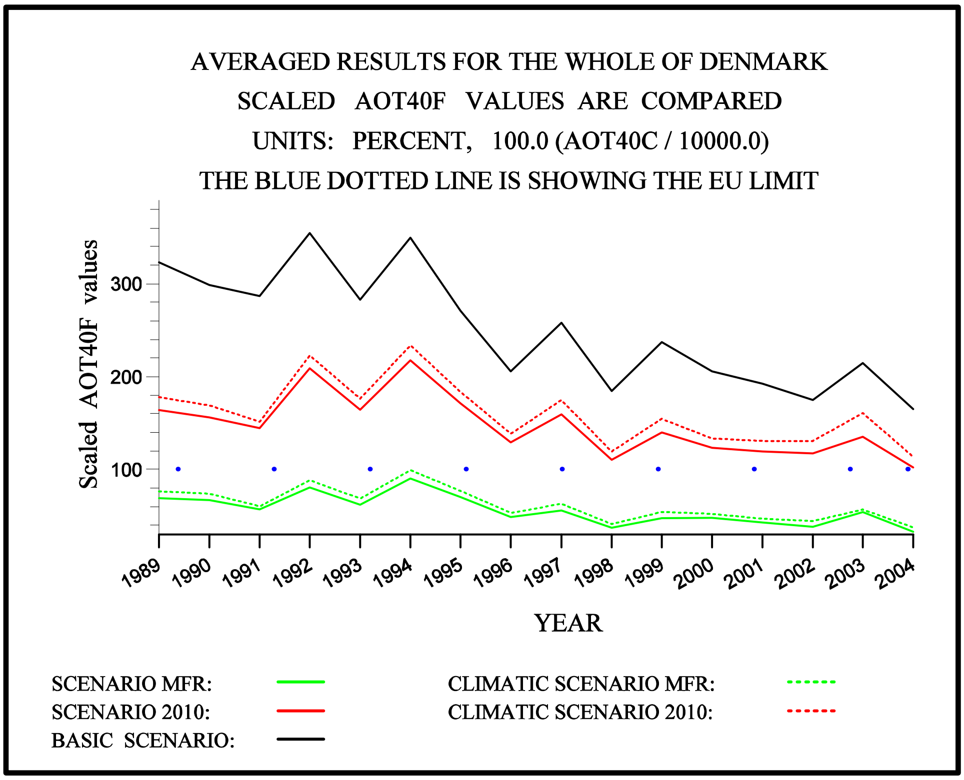


Figure 8.7.h

Variation of the scaled AOT40F (AOT40 for forest trees) values when different scenarios for human-made (anthropogenic) emissions are run.

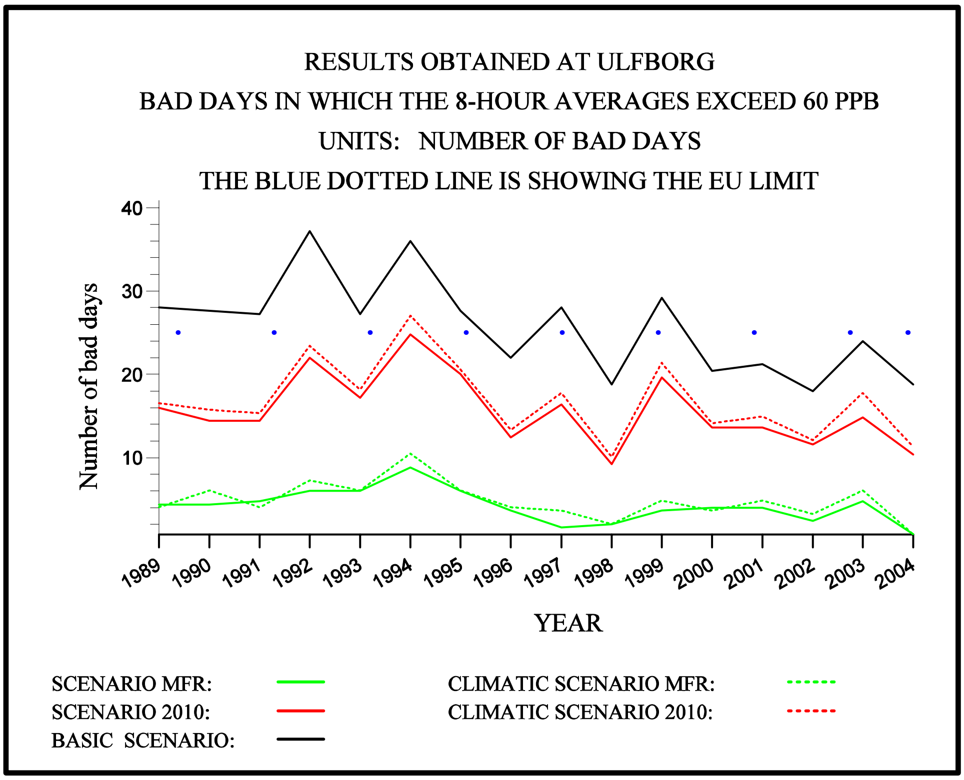


Figure 8.7.i

Variation of the numbers of "bad days" (days in which the averaged eight-hour ozone concentrations exceed at least once the limit of 60 ppb) when different scenarios for human-made (anthropogenic) emissions are run.

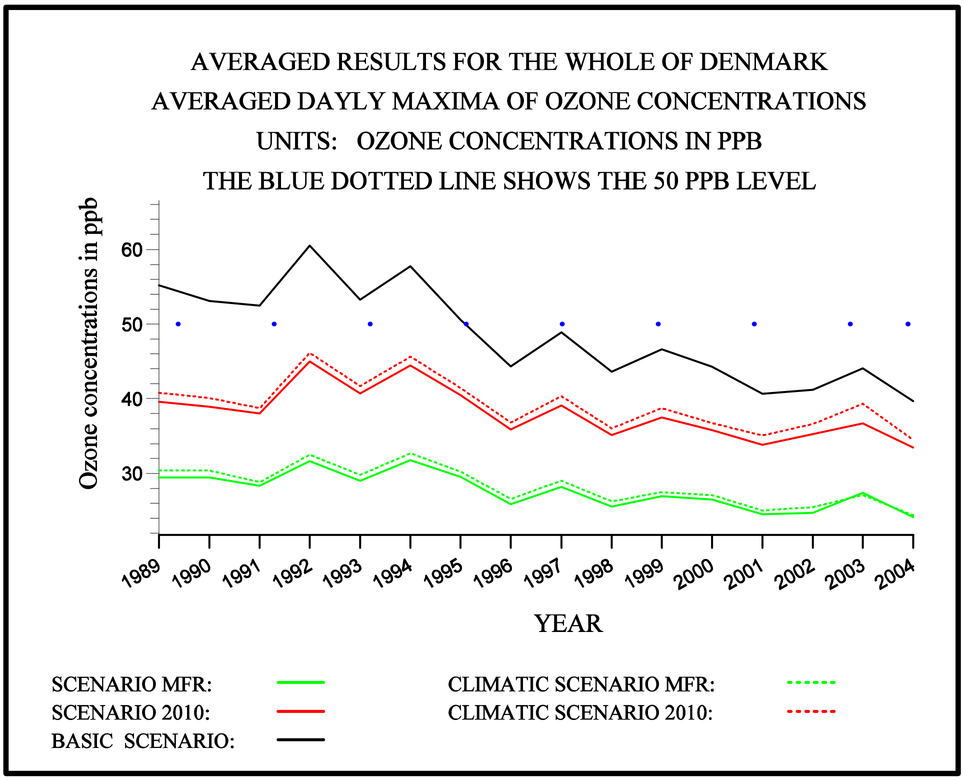


Figure 8.7.j

Variation of the averaged (in the period April 1 – September 30) daily maxima of the ozone concentrations when different scenarios for human-made (anthropogenic) emissions are run.

8.4.2. Spatial variations in different parts of Europe

The changes of the **AOT40C levels** (AOT40 values for crops), when the four emission scenarios (Scenario 2010, the MFR Scenario, Scenario Climate 2010 and Scenario Climate MFR) are used instead of the Basic Scenario, are given (in percent) in Fig. 8.8. The following conclusions can be drawn from the results presented in the four plots of Fig. 8.8:

- The application of both Scenario 2010 and Scenario Climate 2010 leads to considerable reduction of the AOT40C values in nearly the whole Western Europe. This is due to the fact that the predicted for 2010 emissions in Western Europe are as a rule smaller than the emissions for 2004 which are used in the Basic Scenario.
- The application of both Scenario 2010 and Scenario Climate 2010 leads to very considerable increases of the AOT40C levels in a large part of Eastern and Central Europe. At first look, this seems to be a surprise. Scenario 2010 was designed with the primary aim to obtain reductions in the whole of Europe. Therefore, it is assumed that the emissions in nearly all countries will be reduced in comparison with the levels in 1990. However, the emissions in some countries were reduced in the middle of 90s with amounts which are larger than these predicted for 2010. This is especially true for the countries in Eastern and Central Europe (see Table 5). This means that the actual 2004 emissions in many countries in Eastern and Central Europe are in fact lower (and some times considerably lower) than the predicted for 2010 emissions. Note too that the emissions in Scenario 2010 and Scenario Climate 2010 are the same (only the meteorological data that are used in these two scenarios are different).
- The application of Scenario Climate 2010 instead of Scenario 2010 leads to certain increases of the areas with high AOT40C values. This is especially true for parts of Poland, the Check Republic, Hungary, Romania and Bulgaria.
- The application of the MFR Scenario and the Climate MFR Scenario leads to very considerable reductions (by 60% and even more than 60%) of the AOT40C in nearly the whole of Europe. This should be expected, because the emissions used in these two scenarios are much smaller than the emissions used in the Basic Scenario. It should be mentioned here, however, that the reductions, although these are so large, are not reducing the AOT40C levels in the whole of Europe under the critical level of 3000 ppb.hour. This fact could be deduced by comparing carefully the appropriate plots in Fig. 8.5, Fig. 8.6 and Fig. 8.8.
- It is difficult to see which scenario (the MFR Scenario or the Climate MFR Scenario) produces larger AOT40C values. A careful comparison of the two left-hand-side plots of Fig. 8.8 indicates that the AOT40C values obtained by using the Climate MFR Scenario tend to be slightly larger than the AOT40C values obtained by using the MFR Scenario.

The changes of the **AOT40F levels** (AOT40 values for forest trees), when the four emission scenarios (Scenario 2010, the MFR Scenario, Scenario Climate 2010 and Scenario Climate MFR) are used instead of the Basic Scenario, are given (in percent) in Fig. 8.9. Very similar conclusions (as those drawn above for the AOT40C values) can be drawn from the results presented in the four plots of Fig. 8.9.

