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Influence of climatic changes on pollution levels in the Balkan Peninsula

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ABSTRACT

The aim of the paper is to study the influence of future climatic changes on some high pollution levels that can cause damages on plants, animals and human beings. The particular area of interest is the Balkan Peninsula. Four important quantities have been selected: (a) annual concentrations, (b) AOT40C (high AOT40C values can cause damages on plants and, first and foremost, crops), (c) AOT40F (high AOT40F values can cause damages on forest trees), (d) number of "bad days" (large numbers of "bad days" can cause damage to people suffering from asthmatic diseases).

Critical levels for the quantities from (b), (c) and (d) are legislated by several directives of the European Parliament (see, for example, [European Parliament Directive 2002/3/EC of the European Parliament and the Council of 12 February 2002 relating to ozone in ambient air, Official Journal of the European Communities L67 (2002) 14–30]). We are mainly interested in cases where the prescribed in the directives critical values are exceeded.

An advanced mathematical model was used to run fourteen scenarios over a period of sixteen years. Results, which are obtained in the selected domain, the Balkan Peninsula, with some of these scenarios, are carefully studied. The major conclusion is that the increase of the temperature, alone or in combination with some other factors, leads to rather considerable increases of some pollution levels, which might become dangerous for the environment.

1. Introduction

The gradual increase of the global temperature of the Earth is the most important consequence of future climate changes. Both many of the chemical reactions in which the major pollutants are involved and the biogenic emissions depend on the temperature. Therefore, it is clear that the global warming effect will necessarily cause some changes in the pollution levels. The influence of the increased temperatures on some pollution levels in the Balkan Peninsula is the major topic of this paper. More precisely, we shall be interested in the following three important issues:

(a) the contribution of air pollution from other European countries to the air pollution in the Balkan Peninsula,
(b) the impact of climate change (and, first and foremost, the increased temperature) on the pollution levels in the countries of the selected area
and
(c) the changes of the pollution levels that are due to a *combination* of the warming effect with some other important factors.

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In connection with (c), it was important to compare the changes of the pollution levels in the studied area that are caused by future increases of the temperature with the changes that are created by several other factors (different emission sources, inter-annual variability of meteorological conditions, etc.). Such an extensive comparison has successfully been accomplished by designing four categories of scenarios:

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

The mathematical model that was used in the present study, the Unified Danish Eulerian Model, *UNI-DEM*, was run with 14 scenarios. It was necessary to apply a long-time period in order to capture (a) the climatic changes, (b) the inter-annual variations and (c) different trends. A time-period of sixteen years was actually used.

This paper is organized in the following way:

(A) The Unified Danish Eulerian Model (UNI-DEM) is briefly described in Section 2.
(B) The fourteen scenarios that are run with UNI-DEM are sketched in Section 3.
(C) Variations of the concentrations of several pollutants as well as the contribution of European sources on the pollution levels in the Balkan Peninsula are studied in Section 4.
(D) Results obtained in connection with AOT40C values are presented and discussed in Section 5.
(E) Results obtained in connection with AOT40F values are presented and discussed in Section 6.
(F) Results obtained in connection with "bad days" are presented and discussed in Section 7.
(G) General conclusions and remarks are given in the last section.

2. Mathematical description of the unified Danish Eulerian model

The Unified Danish Eulerian model (UNI-DEM) has primarily been developed for studying air pollution levels in the whole of Europe. Different features of this model are fully described in [1–4]. UNI-DEM was extensively used for performing different investigations related to air pollution in

- Bulgaria [5,6],
- Denmark [7,4,8],
- England [9],
- Europe [10–16],
- Hungary [17–19] and
- the North Sea [20].

A previous version of UNI-DEM has also been used in some inter-comparisons of European large-scale air pollution models [21,2].

UNI-DEM is described mathematically by a system of partial differential equations (PDEs). Five important physical processes are taken into account during the derivation of this system: (a) horizontal transport (advection), (b) horizontal diffusion, (c) non-linear chemical reactions plus emissions, (d) dry and wet deposition and (e) vertical transport. The system of PDEs can be written in the following form:

$$\begin{aligned}
\frac{\partial \mathbf{c_i}}{\partial \mathbf{t}} &= -\mathbf{u}\frac{\partial \mathbf{c_i}}{\partial \mathbf{x}} - \mathbf{v}\frac{\partial \mathbf{c_i}}{\partial \mathbf{y}} \quad \text{horizontal transport (advection)} \\
&+ \frac{\partial}{\partial \mathbf{x}}\left(\mathbf{K_x}\frac{\partial \mathbf{c_i}}{\partial \mathbf{x}}\right) + \frac{\partial}{\partial \mathbf{y}}\left(\mathbf{K_y}\frac{\partial \mathbf{c_i}}{\partial \mathbf{y}}\right) \quad \text{horizontal diffusion} \\
&+ \mathbf{Q_i}\left(\mathbf{t}, \mathbf{x}, \mathbf{y}, \mathbf{z}, \mathbf{c}_1, \mathbf{c}_2, \ldots, \mathbf{c}_q\right) + \mathbf{E_i}\left(\mathbf{t}, \mathbf{x}, \mathbf{y}, \mathbf{z}\right) \quad \text{chemical reactions + emissions} \\
&+ \left(\mathbf{k_{1i}} + \mathbf{k_{2i}}\right)\mathbf{c_i} \quad \text{dry and wet depositions} \\
&- \mathbf{w}\frac{\partial \mathbf{c_i}}{\partial \mathbf{z}} + \frac{\partial}{\partial \mathbf{z}}\left(\mathbf{K_z}\frac{\partial \mathbf{c_i}}{\partial \mathbf{z}}\right), \quad \text{vertical transport} \\
&\mathbf{i} = \mathbf{1}, \mathbf{2}, \ldots, \mathbf{q} \quad \text{number of equations (chemical species).}
\end{aligned} \tag{1}$$

