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CHAPTER 4

Part C: Sensitivity of European Pollution Levels to Changes of Human-Made Emissions

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Abstract: Systematic changes of the human-made emissions in Europe were simulated by applying a carefully chosen series of appropriate scenarios and the impact of these changes on the pollution levels in different parts of the model domain was studied. It was established that, while the changes of the sulphur pollutants correspond in a nearly perfect way to the changes of the emissions, for the most of the other pollutants this was not true. Furthermore, the experiments also indicate that the changes in the different part of Europe can be rather different although the emissions were reduced with the same factor. The conclusions are illustrated by many results presented in tables and plots. Several ideas for future research in this direction are briefly discussed in the end of this chapter.

Keywords: Sensitivity, human-made emissions, pollution levels, model domain, sulphur pollutants, UNI-DEM (the Unified Danish Eulerian Model), Africa, Asia, Atlantic Ocean, climate changes, Basic Scenario, EMEP, Minimal reductions, maximal reductions, sulphur di-oxide, $TOTSO_4$ concentrations, critical limits, anthropogenic emission, AOT40 for crops, AOT40 for forest trees, bad days.

INTRODUCTORY REMARKS

The sensitivity of several important chemical species to variations of human-made (anthropogenic) emissions is studied in this chapter.

The mathematical tool applied in this investigation is **UNI-DEM** (The Unified Danish Eulerian Model). The space domain of this model covers the whole of

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Europe together with parts of Africa, Asia, the Atlantic Ocean and some Arctic areas. In this chapter mainly the version in which this domain is divided in 230400 horizontal (10 km x 10 km) cells will be used. Different features of this model are fully described in [1, 2, 3, 4, 5]. UNI-DEM was extensively used for performing different investigations related to air pollution in

- Bulgaria ([6, 7]),
- Denmark ([8-11]),
- England ([12]),
- Europe ([2, 4, 5, 8, 13-15]),
- Hungary ([16-18]) and
- The North Sea ([19]).

A previous version of UNI-DEM has also been used in some inter-comparisons of European large-scale air pollution models ([20, 21]).

Recently the model was extensively used in the efforts to investigate the impact of future climate changes on pollution levels in Europe as a whole and in different parts of this continent (see [10, 11, 13, 14, 18, 22]).

The mathematical background and the physical processes united in UNI-DEM are fully described in [2, 4, 5].

In the present study UNI-DEM is used to quantify the sensitivity of the concentrations and some related quantities (which can cause damages on plants, animals and human beings) to variations of the human-made (anthropogenic) emissions.

SCENARIOS USED IN THIS STUDY

The sensitivity of several important chemical species to variations of human-made (anthropogenic) emissions is studied by designing and applying several appropriate scenarios.

First the **Basic Scenario** for year 1997 is used. The EMEP emission inventories are applied and the meteorological data are also provided by EMEP (see [23, 24]). Then four additional runs, in which the meteorological data are kept the same, but the human-made emissions being successively reduced by 20%, 40%, 60% and 80% respectively, are performed. It is clear that all changes of the pollution levels are entirely caused by the variations of the emissions (the only parameters, which are not the same in the different runs). This fact allows us to draw several useful conclusions.

Minimal and maximal reductions of the concentrations of ten selected chemical species are given in Table **1** for the cases where the human-made (anthropogenic) emissions are decreased by 20%, 40%, 60% and 80% (*i.e.* when the actual emissions used in the corresponding runs are respectively 80%, 60%, 40% and 20% of the real emissions).

Comparing the minimal and maximal values of the concentrations, which are given in Table **1**, it is clearly seen that the sensitivity of the different chemical species to variations of the human-made emissions is quite different. While the changes of the sulphur di-oxide concentrations (and to a certain degree also the $TOTSO_4$ concentrations) are changed nearly by the same factor as that used to change the emissions, bigger or smaller deviation from this factor can clearly be detected in the behaviour of the remaining species.

Often the interval formed by the minimal and the maximal values in Table **1** is rather big. This indicates that for the most of the chemical species the sensitivity effect is different in the different parts of the studied domain and, therefore, visualization of the distribution of the changes in Europe is absolutely necessary.

The linear effect for the sulphur di-oxide concentration changes is illustrated in Figs. **1** and **2** (note the intervals in which the sulphur di-oxide concentrations vary in the four plots given Fig. **2**). The results for all other chemical species that are mentioned in Table **1** have also been obtained and included in an extended version, which can be sent to interested readers if requested.

Table 1: Minimal and maximal values of the selected concentrations registered for different emission reductions. Only the human-made (anthropogenic) emissions are reduced in these four scenarios.

Chemical species	20% Reduction		40% Reduction		60% Reduction		80% Reduction	
	Minimal	Maximal	Minimal	Maximal	Minimal	Maximal	Minimal	Maximal
FORM	81.7	97.9	63.9	93.7	48.4	90.0	29.0	86.5
NH_3	59.1	93.2	8.4	78.0	2.0	57.7	0.9	30.4
NO	75.0	99.4	52.4	98.0	33.1	94.6	16.7	85.6
NO_2	80.6	95.7	61.5	89.2	41.7	79.9	21.3	64.1
O_3	89.6	99.6	78.6	99.2	68.2	98.8	50.7	98.1
OH	84.1	95.6	67.4	89.4	49.2	80.8	26.3	67.3
SO_2	78.5	82.1	58.6	62.3	38.8	41.4	19.2	20.5
$TOTNH_4$	65.3	86.0	38.3	60.3	20.8	40.2	8.4	20.0
$TOTNO_3$	68.9	85.9	40.1	68.7	23.1	50.4	9.3	28.9
$TOTSO_4$	73.5	83.9	55.3	64.0	37.6	43.0	18.4	31.5

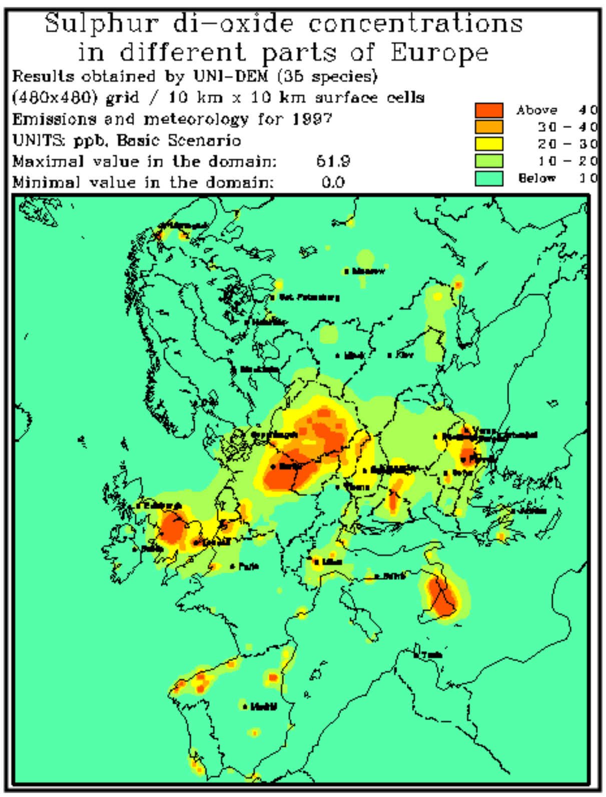

Figure 1: Distribution of the sulphur di-oxide concentrations in the different parts of Europe (these results are obtained by using the Basic Scenario for year 1997).