The changes of the **numbers of "bad days"** (days in which the eight-hour averages of the ozone concentrations exceed at least once the limit of 60 ppb), when the four emission scenarios (Scenario 2010, the MFR Scenario, Scenario Climate 2010 and Scenario Climate MFR) are used instead of the Basic Scenario, are given (in percent) in Fig. 8.10. Very similar conclusions (as those drawn above for the AOT40C values) can be drawn from the results presented in the four plots of Fig. 8.10.

The changes of the **averaged daily maxima of the ozone concentrations** (averaged in the period from April 1 to September 30), when the four emission scenarios (Scenario 2010, the MFR Scenario, Scenario Climate 2010 and Scenario Climate MFR) are used instead of the Basic Scenario, are given (in percent) in Fig. 8.11. The following conclusions can be drawn from the results presented in the four plots of Fig. 8.11:

- The conclusions related to the first two scenarios, Scenario 2010 and Scenario Climate 2010, are very similar to the conclusions for these two scenarios that were made for AOT40C values, AOT40F values and numbers of "bad days" (see the comments given above).
- The results related to the MFR Scenario and to the Climate MFR Scenario are different. The reductions made by using these two scenarios (instead of the Basic Scenarios) are considerably higher than the corresponding reductions for AOT40C values, AOT40F values and numbers of "bad days" (compare the results given in the two left-hand-side plots in Fig. 8.11 with the results given in the corresponding plots in Fig. 8.8, Fig. 8.9 and Fig. 8.10). It is not very clear what the reason for this behaviour is. Note however, that the previous three quantities (AOT40C values, AOT40F values and numbers of "bad days") are accumulated quantities, while the daily maxima are consisting by just one number per day. Let us take one extreme example. If the largest eight-hour average of the ozone concentrations in the day under consideration is 60.1 ppb when the Basic Scenario is used, then we have a "bad day". If this quantity becomes 59.9 ppb when either the MFR Scenario or the Climate MFR Scenario is used, then we have a "good day". It is quite obvious that the daily ozone maxima do not differ too much in these two situations. Thus, although the example is very extreme, it is nevertheless telling us that it is possible to switch from a "bad day" found with the Basic Scenario to a "good day" found with the two MFR scenarios, while, at the same time, the daily ozone maxima do not necessarily differ too much. This might be an explanation of the fact the averaged daily maxima are not very sensitive to the different emission scenarios, but more experiments and runs are needed in order to confirm or reject this conjecture.

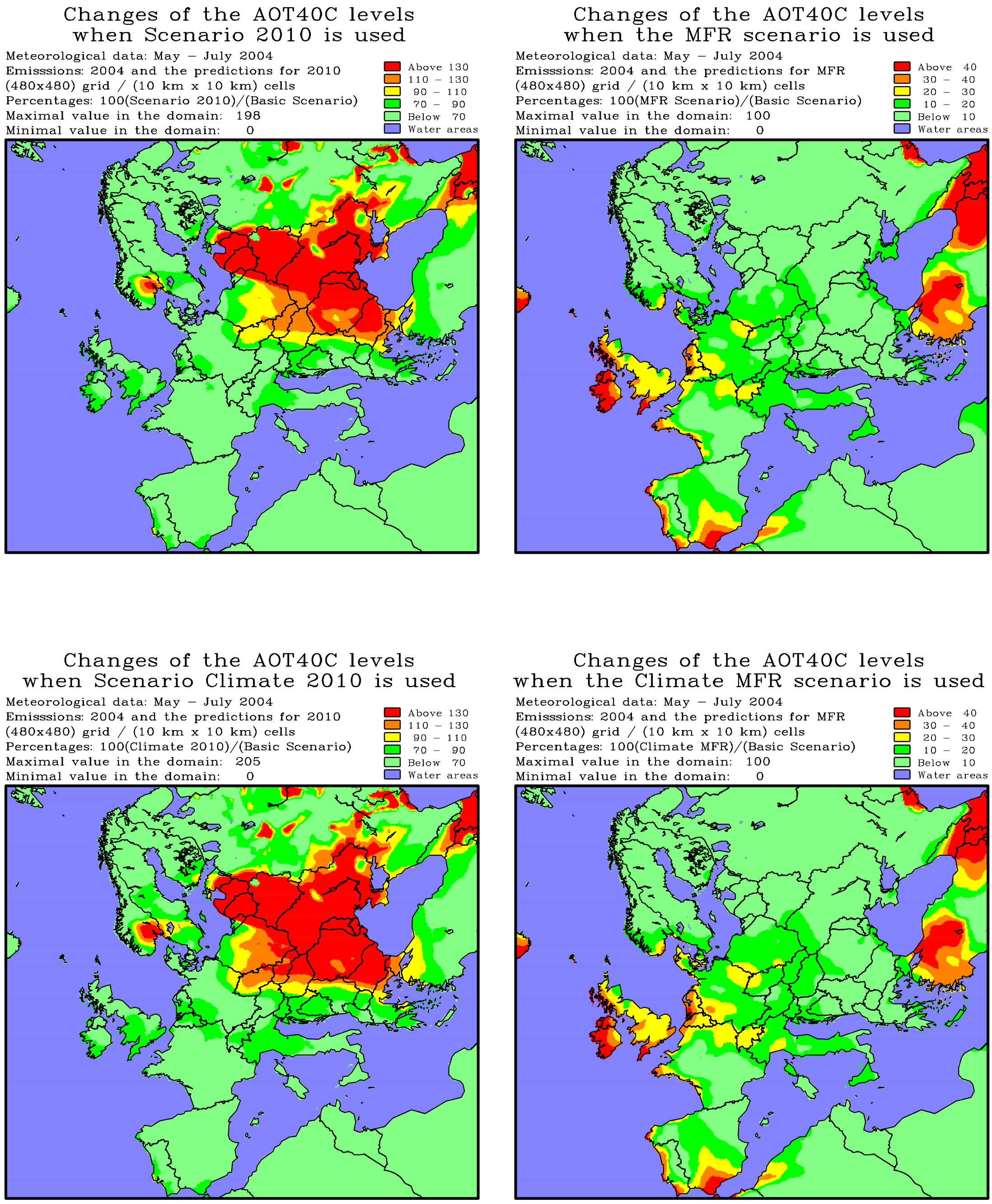


Figure 8.8

Changes of the AOT40C (AOT40 for crops) levels when four human-made (anthropogenic) emission scenarios are compared with the Basic Scenarios for year 2004. The results obtained with Scenario 2010 and the MFR Scenarios are given in the two upper plots. The results obtained when climatic changes are superimposed by applying Climatic Scenario 3 (i.e. the Scenario Climate 2010 and the Scenario Climate MFR) are given in the two lower plots.

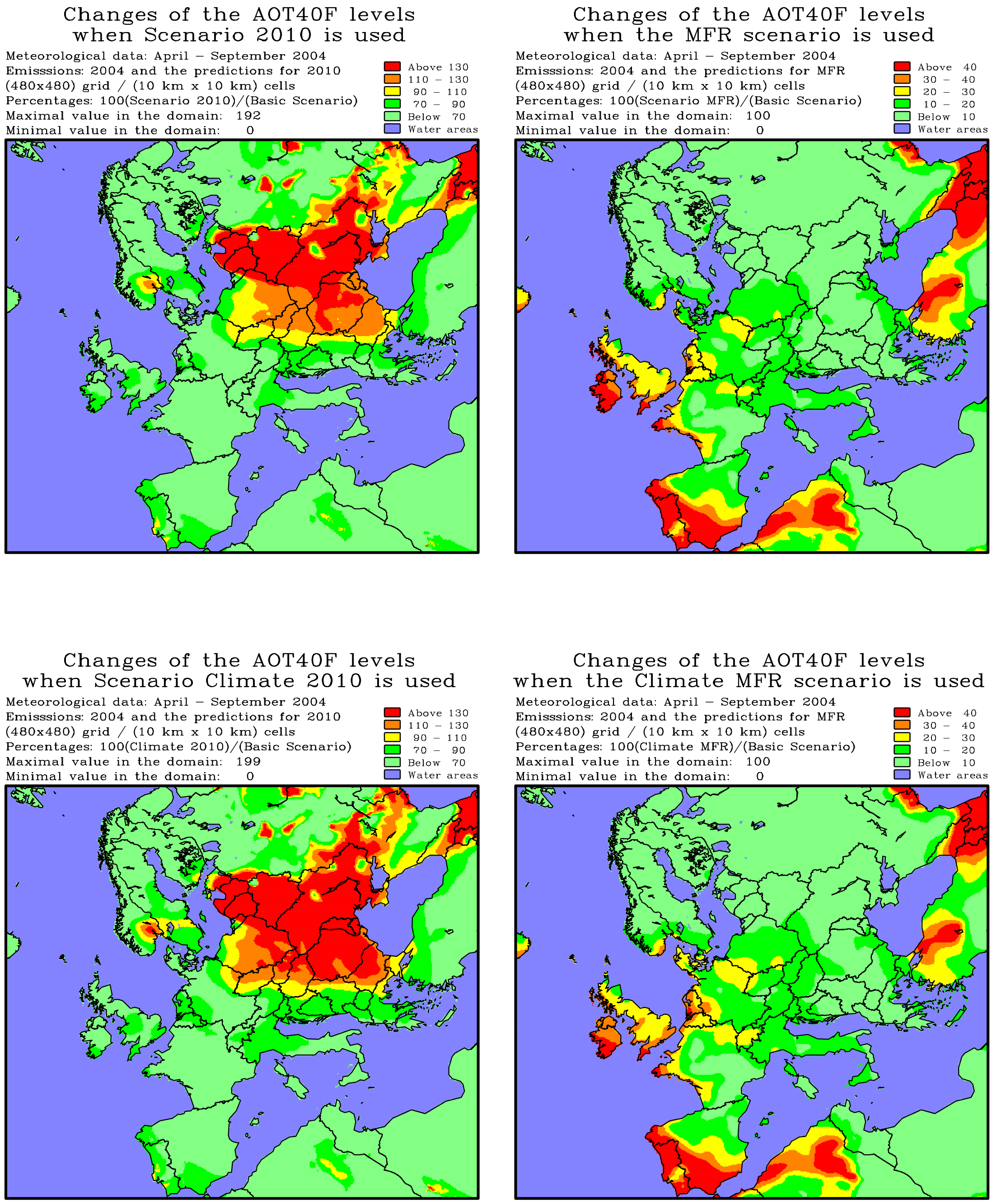
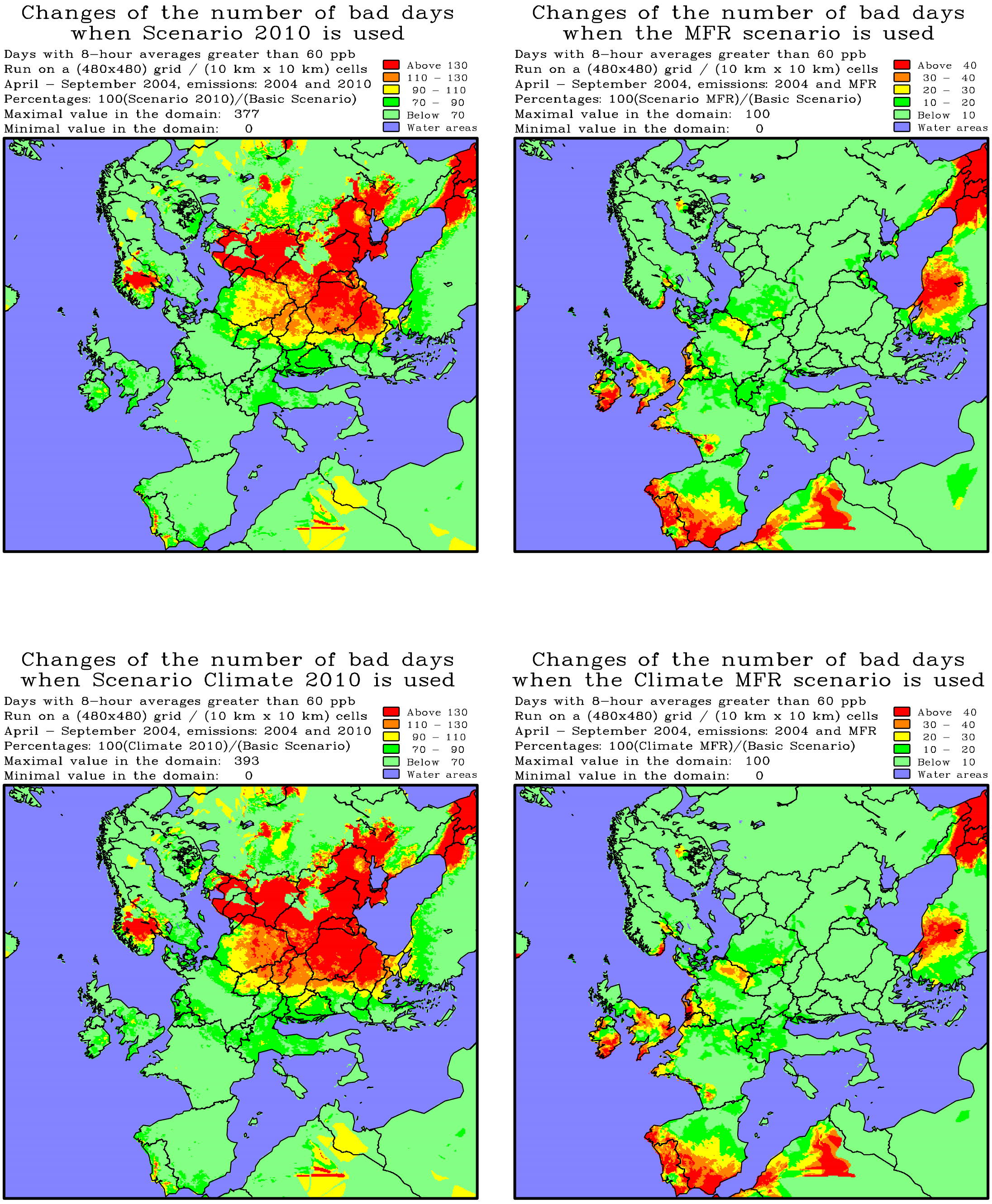