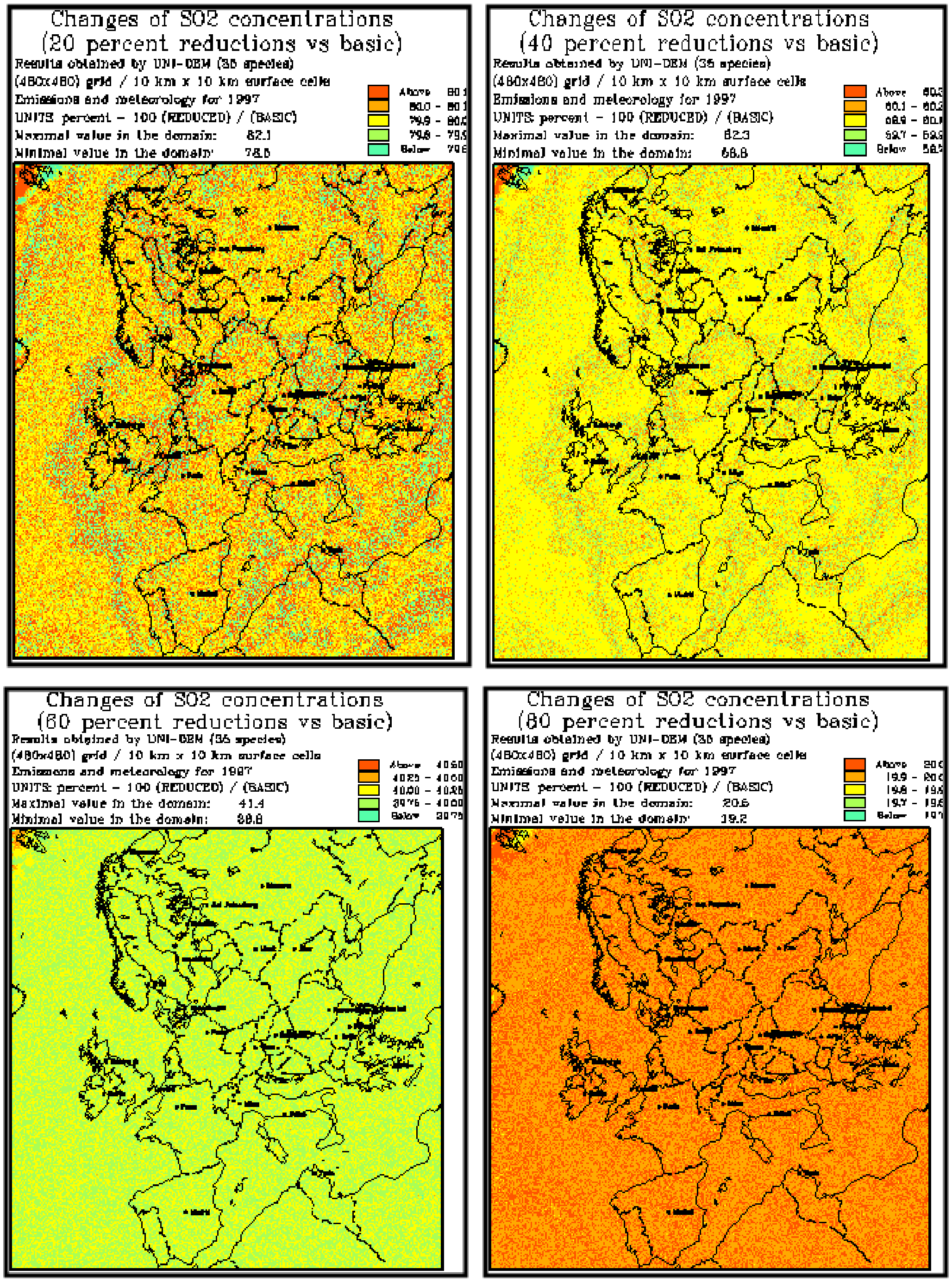

Figure 2: Changes, in percentages, of the sulphur di-oxide concentrations in Europe that are obtained for different reductions of the human-made emissions.

STUDYING SENSITIVITY AT SELECTED SITES

The sensitivity of the concentration levels to variations of the human-made (anthropogenic) emissions at selected sites was also studied. Eight European cities (London, Madrid, Paris, Berlin, Moscow, Milan, Sofia and Copenhagen) were chosen so that as many as possible parts of the continent are represented in these experiments. The results obtained at these cities are shown in Table **2a** – **2j**. Plots, which are corresponding to the numbers presented in Table **2a** – **2j**, are given in Fig. **3a** – **3j**.

Several conclusions can be drawn from the results which are presented in Table **2a** – **2j**:

- It would be very easy for the policy-makers to control the pollution levels if a reduction of the human-made (anthropogenic) emissions with **p%** results in a reduction of the corresponding concentration levels with **p%** too. If this was true, then it will be very straightforward to prescribe a relevant reduction of the human-made emissions in the efforts to keep the pollution levels under some prescribed in advance critical limits. The results presented in Table **2a** – **2j** and in Fig. **3a** – **3j** indicate that this convenient dependence of the sensitivity of the pollution levels on the variation of the human-made emissions holds perfectly only for the sulphur pollutants (which is clearly seen from the plots shown in Fig. **2**). It should be mentioned here that this relationship holds to a certain degree also for NH_3, NO_2 and $TOTHN_4$.

- For FORM, O_3 and OH, a reduction of the human-made (anthropogenic) emissions with **p%** results for all eight cities in a reduction of the corresponding concentration levels which is in general less than **p%**.

- For $TOTNO_3$ a reduction of the human-made (anthropogenic) emissions with **p%** results, again for all eight cities, in a reduction of the corresponding concentration levels which is greater than **p%**.

- The results are rather irregular for NO. This means that a reduction of the human-made (anthropogenic) emissions with **p%** results in a reduction of the corresponding concentration levels which can be either greater than **p%** or less than **p%**.

The above conclusions are confirmed in the plots shown in Fig. **3a** – **3j**.

Table 2a: Sensitivity results (measured in percent) for FORM concentrations to variations of human-made (anthropogenic) emissions at eight European cities.

City	**20% Reduction**	**40% Reduction**	**60% Reduction**	**80% Reduction**
London	82.62	65.39	48.33	31.26
Madrid	94.78	89.55	82.84	74.28
Paris	85.89	71.78	57.66	42.94
Berlin	87.33	74.66	61.25	46.50
Moscow	91.81	82.92	73.31	61.92
Milan	85.76	71.52	57.49	42.61
Sofia	91.61	82.57	73.03	61.35
Copenhagen	89.18	77.92	66.45	53.42

Table 2b: Sensitivity results (measured in percent) for NH_3 concentrations to variations of human-made (anthropogenic) emissions at eight European cities.

City	**20% Reduction**	**40% Reduction**	**60% Reduction**	**80% Reduction**
London	81.48	62.63	42.42	21.45
Madrid	80.49	60.46	40.48	20.25
Paris	81.75	62.72	42.67	21.52
Berlin	81.08	61.35	41.33	20.97
Moscow	80.75	60.56	40.49	20.37
Milan	81.16	61.74	41.75	21.19
Sofia	80.95	60.56	40.49	20.79
Copenhagen	81.00	61.37	41.43	20.90

Remark: The particular choice of the eight sites, which was made in this study, is probably not optimal. The problem is that all eight sites are big European cities.