Figure 8.9

Changes of the AOT40F (AOT40 for forest trees) levels when four human-made (anthropogenic) emission scenarios are compared with the Basic Scenarios for year 2004. The results obtained with Scenario 2010 and the MFR Scenarios are given on the two upper plots. The results obtained when climatic changes are superimposed by applying Climatic Scenario 3 (i.e. the Scenario Climate 2010 and the Scenario Climate MFR) are given in the two lower plots.



<u>Figure 8.10</u>

Changes of the numbers of "bad days" (days in which averaged eight-hour ozone concentrations exceed the limit of 60 ppb at least once) when four human-made (anthropogenic) emission scenarios are compared with the Basic Scenarios for year 2004. The results obtained with Scenario 2010 and the MFR Scenarios are given on the two upper plots. The results obtained when climatic changes are superimposed by applying Climatic Scenario 3 (i.e. the Scenario Climate 2010 and the Scenario Climate MFR) are given in the two lower plots.

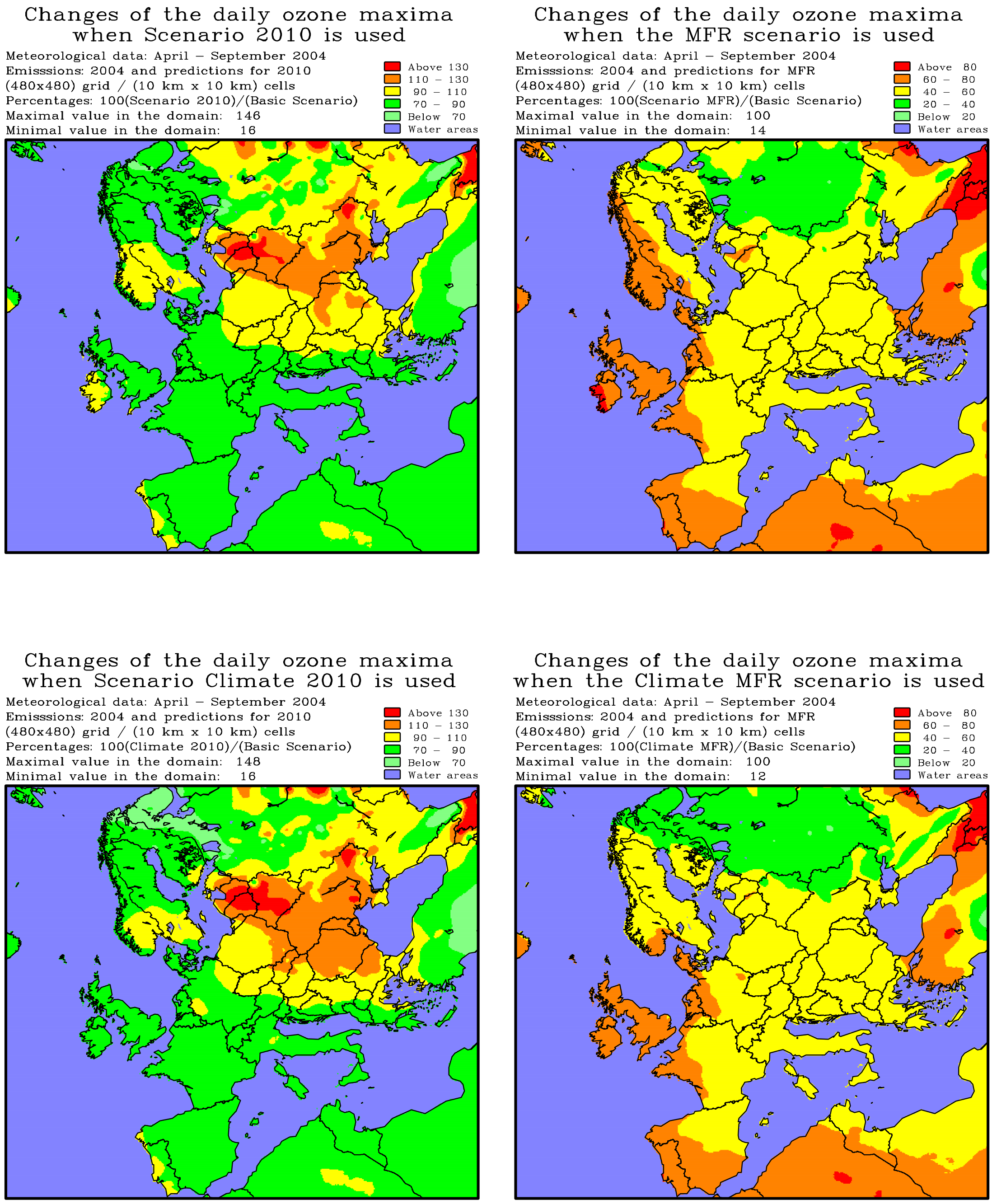


Figure 8.11

Changes of the averaged daily maxima of ozone concentrations when four human-made (anthropogenic) emission scenarios are compared with the Basic Scenarios for year 2004. The results obtained with Scenario 2010 and the MFR Scenarios are given on the two upper plots. The results obtained when climatic changes are superimposed by applying Climatic Scenario 3 (i.e. the Scenario Climate 2010 and the Scenario Climate MFR) are given in the two lower plots.

8.5. Results obtained by using scenarios related to biogenic emissions

The biogenic emission scenarios were discussed in Section 5. The four biogenic scenarios:

- Biogenic Basic Scenario,
- Biogenic Climate 3 Scenario,
- Biogenic 2010 Scenario

and

- Biogenic MFR Scenario

are created by using increased biogenic emissions, while all the other parameters are the same as those in the Basic Scenario, Scenario Climate 3, Scenario Climate 2010 and Scenario Climate MFR respectively. Some results obtained when the biogenic scenarios are run are presented in this section.

8.5.1. Applying high biogenic emissions to Scenario 2010 and the MFR Scenario

The distribution of the numbers of "bad days" (days in which the eight-hour averages of the ozone concentrations exceed at least once the limit of 60 ppb) for the case where **Scenario Climate 2010** is run is given in the upper left-hand-side plot of Fig. 8.12. This means that the normal biogenic emissions are used in this run. It is seen that the EU critical level of 25 days is exceeded mainly in countries of Eastern and Central Europe as well as in Italy. There are also some areas in the Russian Federation, Ukraine and in Caucasus where there are high levels.

The distribution of the numbers of "bad days" for the case where **Scenario Biogenic 2010** is run is given in the upper right-hand-side plot of Fig. 8.12. Comparing the two upper plots of Fig. 8.12, it is easily seen that the major differences can be described as follows:

- The EU critical level of 25 days is exceeded not only in countries of Central and Eastern Europe, but also in some countries of Western Europe (parts of Germany, Switzerland, France, Belgium and the Netherlands) when Scenario Biogenic 2010 is used instead of Scenario Climate 2010. These areas are given in Fig. 8.12 in yellow, orange and red colours.
- The numbers of "bad days" in the areas in the Russian Federation, Ukraine and Caucasus, which were high when Scenario Climate 2010 was used, are now reduced considerably.

Some more details about the differences between the distributions in the upper two plots can be seen if we take the ratios of the corresponding values (multiplying again these ratios with 100 in order to get the changes in percent). This is done in the lower left-hand-side plot of Fig. 8.12. It is seen that an increase of the numbers of "bad days" (shown again in yellow, orange and red colours) takes place in many areas of both Western and Eastern Europe. The only difference between the two scenarios (Scenario Climate 2010 and Scenario Biogenic 2010) is the fact that different biogenic emissions are used in these two scenarios. Therefore, it is quite clear that the increase of the number of "bad days" when Scenario Biogenic 2010 is used can be caused only by the fact that higher biogenic emissions are used in this scenario.

It is also worthwhile **to compare Scenario Biogenic 2010 with the Basic Scenario.** Results from this comparison are presented in the lower right-hand-side plot of Fig. 8.12.Two different major effects can be seen when Scenario Biogenic 2010 is compared with the Basic Scenario:

- The numbers of "bad days" obtained by using Scenario Biogenic 2010 in the most countries of **Eastern Europe** are larger than the corresponding numbers obtained when the Basic Scenario is run. This should be expected because

    (a) the human-made (anthropogenic) emissions in Scenario Biogenic 2010 (the same as the human-made (anthropogenic) emissions in Scenario 2010) are larger than the corresponding human-made (anthropogenic) emissions in the Basic Scenario (see also the figures in Table 5)

    and

    (b) the biogenic emissions in Scenario Biogenic 2010 are larger than the corresponding biogenic emissions in the Basic Scenario.

    Thus, both the human-made (anthropogenic) emissions and the biogenic emissions used in Scenario Biogenic 2010 are larger than the corresponding human-made (anthropogenic) and biogenic emissions used in the Basic Scenario. This results in a natural way in an increase of the numbers of "bad days". In some parts of Europe (the red areas in the plot) the increase is very considerable (by more than 50%).

- The situation in **Western Europe** is much more complicated. Also here the biogenic emissions in Scenario Biogenic 2010 are higher than the corresponding biogenic emissions in the Basic Scenario. However, the similarity of the situation in Western and Eastern Europe stops here. The anthropohenic emissions used in Scenario Biogenic 2010, let us reiterate that these are the same as the human-made (anthropogenic) emission used in Scenario 2010, are smaller than the corresponding anthropogenic emissions in the Basic Scenario. This means that in Western Europe we have two different effects which work in opposite directions:

    (a) the reduced human-made (anthropogenic) emissions will normally lead to a reduction of the numbers of "bad days" in the run with the Biogenic 2010 Scenario if the biogenic emissions in the two scenarios were the same

    and

    (b) the higher biogenic emissions will normally lead to an increase of the numbers of "bad days" if the human-made (anthropogenic) emissions in the two scenarios were the same.

    The reduction of the numbers of "bad days" in the Western Europe indicates that the reduced human-made (anthropogenic) emissions in this part of Europe have greater influence than the higher biogenic emissions on the numbers of "bad days".

8.5.2. Applying high biogenic emissions to the Basic Scenario and Scenario Climate 3

Predicted human-made (anthropogenic) emissions are used to obtain the results shown in Fig. 8.12. It is also interesting to see how the pollution levels are varying in different parts of Europe when the emissions from the Basic Scenario and Scenario Climate 3 are used. Results, which are obtained by using these scenarios both with normal biogenic emissions and with high biogenic emissions, could be seen in the plots in Fig. 8.13.

The distribution of the numbers of "bad days" (days in which the eight-hour averages of the ozone concentrations exceed at least once the critical levels of 60 ppb) in Europe is given in the plots of Fig. 8.13. The results presented in this figure can be commented as follows:

- The dark green areas are the areas where the EU **"target aim"** for 2010 (no more than 25 "bad days") is satisfied (see European Parliament, 2002).

- The light green areas are the areas where the EU **"long-term aim"** (no "bad days" at all) is satisfied. The year in which this aim must be satisfied is not given in the EU Ozone Directive from 2002 (European Parliament, 2002). The long-term aim is satisfied in some small regions of Northern Scandinavia and the Russian Federation.

- The upper two plots in the figure are obtained by using the Basic Scenario (with normal biogenic VOC emissions on the left-hand-side plot and with high biogenic VOC emissions on the right-hand-side plot).

- The lower two plots in the figure are obtained by using Scenario Climate 3 (with normal biogenic VOC emissions on the left-hand-side plot and with high biogenic VOC emissions on the right-hand-side plot).

- It is seen that the areas, in which the EU critical levels are exceeded, are in general becoming larger when the high biogenic VOC emissions are used (compare the left-hand-side plots with the corresponding right-hand-side plots). However, the increase of the biogenic VOC emissions leads to a slight decrease of the numbers of "bad days" in the Russian Federation and Ukraine.

- It is also seen that the areas in which the EU critical level is exceeded are in general becoming larger when the Scenario Climate 3 is used (compare the upper plots with the corresponding lower plots). This tendency is more pronounced for the scenarios with high biogenic VOC emissions (compare the right-hand-side plots in the figure).

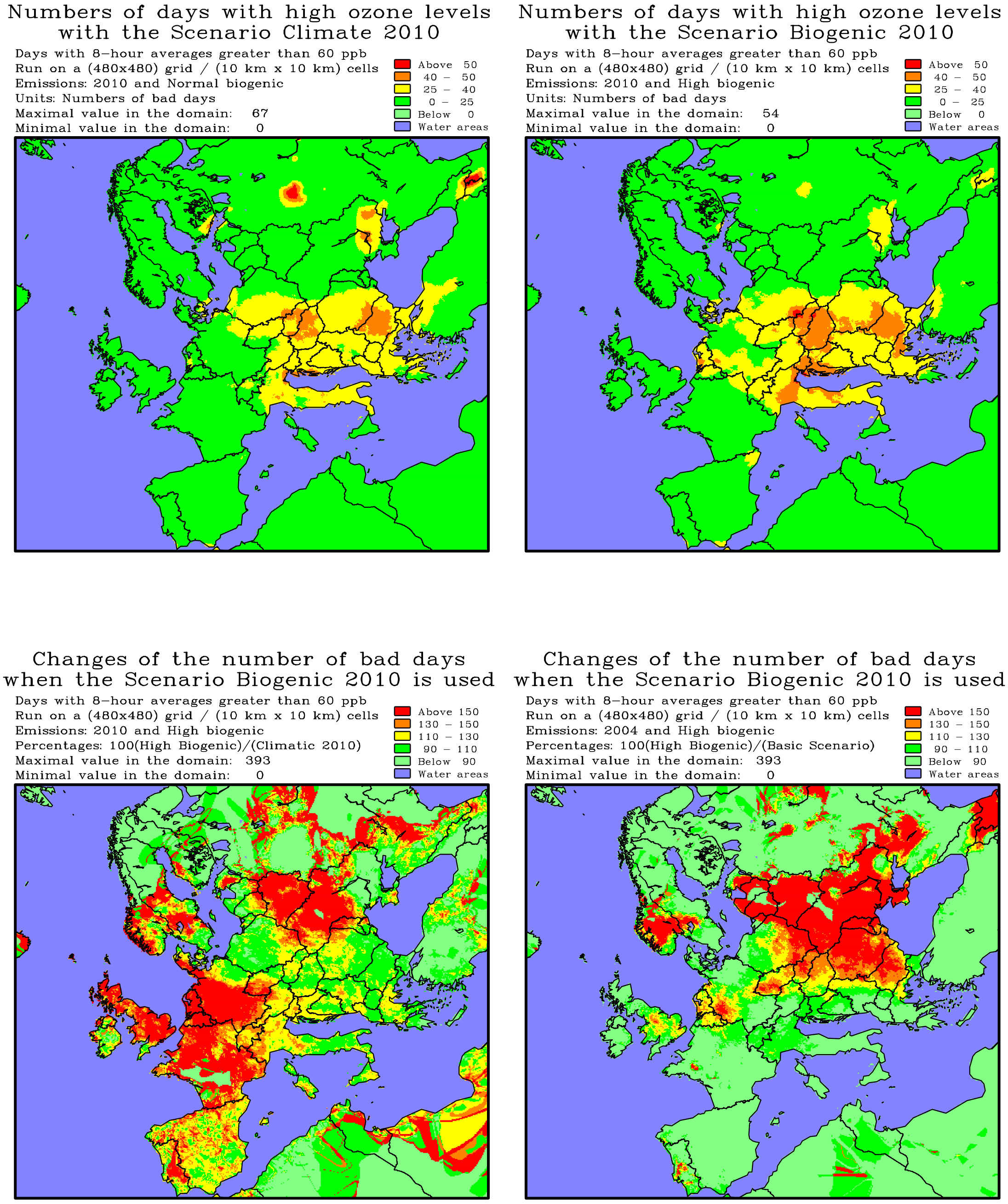


Figure 8.12

Changes of the numbers of "bad days" when different scenarios are used. Results obtained when Scenario 2010 with the climatic changes according to Climatic Scenario 3 and with Normal Biogenic Emissions are given in the left-hand-side upper plot. Corresponding results when the Normal Biogenic Emissions are replaced with High Biogenic Emissions are given in the right-hand-side upper plots. The ratios of the figures from the two upper plots (multiplied by 100) are given in the left-hand-side lower plot. The ratios between the figures obtained by using the Biogenic 2010 Scenario (i.e. Scenario 2010 with the climatic changes according to Climatic Scenario 3 and with High Biogenic Emissions) and the Basic Scenario (again multiplied by 100) are given in the right-hand-side lower plot.