This fact implies that they are located in highly polluted areas of the continent and, thus, the sensitivity of the concentrations to human-made (anthropogenic) emission changes was studied only in highly polluted areas in this chapter. We are nevertheless convinced that this is a good choice, because precisely the high pollution levels might cause different damages and a lot of people in the selected eight sites are exposed to potential damaging effects caused by highly polluted air.

Table 2c: Sensitivity results (measured in percent) for NO concentrations to variations of human-made (anthropogenic) emissions at eight European cities.

City	20% Reduction	40% Reduction	60% Reduction	80% Reduction
London	80.10	61.26	43.31	24.76
Madrid	87.29	72.88	55.93	34.70
Paris	84.11	67.95	50.51	30.64
Berlin	84.48	68.79	51.90	32.24
Moscow	76.10	53.96	34.15	16.86
Milan	86.45	71.83	55.16	34.73
Sofia	88.42	74.92	58.84	37.94
Copenhagen	83.12	66.50	49.62	30.23

Table 2d: Sensitivity results (measured in percent) for NO_2 concentrations to variations of human-made (anthropogenic) emissions at eight European cities.

City	20% Reduction	40% Reduction	60% Reduction	80% Reduction
London	81.82	62.47	42.73	22.08
Madrid	82.77	64.53	45.61	24.90
Paris	82.21	63.80	44.42	23.80
Berlin	82.17	63.79	44.44	23.73
Moscow	81.73	63.00	43.19	22.29
Milan	82.84	64.85	45.69	27.77
Sofia	84.09	67.42	49.24	28.03
Copenhagen	81.89	63.22	43.99	23.48

Table 2e: Sensitivity results (measured in percent) for O_3 concentrations to variations of human-made (anthropogenic) emissions at eight European cities.

City	20% Reduction	40% Reduction	60% Reduction	80% Reduction
London	91.45	81.77	70.66	56.98
Madrid	91.58	81.78	71.15	58.35
Paris	90.91	80.81	69.19	54.80
Berlin	91.13	81.57	70.65	57.34
Moscow	95.30	90.17	84.19	77.35
Milan	90.07	79.23	66.82	51.69
Sofia	92.78	84.41	74.52	62.74
Copenhagen	92.71	84.26	74.93	63.56

Table 2f: Sensitivity results (measured in percent) for OH concentrations to variations of human-made (anthropogenic) emissions at eight European cities.

City	20% Reduction	40% Reduction	60% Reduction	80% Reduction
London	84.91	68.79	50.96	29.94
Madrid	86.33	71.16	54.12	33.29
Paris	85.43	69.84	52.13	31.28
Berlin	86.50	71.39	54.01	32.62
Moscow	84.62	67.92	49.93	28.88
Milan	86.13	71.09	53.80	32.85
Sofia	87.42	73.03	56.40	35.73
Copenhagen	86.19	70.92	53.35	32.22

Table 2g: Sensitivity results (measured in percent) for SO_2 concentrations to variations of human-made (anthropogenic) emissions at eight European cities.

City	20% Reduction	40% Reduction	60% Reduction	80% Reduction
London	79.28	59.94	40.06	20.00
Madrid	79.91	59.92	39.93	20.00
Paris	79.77	60.12	40.00	20.00
Berlin	80.00	60.00	40.00	20.03
Moscow	79.72	59.79	39.93	19.91
Milan	80.00	60.00	40.00	20.00
Sofia	79.78	60.11	40.00	20.00
Copenhagen	80.30	60.08	40.07	20.00

Table 2h: Sensitivity results (measured in percent) for $TOTNH_3$ concentrations to variations of human-made (anthropogenic) emissions at eight European cities.

City	20% Reduction	40% Reduction	60% Reduction	80% Reduction
London	77.62	56.03	35.98	17.63
Madrid	78.67	57.99	38.04	18.72
Paris	75.62	52.98	33.33	15.91
Berlin	78.30	57.61	37.41	18.32
Moscow	78.95	58.41	38.44	18.99
Milan	76.73	54.82	34.91	16.73
Sofia	78.66	57.90	37.83	18.71
Copenhagen	77.04	55.62	35.95	17.01

Table 2i: Sensitivity results (measured in percent) for $TOTNO_3$ concentrations to variations of human-made (anthropogenic) emissions at eight European cities.

City	20% Reduction	40% Reduction	60% Reduction	80% Reduction
London	74.92	51.27	29.82	11.84
Madrid	75.93	53.36	32.51	13.78
Paris	75.01	51.96	30.69	12.37
Berlin	75.69	52.39	31.30	13.13
Moscow	77.43	55.98	35.57	16.45
Milan	74.96	51.10	30.05	11.97
Sofia	76.08	53.86	33.02	14.33
Copenhagen	77.37	55.91	35.06	15.69

Table 2j: Sensitivity results (measured in percent) for $TOTSO_4$ concentrations to variations of human-made (anthropogenic) emissions at eight European cities.

City	20% Reduction	40% Reduction	60% Reduction	80% Reduction
London	80.06	59.98	39.96	19.98
Madrid	80.13	60.11	40.08	20.04
Paris	80.00	60.02	40.06	19.96
Berlin	79.94	59.91	39.83	19.97
Moscow	80.01	59.98	39.99	20.02
Milan	80.13	60.05	39.99	20.05
Sofia	79.99	60.02	39.96	20.05
Copenhagen	79.90	60.02	39.94	19.99

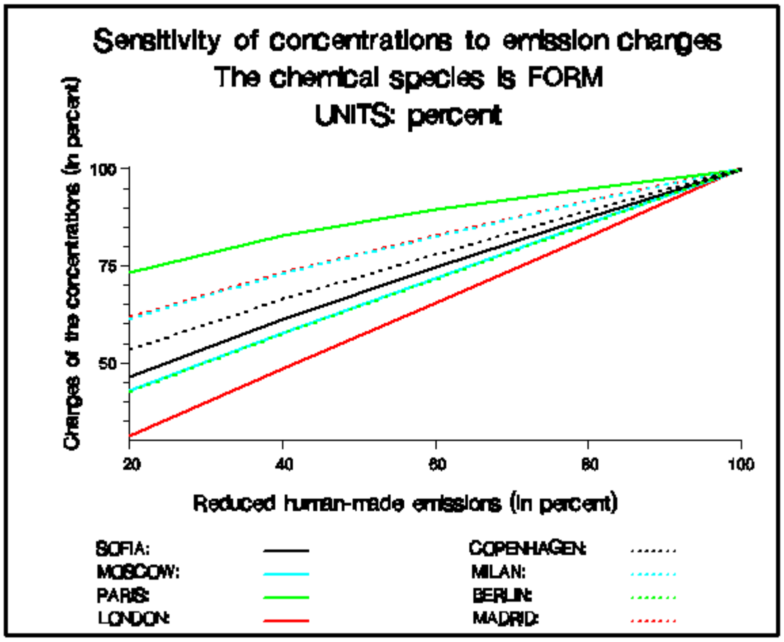

Figure 3a: Sensitivity of the FORM concentrations to changes of human-made (anthropogenic) emissions.