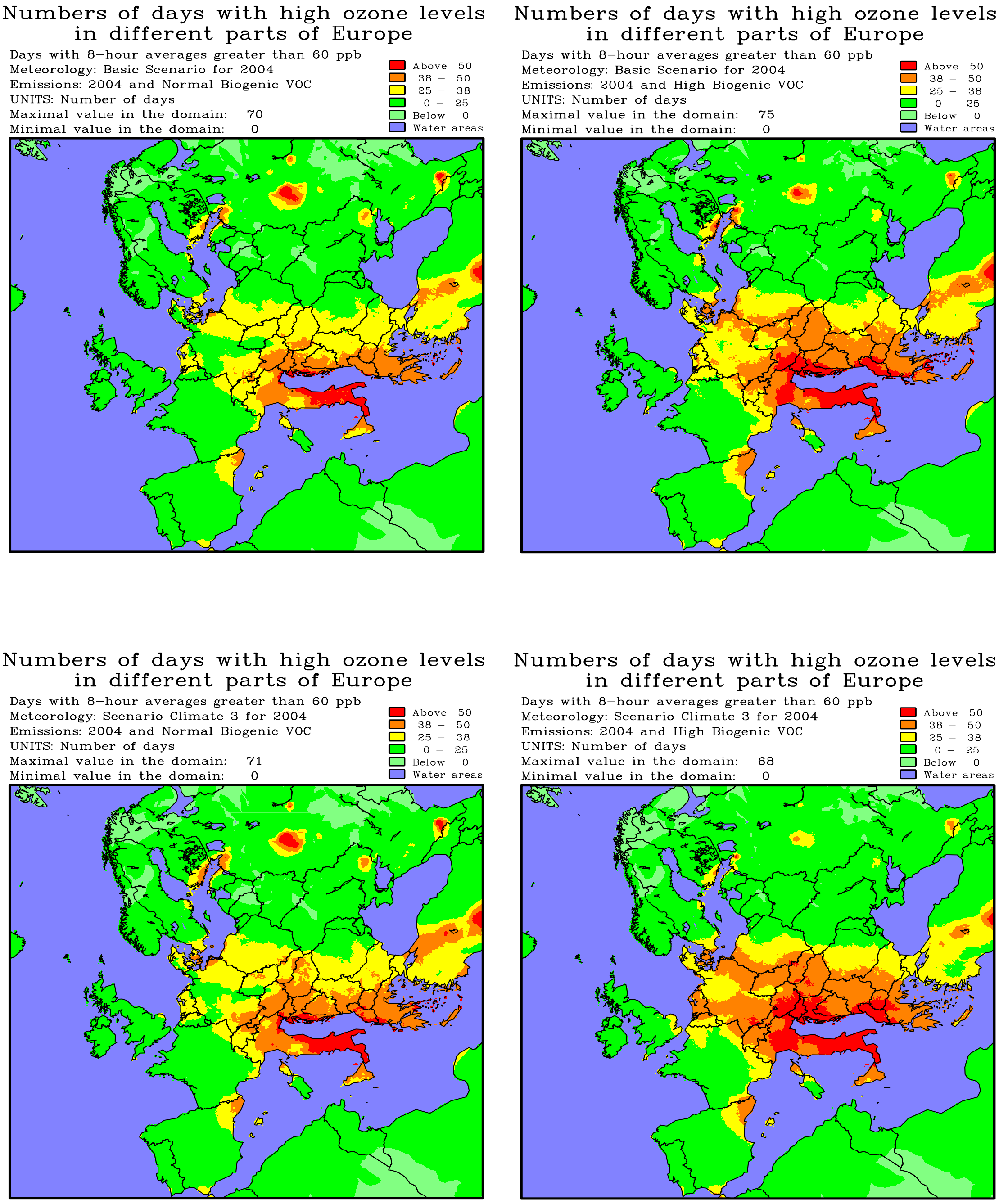


Figure 8.13

The upper two plots in the figure are obtained by using the Basic Scenario (with normal biogenic VOC emissions on the left-hand-side plot and with high biogenic VOC emissions on the right-hand-side plot). The lower two plots in the figure are obtained by using Scenario Climate 3 (with normal biogenic VOC emissions on the left-hand-side plot and with high biogenic VOC emissions on the right-hand-side plot).

8.6. Some results about variation of high ozone levels in the countries of the participants in the NATO Project CLG 980505

Some results about the variation of four important quantities related to high ozone concentrations in the countries of the participants in the project are given in Fig. 8.14.We added also the results (both model results and measurements) obtained at Ispra (in Northern Italy).

Following conclusions can be drawn from the plots of Fig. 8.14:

- The ozone levels at Ispra are higher than the ozone levels in the remaining six sites.
- At the end of the period of sixteen years, the ozone levels in Budapest, Sofia and Copenhagen are becoming comparable with those in Ispra.
- The ozone levels in Kiev and Iasi seem to be considerably lower than those in remaining sites.
- At the end of the time-period of sixteen years the numbers of “bad days” in Kiev and Iasi seem to be well under the EU critical level of 25 days (the target aim in the EU Ozone Directive, see European Parliament, 2002).

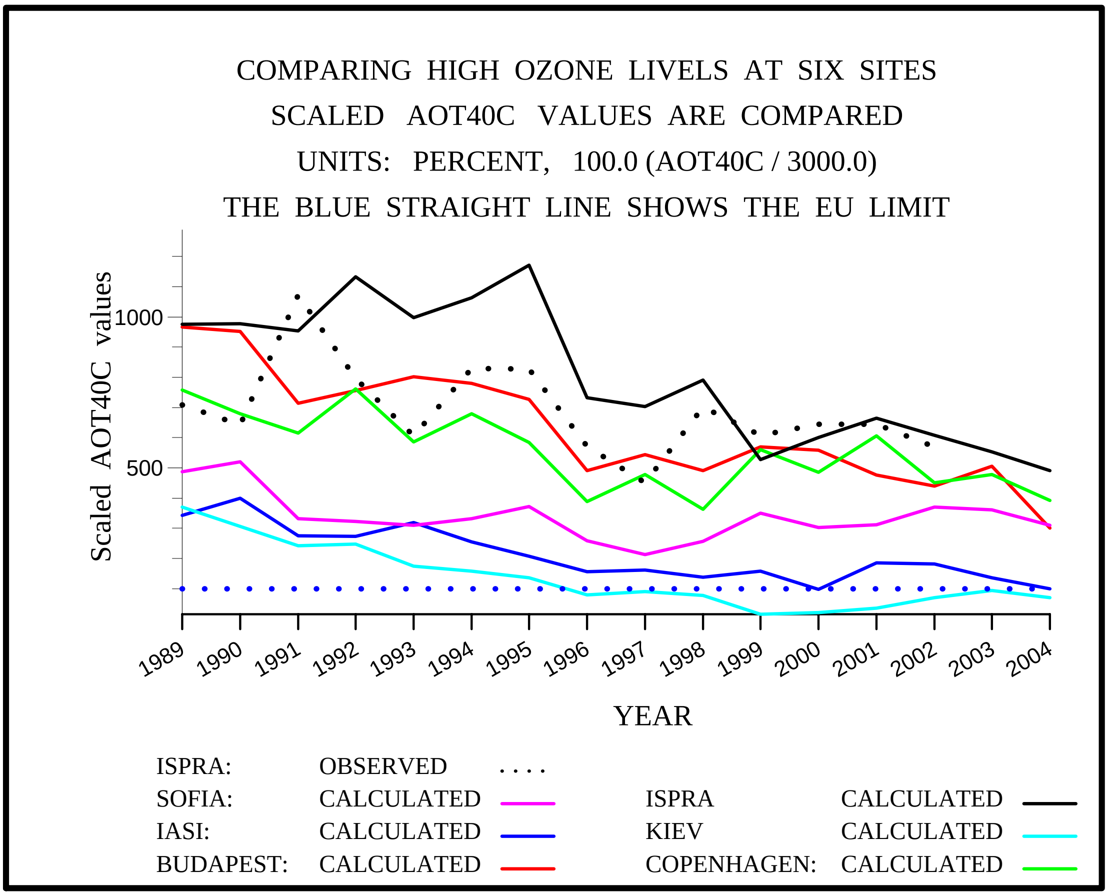


Figure 8.14.a

Comparing scaled AOT40C values at six European cities.

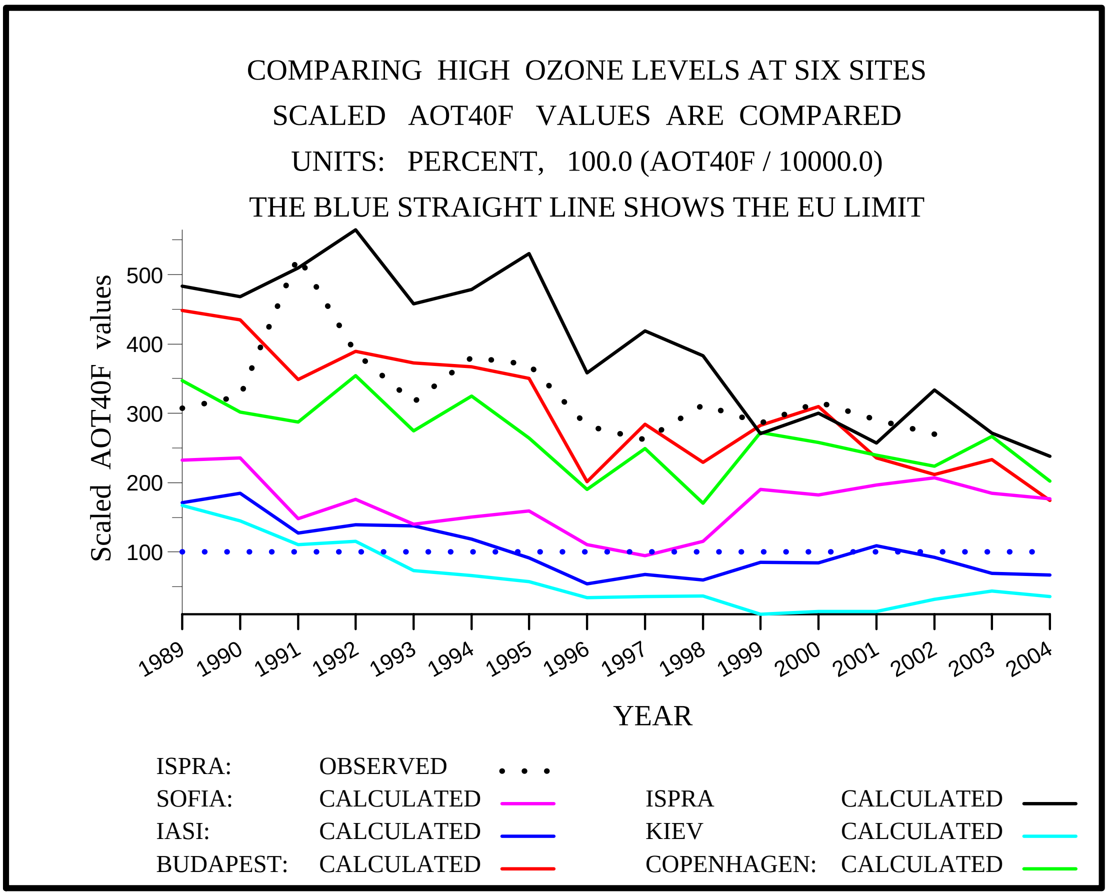


Figure 8.14.b

Comparing scaled AOT40F values at six European cities.

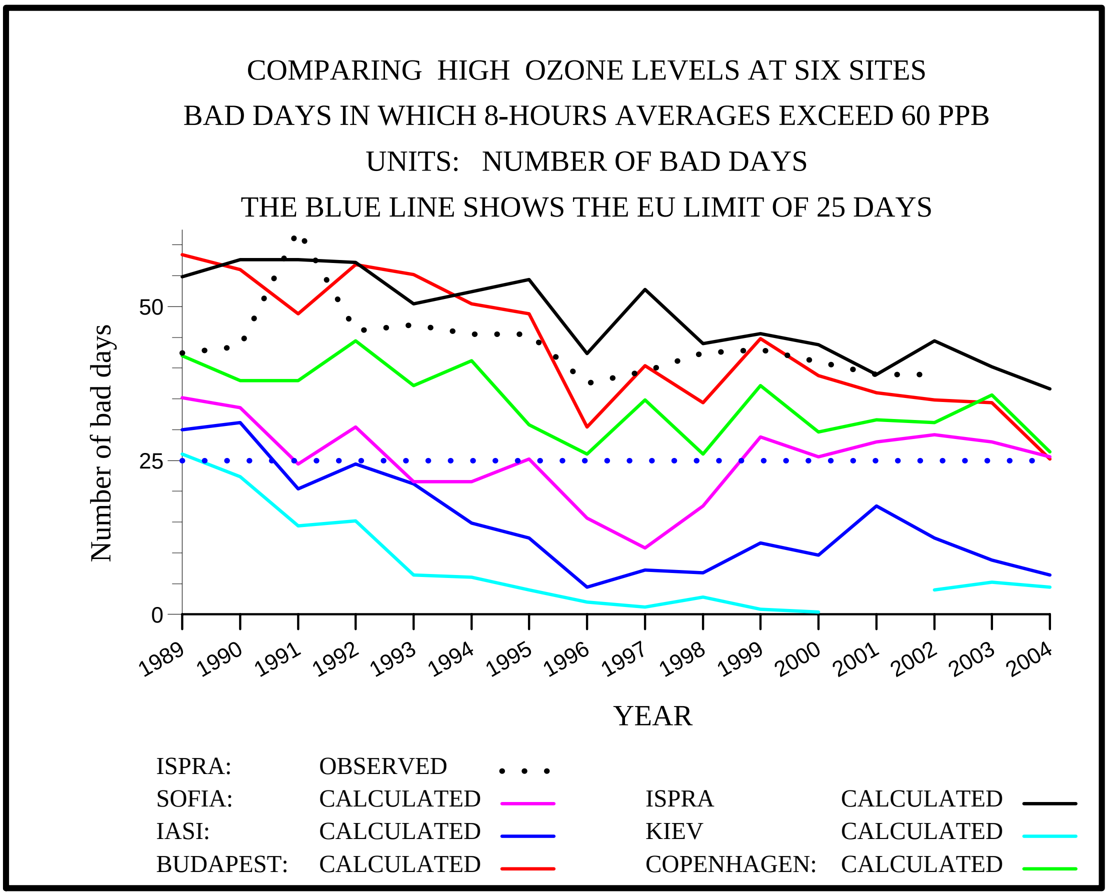


Figure 8.14.c

Comparing scaled numbers of "bad days" at six European cities.

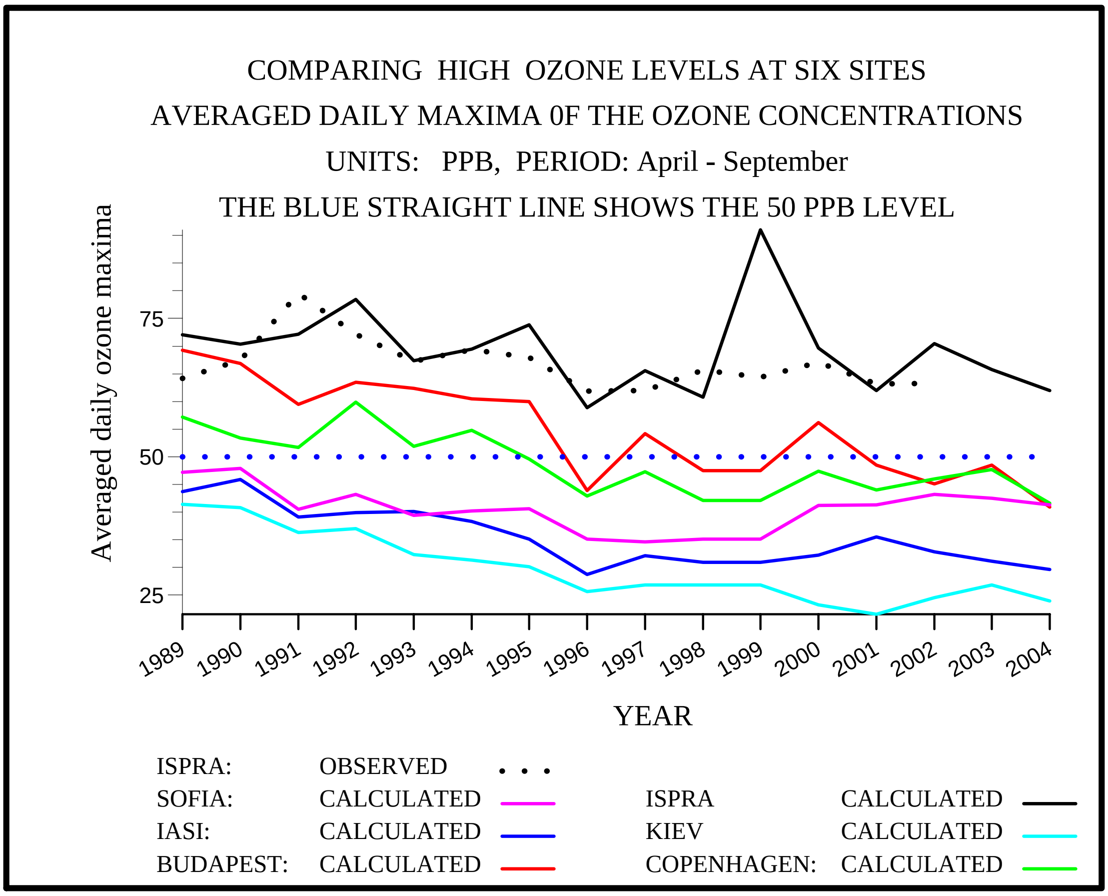


Figure 8.14.d

Comparing averaged (in the period from April 1 to September 30 daily maxima of the ozone concentrations at six European cities.

9. Concluding remarks

The results, which are presented in this report, show very clearly that the variations of the pollution levels in Europe that are caused by climatic changes must be studied in relation with variations of a series of other parameters related to

- human-made (anthropogenic) and biogenic emissions

and

- inter-annual variation of the meteorological conditions.

This makes the problem very complex and imposes several rather strict requirements, which must simultaneously be satisfied:

- necessity of efficient codes,
- availability of very powerful computers with many processors,
- runs over long time-intervals (a period of 16 years was actually used),
- runs of a long sequence of scenarios (not only climatic scenarios),
- handling of enormous sets of data,
- good graphical tools.

If only the concentrations of the harmful pollutants are studied, then the conclusion will be that the climatic changes are not affecting too much the pollution levels. However, many of the critical levels are not expressed directly by the concentrations. This can be illustrated by several examples:

- Let us consider first the number of "bad days", which can cause damages on human health (for some groups of humans, at least). This quantity is only related to ozone concentrations which vary around 60 ppb. A day is declared as a "bad day" if the 8-hour averages of the ozone concentrations exceed at least once the limit of 60 ppb. It is clear from this definition that parts of Europe where the ozone concentrations are often varied around 60 ppb, will be very sensitive to small changes of ozone. If in such areas the ozone concentrations are increased by only several percent, the changes of the numbers of "bad days" could be rather significant.
- The situation for AOT40C and AOT40F values, which can cause damages on crops and forest trees respectively, is rather similar. In the parts of Europe where the ozone concentrations vary around 40 ppb, the AOT40 values (both the AOT40C and the AOT40F values) will be very sensitive to small changes of the ozone concentrations.
- The two examples given above show that if some measures are to be taken in order to reduce the ozone pollution levels, then one has to be careful.
    - The measures, which will reduce significantly the numbers of "bad days" in some parts of Europe, might be quite inefficient in the reduction of the AOT40 values.

- On the other hand, measures that lead to a significant reduction of the AOT40 values might be very restrictive for the numbers of “bad days”. Thus, if the reduction of the numbers of “bad days” is desired (instead of reduction of AOT40 values), then one might relax the measures that are to be taken.

Thus, it is important to take into account what precisely is required, because different measures might be more efficient if requirements related to different critical levels are to be satisfied.

The most important effect of the climate changes is the warming effect (the green-house effect). Therefore, it is important to show what precisely will happen if the temperatures are increased (according to the scenarios of IPCC, see Houghton et al., 2001). This could be done only if the wind fields used in the Basic Scenario are kept the same in the transition from this scenario to the corresponding climatic scenarios. This important principle was consistently used in the preparation of the climatic scenarios. This ensures that the changes of the pollution levels, prescribed by the model when it is run by using the climatic scenarios, are caused only by the green-house effect.

The green-house effect has different consequences on biogenic and human-made (anthropogenic) emissions, wind fields, cloud covers, precipitation, humidity, etc. Most of these consequences were also taken into account during the preparation of the scenarios used in this study.

- Special scenarios were designed to take into account the changes of cloud covers, precipitation and humidity.
- The influence of the climatic changes on the biogenic emissions is automatically taken into account during the creation of these emission fields (because the biogenic emissions depend on the temperature).
- Many scenarios with different human-made (anthropogenic) emissions have been created and tested. However, it should be emphasized here that **the change of the human-made (anthropogenic) emissions in the future will, first and foremost, be a result of technological progress and, therefore, it is not directly connected to the green-house effect.** Nevertheless, it is reasonable to assume that the technological progress will lead to some decrease of the human-made (anthropogenic) emissions. The scenarios for human-made (anthropogenic) emissions were created by taking into account this assumption.
- It is not very clear how to create wind fields by which the climatic changes can reliably be studied. It is seen from the results presented in this report that even inter-annual variations of the wind fields in the Basic Scenario are causing considerable changes in the pollution levels. Indeed, the inter-annual changes of the pollution levels in the Basic Scenarios are greater than the changes due to the climatic scenarios. Variation of the wind fields will cause difficulties when we should distinguish between changes similar to the inter-annual changes and changes caused by consequences of the green-house effect. Preparation of wind fields, which will allow us to study in a robust and reliable manner the consequences of the green-house effect on the pollution levels through the variability of the wind-fields, is a very challenging task.

The influence of the pollution levels on the climatic changes is beyond the scope of this study. This issue is recently discussed in, for example, Air Quality Archive (2006) and Air Quality and Climate Change: A UK perspective (2006).

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Appendix 1

Publications of the participants of the NATO Project CLG 9805056

A list of the publications of the participants in the NATO Project CLG 980505 is given in this appendix. This list is prepared according to the requirements stated in the NATO web-site. Information about acknowledgement of the NATO grant is also given in the list.

The types of publications, which are listed in this appendix, are given in the table below.