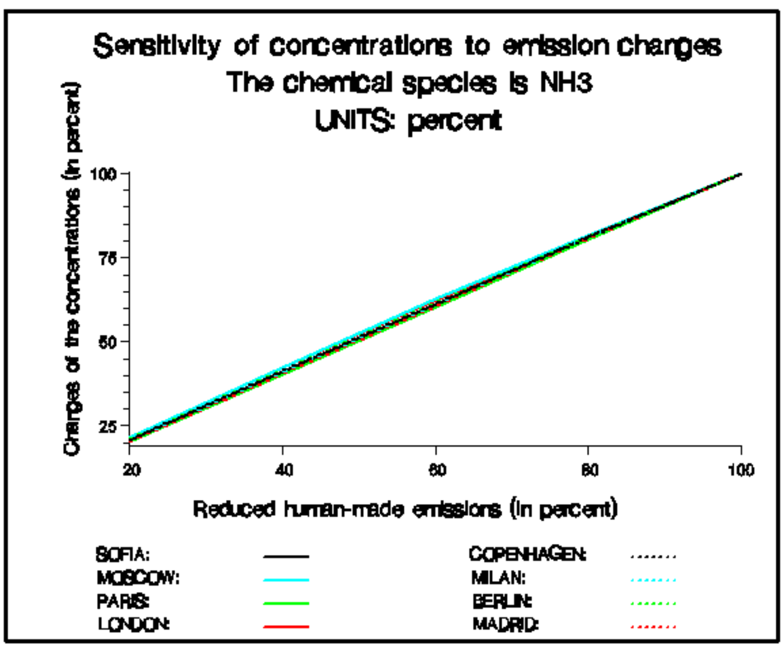

Figure 3b: Sensitivity of the NH_3 concentrations to changes of human-made (anthropogenic) emissions.

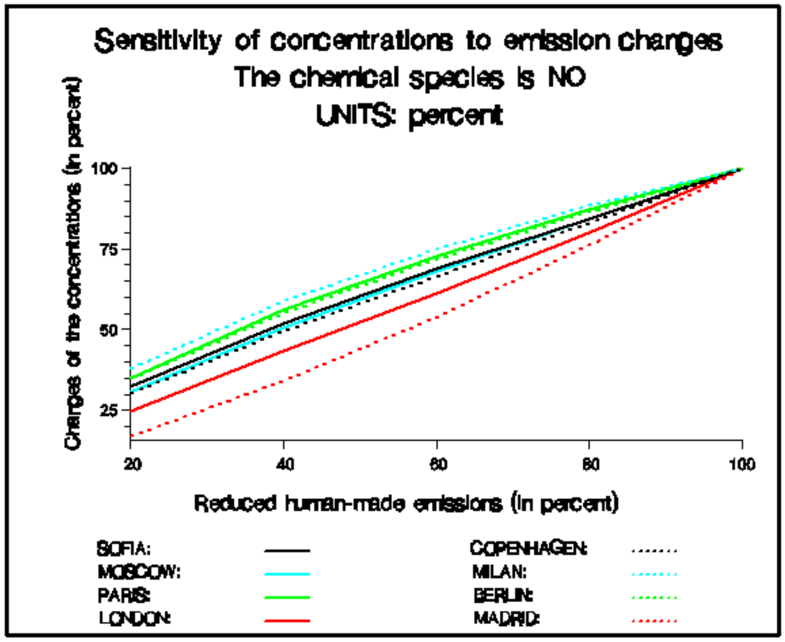

Figure 3c: Sensitivity of the NO concentrations to changes of human-made (anthropogenic) emissions.

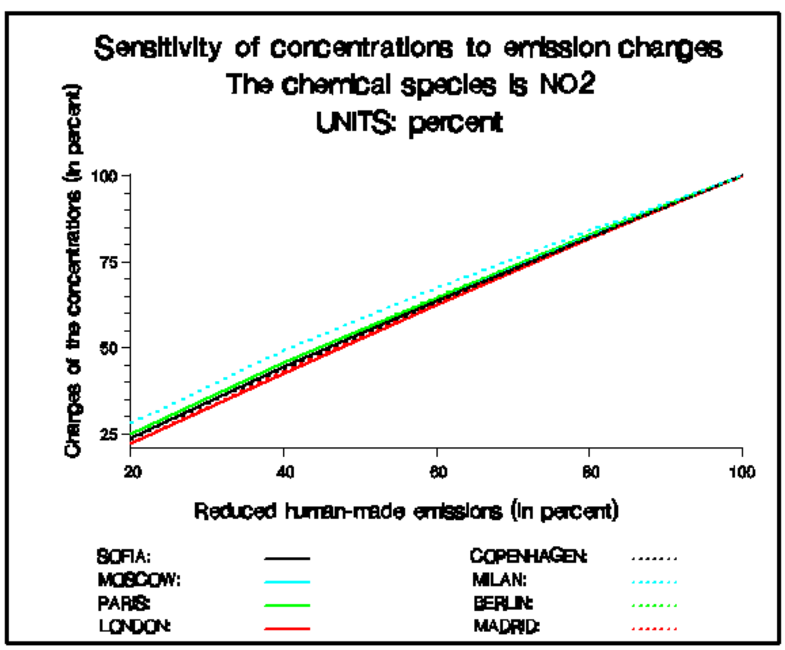

Figure 3d: Sensitivity of the NO_2 concentrations to changes of human-made (anthropogenic) emissions.

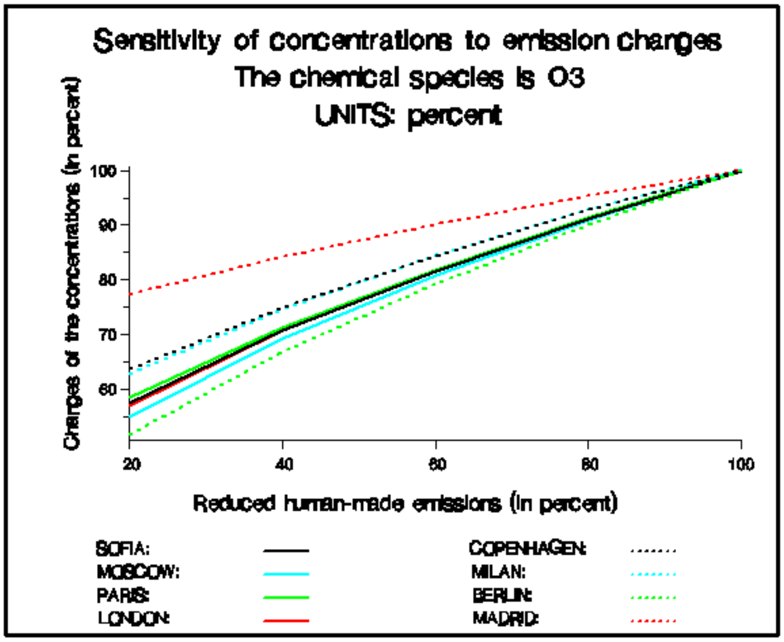

Figure 3e: Sensitivity of the O_3 concentrations to changes of human-made (anthropogenic) emissions.

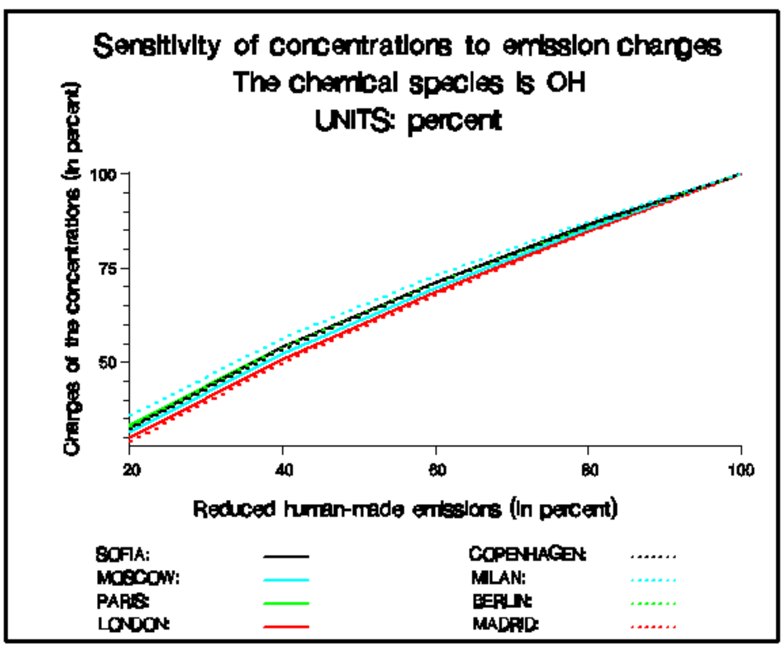

Figure 3f: Sensitivity of the OH concentrations to changes of human-made (anthropogenic) emissions.

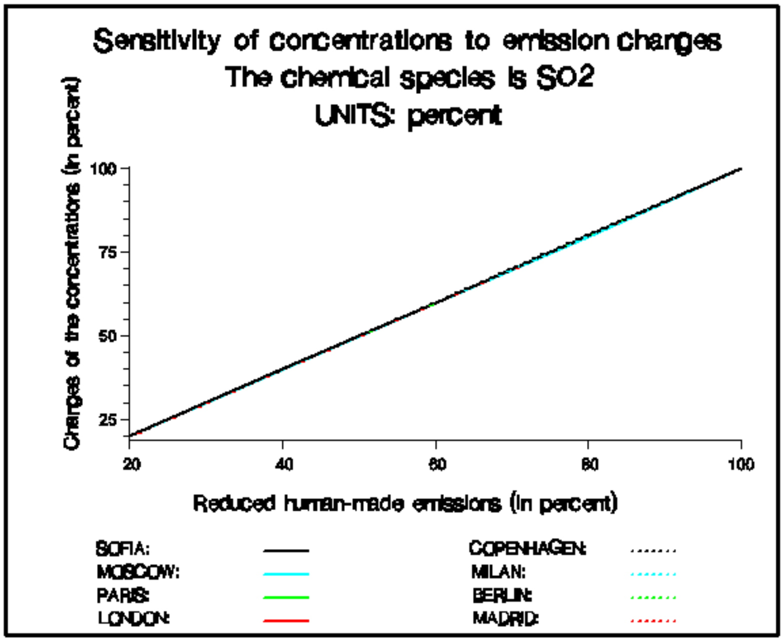

Figure 3g: Sensitivity of the SO_2 concentrations to changes of human-made (anthropogenic) emissions.

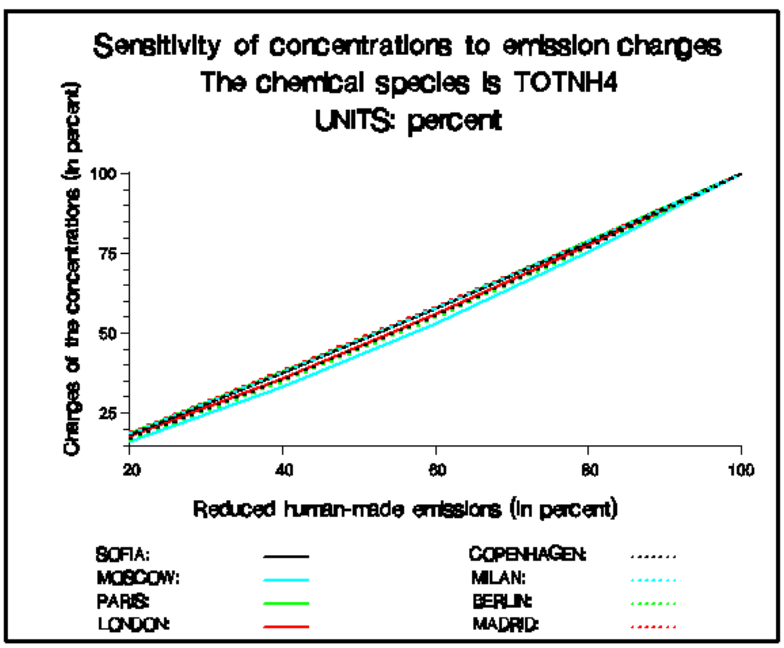

Figure 3h: Sensitivity of the $TOTNH_4$ concentrations to changes of human-made (anthropogenic) emissions.

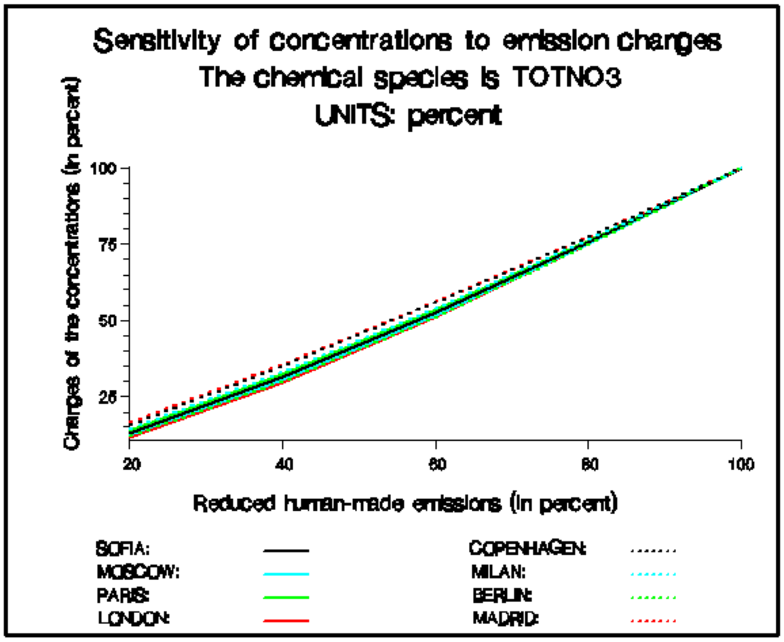

Figure 3i: Sensitivity of the $TOTNO_3$ concentrations to changes of human-made (anthropogenic) emissions.

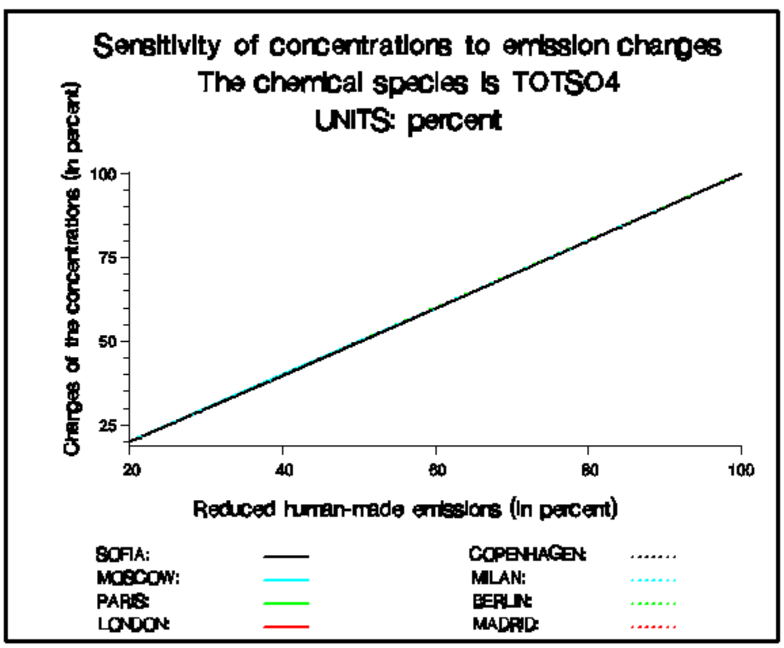

Figure 3j: Sensitivity of the $TOTSO_4$ concentrations to changes of human-made (anthropogenic) emissions.