Type of the publication	Number of publications
Monographs	1
Special issues of scientific journals	1
Proceedings volumes edited by the participants	1
Journal papers	21
Proceedings papers	28

Nº	List the publications (authors, titles and places where the papers are published with years and pages)	NATO support acknowledged
1	**V. N. Alexandrov, W. Owczarz, P. G. Thomsen and Z. Zlatev:** *"Parallel runs of a large air pollution model on a grid of Sun computers".* Mathematics and Computers in Simulation **Vol. 65 (2004),** pp. 557-577.	X
2	**V. N. Alexandrov and Z. Zlatev:** *"Using Parallel Monte Carlo Methods in Large-Scale AirPollution Modelling".* In: **"Computational Science – ICCS 2004"** (M. Bubak, M., G. D. v. Albada, P. M. A. Sloot and J. Dongarra, eds.), pp. 491-498, Lecture Notes in Computer Science 3039, Springer, Berlin, **2004.**	
3	**A. Antonov, K. Georgiev, E. Komsalova and Zlatev:** *"Comparison of Two Local Refinement Methods for Large Scale Air Pollution Simulations".* In: **"Large-Scale Scientific Computing"** (I. Lirkov, S. Margenov, J. Wasniewski and P, Yalamov, eds.), pp. 287-294. Lecture Notes in Computer Science 2907, Springer, Berlin, **2004.**	
4	**M. Botchev, I. Faragó, Á. Havasi:** *"Testing weighted splitting schemes on a one-column transport-chemistry model",* International Journal of Environment and Pollution, **Vol. 22 (2004),** pp. 3-16.	

5	**M. Botchev, I. Faragó, Á. Havasi:** *"Testing weighted splitting schemes on a one-column transport-chemistry model"*, In: **"Large-Scale Scientific Computing"** (S. Margenov, J. Wasniewski, P. Yalamov, eds), pp. 295-302, Lecture Notes in Computing Science 2907, Springer, Berlin, **2004.**	
6	**P. Csomós:** *"Some aspects of interaction between operator splitting procedures and numerical methods"*, In: **"Advances in Air Pollution Modeling for Environmental Security"**, (I. Faragó, Á. Havasi, K. Georgiev, eds.), pp. 77-91, NATO Science Series, 54, Springer, Berlin, **2005.**	X
7	**P. Csomós:** "*Some aspects of interaction between operator splitting procedures and numerical methods*". In: **"Large Scale Scientific Computing"** (I. Lirkov, S. Margenov and J. Wasniewski, eds.), pp. 331-338. Lecture Notes in Computer Science 3732, Springer, Berlin, **2006.**	X
8	**P. Csomós, Á. Havasi and I. Faragó:** *"Weighted sequential splittings and their analysis*", Comp. Math. Appl., **Vol. 50 (2005),** pp. 1017-1031.	
9	**R. Cuciureanu and G. Dimitriu:** *"Photochemical reactions in the atmosphere – a source for secondary pollutants"*. Problems in Programming, **Vol. 8 (2006),** No. 2-3, 682-687.	
10	**G. Dimitriu:** "*Data assimilation for a model in atmospheric chemistry and oceanography*", In: **"Proceedings of the International Symposium on Systems Theory",** SINTES 12, XIIth Edition, October 20-22, Craiova, Romania, Vol. IV:Computer Engineering, pp. 717-722, **2005.**	
11	**G. Dimitriu:** *"Adjoint computations in data assimilation problems using a 4-stage Rosenbrock method"*. In: **"Large Scale Scientific Computing"** (I. Lirkov, S. Margenov and J. Wasniewski, eds.), pp. 339-346. Lecture Notes in Computer Science 3732, Springer, Berlin, **2006.**	X
12	**G. Dimitriu and R. Cuciureanu:** *"Mathematical aspects of data assimilation for atmospheric chemistry models"*, In: **"Advances in Air Pollution Modeling for Environmental Security"**, (I. Faragó, Á. Havasi, K. Georgiev, eds.), pp. 93-103, NATO Science Series, 54, Springer, Berlin, **2005.**	X
13	**G. Dimitriu and R. Cuciureanu:** *"Data assimilation using Kalman filter techniques"*. Problems in Programming, **Vol. 8 (2006),** No. 2-3, 688-693.	X
14	**I. Dimov, I. Faragó, Á. Havasi and Z. Zlatev:** *"Operator splitting and commutativity analysis in the Danish Eulerian Model"*, Mathematics and Computers in Simulation, **Vol. 67 (2004),** pp. 217-233.	X
15	**I. Dimov, G. Geernaert and Z. Zlatev:** **"***Fighting the great challenges in large-scale environmental modelling"*, In: **"Advances in Air Pollution Modeling for Environmental Security"**, (I. Faragó, Á. Havasi, K. Georgiev, eds.), pp. 105-114, NATO Science Series, 54, Springer, Berlin, **2005.**	X
16	**I. Dimov, K.Georgiev, Tz. Ostromsky and Z. Zlatev:** *"Computational Challenges in the Numerical Treatment of Large Air Pollution Models"*, Ecological Modelling, **Vol. 179 (2004),** pp. 187-203.	X
17	**I. Dimov, Tz. Ostromsky, and Z. Zlatev:** "*Challenges in using splitting techniques for large-scale environmental modelling*", In: **"Advances in Air Pollution Modeling for Environmental Security"**, (I. Faragó, Á. Havasi, K. Georgiev, eds.), pp. 115-131, NATO Science Series, 54, Springer, Berlin, **2005.**	X

18	**A. Yu. Doroshenko and V. A. Prusov:** *"Methods of efficient modeling and forecasting regional atmospheric processes"*, In: **"Advances in Air Pollution Modeling for Environmental Security"**, (I. Faragó, Á. Havasi, K. Georgiev, eds.), pp. 142-152, NATO Science Series, 54, Springer, Berlin, **2005.**	**X**
19	**A. Yu. Doroshenko and Yu. M. Tyrchak:** *"Efficient parallelization of computation in atmosphere physics problems "* In: Procedings of the International Conference: **"Theoretical and Applied Aspects in Software Systems Construction"** (I. A. Antonova, ed.), pp. 325-329, Kyiv National University "Taras Schevchenko", Kyiv, Ukraine, **2004.**	
20	**I. Faragó:** *"Splitting methods for abstract Cauchy problems"*, In: **"Numerical Analysis and Its Application"** (Z. Li, L. Vulkov, J. Waśniewski eds.), pp. 35-45, Lecture Notes in Computer SciScience 3401, Springer, Berlin , **2005**	
21	**I. Faragó:** *"Operator splittings and numerical methods".* In: **"Large Scale Scientific Computing"** (I. Lirkov, S. Margenov and J. Wasniewski, eds.), pp. 347-354. Lecture Notes in Computer Science 3732, Springer, Berlin, **2006.**	**X**
22	**I. Faragó:** *"On the efficiency of the operator splitting method".* Problems in Programming, **Vol. 8 (2006),** No. 2-3, 654-658.	**X**
23	**I. Faragó, Á. Havasi, K. Georgiev (eds.):** *"Advances in air pollution modeling for environmental security"*, **NATO Science Series 54**, 406 pages, Springer, Berlin, **2005.**	
24	**I. Farago, R. Horvath and S. Korotov:** *"Discrete maximum principle for linear parabolic problems solved on hybrid meshes".* Applied Numerical Mathematics, **Vol. 43 (2005),** pp. 249-264.	
25	**I. Farago, R. Horvath and S. Korotov:** *"Investigation of numerical time-integrations of the Maxwell equations using staggered grid spatial discretization".* International Journal of Numerical Modelling, **Vol. 18 (2005),** pp. 149-169.	
26	**G. Geernaert and Z. Zlatev:** *"Studying the influence of biogenic emissions on AOT40 levels in Europe"*, International Journal of Environment and Pollution, **Vol. 22 (2004),** pp. 29-42.	**X**
27	**I. Georgiev, J. Krauss and S. Margenov:** *"Two-level algorithms for Rannacher-Turek FEM".* Problems in Programming, **Vol. 8 (2006),** No. 2-3, pp. 694-700.	**X**
28	**K. Georgiev and E. Donev:** *"On some ozone studies: comparison of model results and measurements over the territory of Bulgaria"*, Problems in Programming, **Vol. 8 (2006),** No. 2-3, pp.767-770.	**X**
29	**K. Georgiev and S. Margenov:** *"Higher order non-conforming FEM up-winding"*, In: **"Advances in Air Pollution Modeling for Environmental Security"**, (I. Faragó, Á. Havasi, K. Georgiev, eds.), pp. 209-218, NATO Science Series, 54, Springer, Berlin, **2005.**	
30	**K. Georgiev, S. Margenov and V.M. Veliov:** *"Emission control in single species air pollution problems"*, In: **"Advances in Air Pollution Modeling for Environmental Security"**, (I. Faragó, Á. Havasi, K. Georgiev, eds.), pp. 219-228, NATO Science Series, 54, Springer, Berlin, **2005.**	
31	**B. Gnandt:** *"A new operator splitting method and its numerical investigation"*, In: **"Advances in Air Pollution Modeling for Environmental Security"**, (I. Faragó, Á. Havasi, K. Georgiev, eds.), pp. 229-241, NATO Science Series, 54, Springer, Berlin, **2005.**	

32	**Á. Havasi:** *"Dispersion analysis of operator splittings in the linearized shallow water equations".* In: **"Large Scale Scientific Computing"** (I. Lirkov, S. Margenov and J. Wasniewski, eds.), pp. 355-362. Lecture Notes in Computer Science 3732, Springer, Berlin, **2006.**	X
33	**R. Horvath:** *"On the maximum-minimum principle for advection-diffusion equations".* Problems in Programming, **Vol. 8 (2006),** No. 2-3, 664-668.	
34	**V. Prusov, A. Doroshenko, I. Faragó and Á. Havasi:** *"On the numerical solution of the three–dimensional advection-diffusion equation".* Problems in Programming, **Vol. 8 (2006),** No. 2-3, 641-647.	**X**
35	**V. A. Prusov, A. Yu. Doroshenko, S. V. Prykhodko, Yu. M. Tyrchak and I. R. Chernysh:** *"Methods for efficient solution of problems of regional meteorological forecasting",* Problems in Programming, **Vol. 6 (2004),** pp. 556-569.	
36	**Tz. Ostromsky, I. Dimov and Z. Zlatev:** *"Parallel implementation and one year experiments with the Danish Eulerian Model",* In: **"Numerical Analysis and Its Application"** (Z. Li, L. Vulkov, J. Wasniewski eds.), pp. 440-447, Lecture Notes in Computer Science 3401, Springer, Berlin, **2005.**	
37	**Tz. Ostromsky and K. Georgiev:** *"Performance results of a large air pollution model on two parallel computers",* International Journal on Environmental Pollution, **Vol. 22, (2004),** pp. 43-50.	
38	**Z. Zlatev:** *"Comprehensive air pollution studies with the Unified Danish Eulerian Model",* In: **"Parallel Processing and Applied Mathematics"** (R. Wyrzykowski, J. Dongarra, M. Paprzycky and J. Wasniewski, eds.), pp. 1125-1137, Lecture Notes in Computer Science 3019, Springer, Berlin, **2004.**	**X**
39	**Z. Zlatev:** *"Parallel solution of very large sparse systems of linear algebraic equations".* In: **"Large-Scale Scientific Computing"** (I. Lirkov, S. Margenov, J. Wasniewski and P, Yalamov, eds.), pp. 53-64. Lecture Notes in Computer Science 2907, Springer, Berlin, **2004.**	
40	**Z.Zlatev:** *"Computer treatment of partial differential equations arising in environmental modelling".* Mathematica Balcanica, **Vol. 20 (2006),** pp. 101-124.	**X**
41	**Z. Zlatev:** *"Large-scale computations with the Unified Danish Eulerian Model".* In: **"Applied Parallel Computing: State of the Art in Scientific Computing"** (J. Dongarra, K. Madsen and J. Wasniewski, eds.), pp. 43-52. Lecture Notes in Computer Science 3732, Springer, Berlin, **2006.**	**X**
42	**Z. Zlatev:** *"Parallel treatment of general sparse matrices".* In: **"Large Scale Scientific Computing"** (I. Lirkov, S. Margenov and J. Wasniewski, eds.), pp. 53-64. Lecture Notes in Computer Science 3743, Springer, Berlin, **2006.**	**X**
43	**Z. Zlatev:** *"Imapact of climate changes in Europe on European pollution levels".* Problems in Programming, **Vol. 8 (2006),** No. 2-3, 659-663.	**X**