SENSITIVITY EFFECTS RELATED TO QUANTITIES WHICH MAY HAVE DAMAGING EFFECTS

It is even more important to investigate the sensitivity to emission changes of some quantities that may have damaging effects on plant, animal and human beings when certain critical levels are exceeded. Three such quantities, **AOT40 for crops, AOT40 for forest trees and bad days**, will be used here. All these three quantities are related to the ozone concentrations. The relationship is explained in the following three sub-sections.

Definition of AOT40 For Crops

The AOT40 values for crops, which will be shortened as **AOT40C** in this section, are related to ozone concentrations in the following way (more details can be found, for example, in [5, 10, 18]):

$$\mathbf{AOT40C} = \sum_{i=1}^{N} \max(c_i - 40, 0), \qquad (1)$$

where

- $\mathbf{N}$ is the number of day-time hours in the period from the beginning of May to the end of July

and

- $\mathbf{c_i}$ is the ozone concentration (measured at a given station or calculated by a model at a given grid-square) at hour $\mathbf{i}$, where $\mathbf{i} \in \{1, 2, \ldots, N\}$.

If AOT40C exceeds **3000 ppb.hours**, then this fact may lead to losses from crops for the area where this critical level is exceeded. This is why it is desirable to prevent the situations where the AOT40C values exceed **3000 ppb.hours**. This is emphasized in several official documents of the European Union (EU); see, for example, [25].

Definition of AOT40 For Forest Trees

The AOT40 values for forest trees, which will be shortened as **AOT40F** in this section, are related to ozone concentrations in a very similar way as the AOT40C values (see also [5, 13, 25]):

$$\mathbf{AOT40F} = \sum_{i=1}^{N} \max(c_i - 40, 0), \quad \textbf{(2)}$$

where

- $\mathbf{N}$ is the number of hours in the period from the beginning of April to the end of September,

and

- $\mathbf{c_i}$ is the ozone concentration (measured at a given station or calculated by a model at a given grid-square) at hour $\mathbf{i}$, where $\mathbf{i} \in \{1, 2, \ldots, N\}$.

If AOT40F exceeds 10000 ppb.hours, then this fact may lead to damages of forest trees and, therefore, such situations should be avoided. This critical level is imposed in [25].

Definition of Bad Days

Assume that $\mathbf{c_{max}}$ is the maximum of the eight-hour averages of the calculated by some model or measured at some station ozone concentrations in a given day at some site $\mathbf{A}$. If the condition $\mathbf{c_{max} > 60}$ ppb is satisfied at least once during the day under consideration, then the expression a **bad day** will be used for such a day at site $\mathbf{A}$.

Bad days can have damaging effects on some groups of human beings (people who suffer from asthmatic diseases). Therefore, the number of such days should be reduced as much as possible. Two important aims are stated in the Ozone Directive issued by the EU Parliament in year 2002 [25]:

- **Target Aim:** The number of "bad days" in any site of the European Union should not exceed 25 after year 2010.

- **Long-term Aim:** No "bad day" should occur in the European Union (the year after which the long-term aim has to be satisfied is not specified in the EU Ozone Directive).

Presentation of the Results

The distribution of the AOT40C levels, the AOT40F levels and the bad days in Europe is shown in Fig. **4a** – **4c**. The reductions obtained by the four scenarios are presented in Fig. **5a** – **5c**.

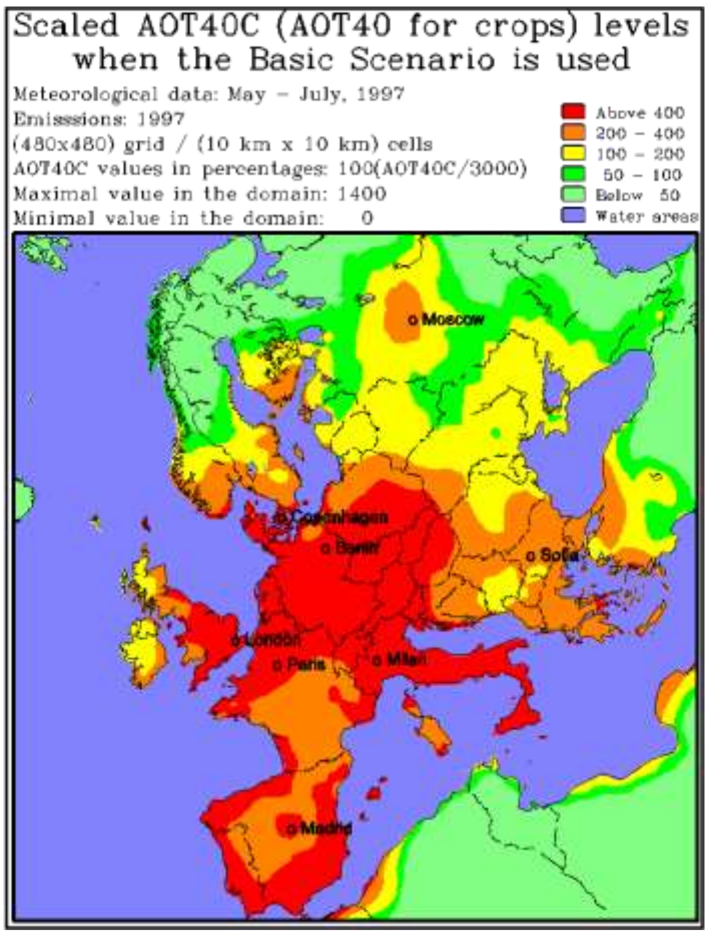

Figure 4a: Distribution of the AOT40C (AOT40 for crops) values for 1997 in Europe.

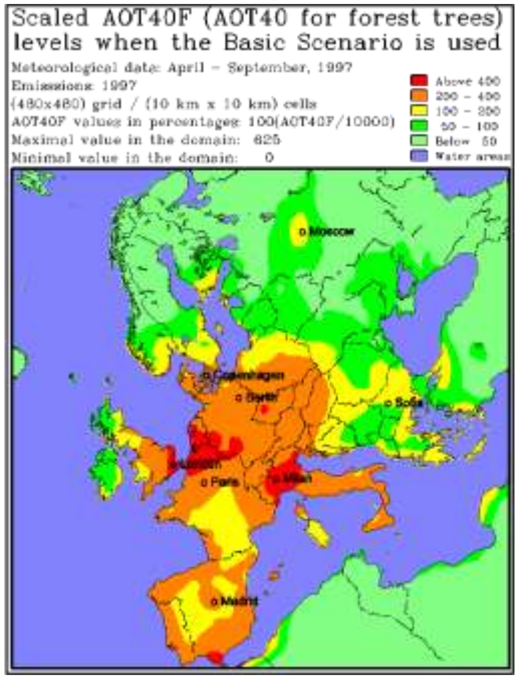

Figure 4b: Distribution of the AOT40F (AOT40 for forest trees) values for 1997 in Europe.