44	**Z. Zlatev and J. Brandt:** *"Testing variational data assimilation modules".* In: **"Large Scale Scientific Computing"** (I. Lirkov, S. Margenov and J. Wasniewski, eds.), pp. 395-403. Lecture Notes in Computer Science 3743, Springer, Berlin, **2006**	X
45	**Z. Zlatev and I. Dimov:** *"Computational and numerical challenges in environmental modelling",* Studies In Computational Mathematics, Vol. 13, Elsevier, Amsterdam, **2006.**	X
46	**Z. Zlatev, A. Ebel, I. Faragó and K. Georgiev:** **"***Major conclusions from the discussions",* In: **"Advances in Air Pollution Modeling for Environmental Security"**, (I. Faragó, Á. Havasi, K. Georgiev, eds.), pp. 395-399, NATO Science Series, 54, Springer, Berlin, **2005.**	
47	**Z. Zlatev, A. Ebel and K. Georgiev (eds.):** *"Large-Scale Scientific Computations in Air Pollution Modelling",* International Journal of Environment and Pollution, **Vol. 22, No. 1-2 (2004).**	
48	**Z. Zlatev and K. Georgiev:** *"Treatment of large scientific problems: An introduction".* In: **"Applied Parallel Computing: State of the Art in Scientific Computing"** (J. Dongarra, K. Madsen and J. Wasniewski, eds.), pp. 828-830. Lecture Notes in Computer Science 3732, Springer, Berlin, **2006.**	
49	**Z. Zlatev and D. Syrakov:** *"A fine-resolution modelling study of pollution levels in Bulgaria",* *Part 1: SOx and NOx pollution",* International Journal of Environment and Pollution, **Vol. 22 (2004),** pp. 186-202.	X
50	**Z. Zlatev and D. Syrakov:** *"A fine-resolution modelling study of pollution levels in Bulgaria",* *Part 1: SOx and NOx pollution",* International Journal of Environment and Pollution, **Vol. 22 (2004),** pp. 186-202.	X
51	**Z. Zlatev and D. Syrakov:** *"Studying high ozone levels in Bulgaria and Europe",* In: **"Large-Scale Scientific Computing"** (I. Lirkov, S. Margenov, J. Wasniewski and P, Yalamov, eds.), pp. 337-344, Lecture Notes in Computer Science 2907, Springer, Berlin, **2004.**	
52	**Z. Zlatev and D. Syrakov:** *"Studying pollution levels in Bulgaria by using a fine resolution dispersion Model".* In: **"Air Pollution Modeling and Its Application XVI "** (C. Borrego and S. Incecik, eds.), pp. 245-252, NATO Challenges of Modern Society Series. Kluwer Academic/Plenum Publishers, Dordrecht, **2004.**	

Appendix 2

Major topics discussed in the publications

The scientific work, which was carried out in this project, can be divided into two parts:

(a) **preparation** of environmental models for the computer treatment of very large tasks related to different scientific studies

and

(b) **performance** of a long-term, fine resolution climatic runs with many scenarios and analysing the results obtained in these runs.

Different computational modules were prepared during the first part of the work. After that the best of the prepared modules were incorporated in a particular model, UNI-DEM, which was used in the climatic study. The two parts of the scientific work are discussed in detail in the publications of the participants in the project which are listed in Appendix 1.

The major topics discussed in the publications, which are listed in Appendix 1, are given below (the numbers of the publications quoted below are according to the numeration in Appendix 1):

- Publications related to **numerical methods** that can be used in the **advection-diffusion sub-models** of a large-scale air pollution model: [3], [15], [18], [23] – [25], [27], [29], [32] - [35], [38], [39], [40], [43] and [45].
- Publications related to **numerical methods** that can be used in the **chemical sub-models** of a large-scale air pollution model: [9], [38], [39] – [41] and [45].
- Publications related to the applications of different **splitting procedures** in a large air pollution model: [4] – [8], [14], [20] – [23], [31], [40], [41] and [45].
- Publications related to running a large air pollution model on **parallel computers and on computer grids**: [1], [2], [16], [17] - [19], [36] - [42], [44] and [45].
- Publications related to the use of different types of **data assimilation** techniques: [10] - [13], [30], [44] - [46].
- Publications related the development of **long sequences of scenarios**: [15], [41], [45] and [47] – [52].
- Publications related to different **air pollution studies** and to the analysis of the results obtained in such studies: [26], [28], [40], [41], [45] and [47] – [52].
- Publications related to **climatic studies**: [41], [43], [45] and [47] – [52].

Appendix 3

Short description of UNI-DEM

The air pollution model, which was actually used in this study, is **UNI-DEM** (the Unified Danish Eulerian Model). The model is fully described in Zlatev and Dimov (2006); see also reference [45] in the list of publications of the participants in Appendix 1. It has been used in many comprehensive air pollution studies (see the beginning of Section 1 in this report and Zlatev and Dimov, 2006).

The model has been enhanced by incorporating several numerical methods, splitting procedures and parallel techniques developed under the work on the NATO Project CLG 980505 (see the list of the publications of the participants, which is given in Appendix 1 and the topics of the publications summarized in Appendix 2).

Different versions of the original air pollution model DEM (the Danish Eulerian Model, fully described in Zlatev, 1995) are united in **UNI-DEM**. The new model **UNI-DEM** allows us to avoid:

- preparation of different codes for the different versions,

and

- compilation of the code when we want to switch from one version to another.

Moreover, it is much easier to make corrections in **UNI-DEM** and to include new algorithms there when this is necessary.

Finally, **UNI-DEM** allows us to apply

- different spatial resolution meshes,
- different time-steps

and

- different chemical schemes.

UNI-DEM is driven by several parameters. Any of these parameters or several of them can be initialized in a special small file *"initial-input"*, before starting the first run with the selected set of parameters. If the next run is to be performed by using the same set of parameters, then no change in file *"initial-input"* is needed. If we want to change the values of some parameters (or, in other words, if we want to switch from one version of **UNI-DEM** to another version), then only some changes in file *"initial-input"* will be quite sufficient (i.e. there is no need to recompile the code which contains more than 100 subroutines divided in 10 sub-directories).

The major parameters used in file *"initial-input"* are listed in the table which is given on the next page (the desirable features, which are listed in the third column of the table, will be included, as additional options, in the near future).

Parameter	Allowed values	Desirable features
NX	96, 288 or 480	
NY	NY=NX (only square domains are allowed)	Rectangular domains
NZ	1 or 10	More layers
NSPECIES	35, 56 or 168	RADM2 and RACM
NCHUNKS	Can be varied, 48 is recommended	
NREFINED	0 or 1	
NYEAR	From 1989 to 2005	

<u>Comments:</u>

- NX and NY are giving the numbers of grid-points along the Ox and Oy axes respectively. NX=96 and NY=NX leads to 50 km x 50 km surface cells, NX=288 and NY=NX leads to 16.67 km x 16.67 km surface cells, while NX=480 and NY=NX leads to 10 km x 10 km surface cells (the last choice has consistently been used in this study).
- The restriction NY=NX could be removed (or, in other words, the use of rectangular model domains could be allowed). Removing the restriction NY=NX will increase the flexibility of the model.
- The thickness of the layers is not equidistant. Thin layers are used close to the surface and the thickness is gradually increased for the higher layers.
- Three chemical schemes are available at present. The chemical scheme with 35 species was used in this study. It is desirable to implement and try several other commonly used chemical schemes (two such schemes, RADM2 and RACM, are listed in the table).
- Parameter NCHUNKS is used in order to improve the efficiency (the biggest data arrays are divided into small portions, chunks, which results in a better exploitation of the cache memory of the available computer). The value 48 is experimentally found to be good when parallel SUN computers are used.
- NREFINED=0 implies the direct use of EMEP emissions (some interpolation rules are automatically used when the fine resolution versions are selected). NREFINED=1 is used for emission inventories prepared on a fine resolution mesh at the National Environmental Research Institute (NERI) by Ole Hertel and Carsten Ambelas Skjøth. Some details about these emissions are given in Hertel et al. (2002). It should be mentioned here that even more detailed emission inventories are now in process of preparation at NERI.
- The year for which the model is to be run can be specified by using parameter NYEAR. Input data for year 2005 were recently received and attached to UNI-DEM. Results for 2005 are not included in this report.

The variations of the pollution levels in Europe that are caused by climatic changes must be studied in relation with variations of a series of other parameters: human-made (anthropogenic) and biogenic emissions as well as inter-annual variation of the meteorological conditions. This makes the problem very complex and imposes several rather strict requirements, which must simultaneously be satisfied:

- **necessity of efficient codes,**
- **availability of very powerful computers with many processors,**
- **runs over long time-intervals (a period of 16 years was actually used),**
- **runs of a long sequence of scenarios (not only climatic scenarios),**
- **handling of enormous sets of output data,**
- **good graphical tools.**

If only the concentrations of the harmful pollutants are studied, then the conclusion will be that the climatic changes are not affecting too much the pollution levels. However, many of the critical levels are not expressed directly by the concentrations. It is explained in this report why small changes of the concentrations can lead to rather significant changes of the most of the quantities involved in the definitions of the critical levels, which is one of the main reasons to study carefully the impact of climatic changes on the pollution levels.

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