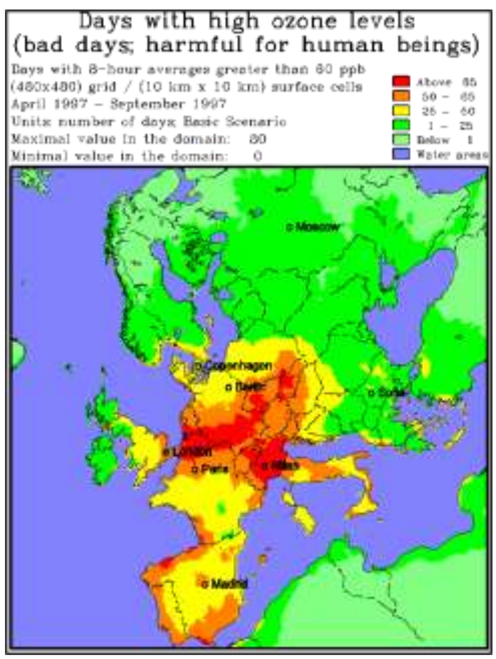

Figure 4c: Distribution of the bad days (days with the eight-hour ozone averages greater than 60 ppb).

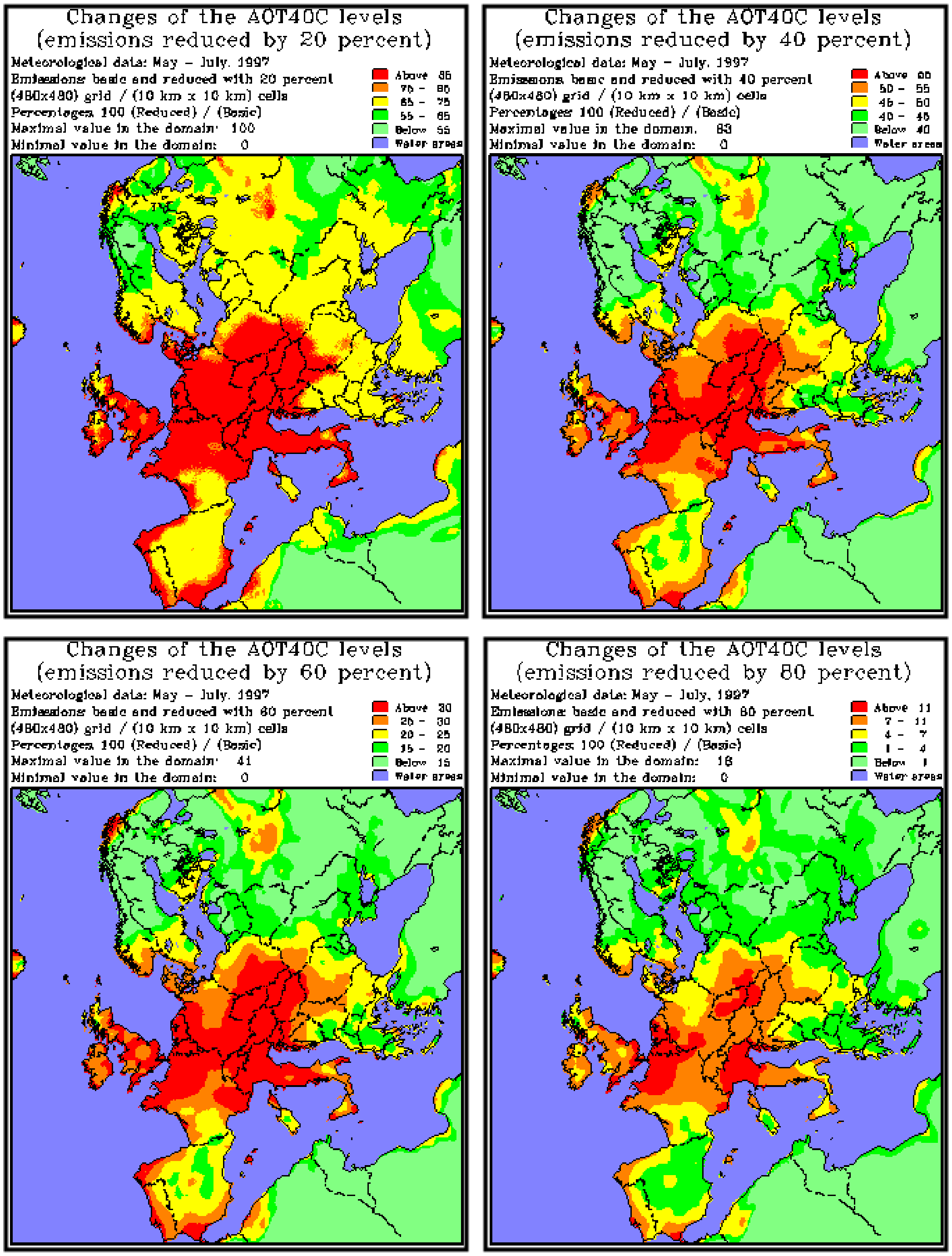

Figure 5a: Sensitivity of the AOT40C (AOT40 for crops) values in Europe to variations of the human-made (anthropogenic) emissions.

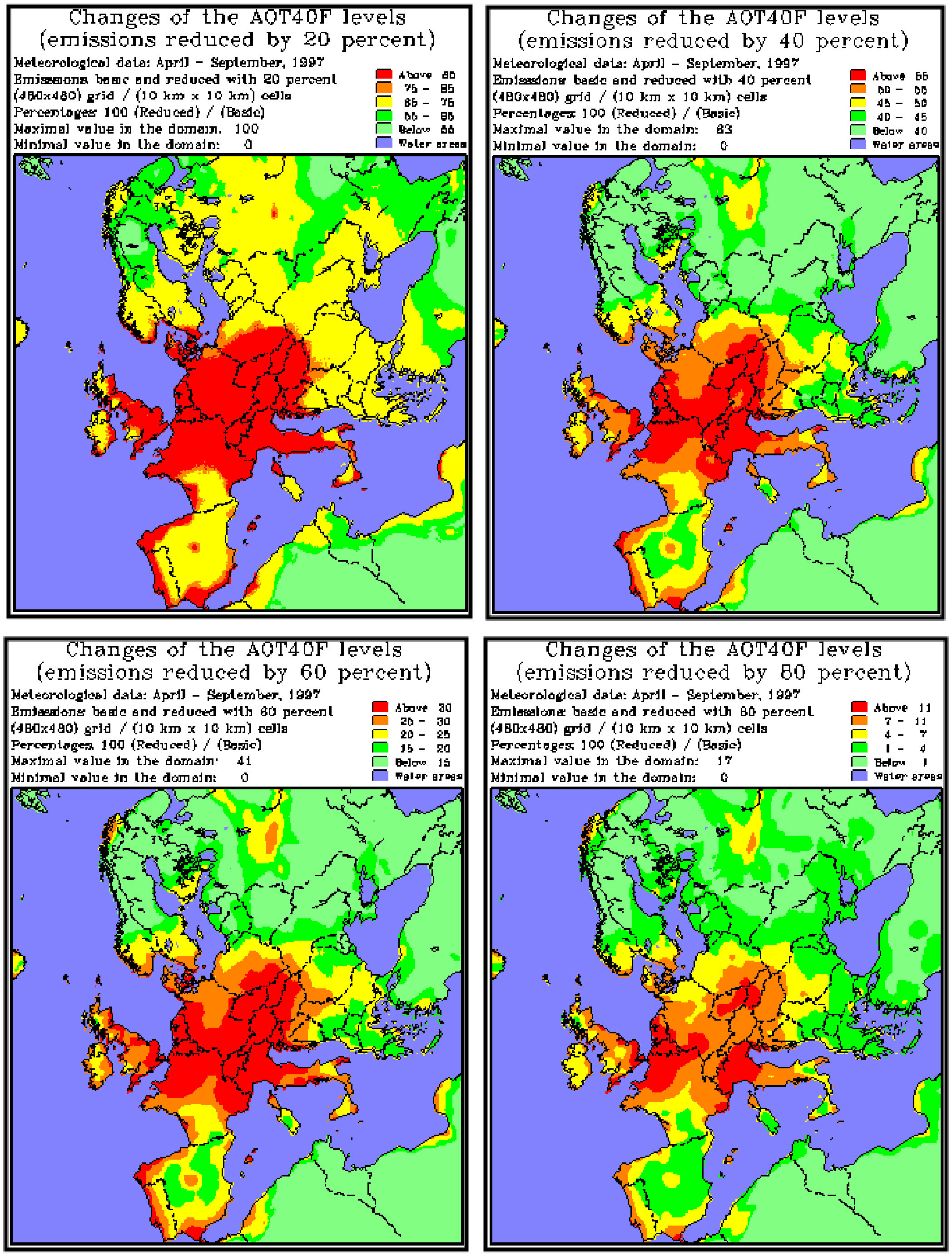

Figure 5b: Sensitivity of the AOT40F (AOT40 for forest trees) values in Europe to variations of the human-made (anthropogenic) emissions.

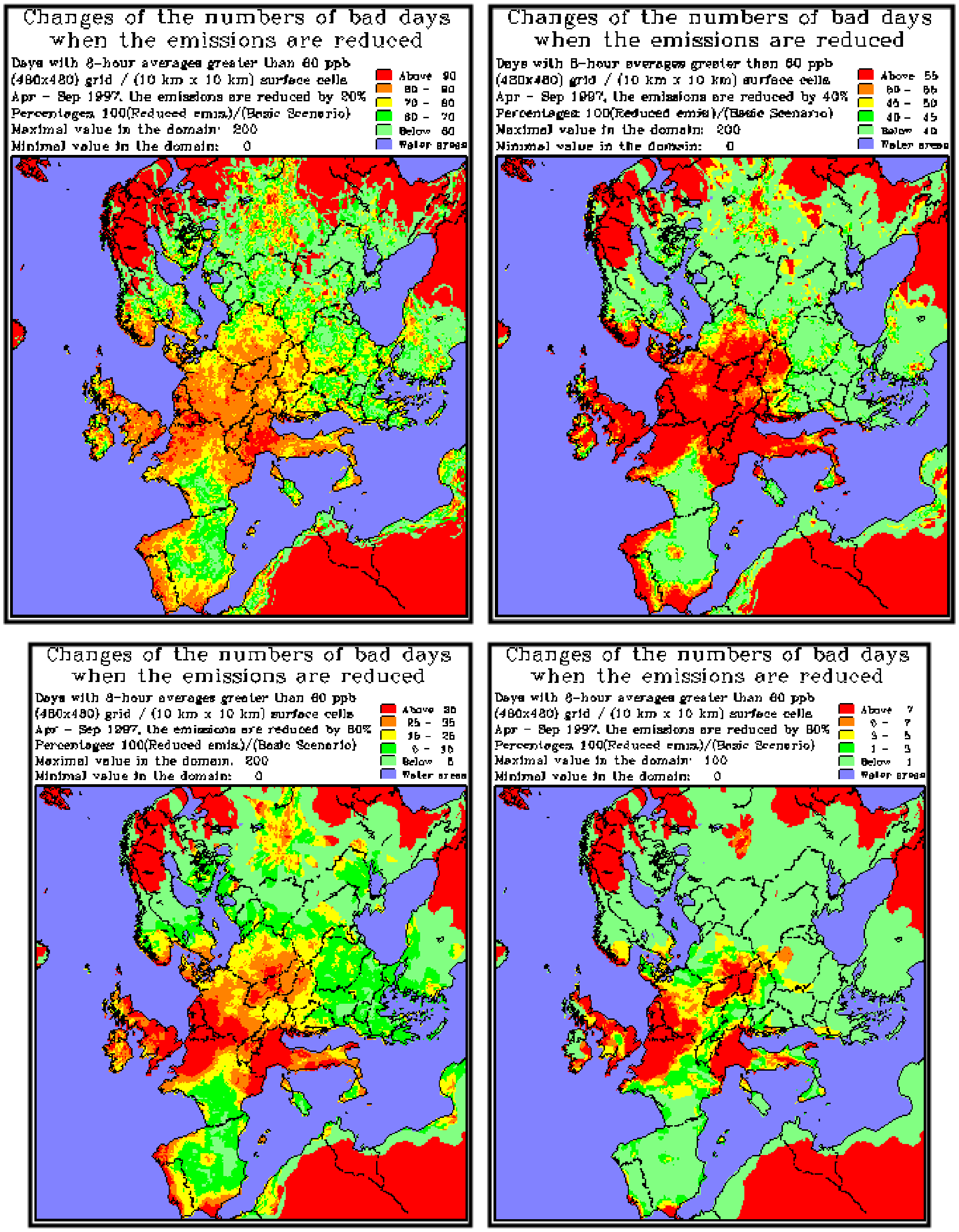

Figure 5c: Sensitivity of the numbers of bad days in Europe (days in which the eight-hour averages of the ozone concentrations exceed 60 ppb) to variations of the human-made (anthropogenic) emissions.

It is seen that the most polluted areas are in Central Europe, Nothern Italy and England and, thus, reductions are mostly needed there. The ratios $\mathbf{100A/B}$, where $\mathbf{A}$ is the quantity calculated by reduced emissions and $\mathbf{B}$ is the corresponding quantity obtained by the Basic Scenario for year 1997, are given in Fig. **5a** – **5c**. A careful study of the plots in Fig. **5a** – **5c** indicates that the reductions in the most polluted areas are in fact smallest.

SOME CONCLUDING REMARKS

Results from a comprehensive study related to the sensitivity of pollution levels are presented in this chapter. It is worthwhile to continue this study in several directions:

It will be useful to investigate the sensitivity of the pollution levels to changes of the human-made emissions only in some parts of Europe (say, only in the most polluted areas). In this way some information of the sensitivity of the pollution levels on the combined effect of reductions of human-made emissions in highly polluted areas and long-range transport of pollutants to neighbouring areas will be obtained.

All human-made (anthropogenic) emissions were simultaneously varied. It would be appropriate to examine the effect of varying only one or two of these emissions. In this way, it would be possible to understand which species are not sensitive to the variation of the chosen emissions and which of the other species are most sensitive.

Only human-made emissions are varied in the scenarios that are used in this chapter. It will also be interesting to study the sensitivity of the pollution levels on natural (biogenic) emissions. This seems to be relevant in connection with the climate changes. The biogenic emissions depend on the temperature. Therefore, the future increase of the temperature will probably lead to some changes of the natural emissions.

The effect of the variations of human-made emissions on the pollution levels is studied in this chapter by using emission scenarios. Some other approaches, as for example those used in [26, 27], can also be applied. It would be applied. It would be interesting to compare the results obtaining by other approaches with the results presented in this chapter.

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CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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