The different quantities involved in (1) are briefly described below:

- $\mathbf{c_i} = \mathbf{c_i}(\mathbf{t}, \mathbf{x}, \mathbf{y}, \mathbf{z})$ is the concentration of the chemical species $\mathbf{i}$ at point $(\mathbf{x}, \mathbf{y}, \mathbf{z})$ of the space domain and at time $\mathbf{t}$ of the time-interval,
- $\mathbf{u} = \mathbf{u}(\mathbf{t}, \mathbf{x}, \mathbf{y}, \mathbf{z})$, $\mathbf{v} = \mathbf{v}(\mathbf{t}, \mathbf{x}, \mathbf{y}, \mathbf{z})$ and $\mathbf{w} = \mathbf{w}(\mathbf{t}, \mathbf{x}, \mathbf{y}, \mathbf{z})$ are wind velocities along the **Ox**, **Oy** and **Oz** directions respectively at the spatial point $(\mathbf{x}, \mathbf{y}, \mathbf{z})$ and time $\mathbf{t}$,
- $\mathbf{K_x} = \mathbf{K_x}(\mathbf{t}, \mathbf{x}, \mathbf{y}, \mathbf{z})$, $\mathbf{K_y} = \mathbf{K_y}(\mathbf{t}, \mathbf{x}, \mathbf{y}, \mathbf{z})$ and $\mathbf{K_z} = \mathbf{K_z}(\mathbf{t}, \mathbf{x}, \mathbf{y}, \mathbf{z})$ are diffusivity coefficients at the spatial point $(\mathbf{x}, \mathbf{y}, \mathbf{z})$ and time $\mathbf{t}$ (it is often assumed that $\mathbf{K_x}$ and $\mathbf{K_y}$ are non-negative constants, while the calculation of $\mathbf{K_z}$ is normally rather complicated),

- $\mathbf{k_{1i}} = \mathbf{k_{1i}}\,(\mathbf{t}, \mathbf{x}, \mathbf{y}, \mathbf{z})$ and $\mathbf{k_{2i}} = \mathbf{k_{2i}}\,(\mathbf{t}, \mathbf{x}, \mathbf{y}, \mathbf{z})$ are deposition coefficients (dry and wet deposition respectively) of chemical species $\mathbf{i}$ at the spatial point $(\mathbf{x}, \mathbf{y}, \mathbf{z})$ and time $\mathbf{t}$ of the time-interval. It should be mentioned here that for some of the species these coefficients are non-negative constants. The wet deposition coefficients $\mathbf{k_{2i}}$ are equal to zero when it is not raining.
- $\mathbf{E_i}(\mathbf{t}, \mathbf{x}, \mathbf{y}, \mathbf{z})$ is an emission source for chemical species $\mathbf{i}$ at the spatial point $(\mathbf{x}, \mathbf{y}, \mathbf{z})$ and time $\mathbf{t}$ of the time-interval.

UNI-DEM is normally split (see [1,5]) into the following three sub-models:

$$\frac{\partial\,\mathbf{c_i^{(1)}}}{\partial\,\mathbf{t}} = -\mathbf{w}\,\frac{\partial\,\mathbf{c_i^{(1)}}}{\partial \mathbf{z}} + \frac{\partial}{\partial \mathbf{z}}\left(\mathbf{K_z}\frac{\partial\,\mathbf{c_i^{(1)}}}{\partial \mathbf{z}}\right), \tag{2}$$

$$\frac{\partial\,\mathbf{c_i^{(2)}}}{\partial\,\mathbf{t}} = -\mathbf{u}\,\frac{\partial\,\mathbf{c_i^{(2)}}}{\partial \mathbf{x}} - \mathbf{v}\,\frac{\partial\,\mathbf{c_i^{(2)}}}{\partial \mathbf{y}} + \frac{\partial}{\partial \mathbf{x}}\left(\mathbf{K_x}\frac{\partial\,\mathbf{c_i^{(2)}}}{\partial \mathbf{x}}\right) + \frac{\partial}{\partial \mathbf{y}}\left(\mathbf{K_y}\frac{\partial\,\mathbf{c_i^{(2)}}}{\partial \mathbf{y}}\right), \tag{3}$$

$$\frac{\partial\,\mathbf{c_i^{(3)}}}{\partial\,\mathbf{t}} = \mathbf{Q_i}\left(\mathbf{t}, \mathbf{x}, \mathbf{y}, \mathbf{z}, \mathbf{c_1^{(3)}}, \mathbf{c_2^{(3)}}, \ldots, \mathbf{c_q^{(3)}}\right) + \mathbf{E_i}\,(\mathbf{t}, \mathbf{x}, \mathbf{y}, \mathbf{z}) + (\mathbf{k_{1i}} + \mathbf{k_{2i}})\ \mathbf{c_i^{(3)}}. \tag{4}$$

The first of these three sub-models describes the vertical exchange. The second sub-model describes the combination of the horizontal transport (the advection) and the horizontal diffusion. The last sub-model describes the chemical reactions together with the emission sources and the deposition terms.

Splitting allows us to apply different numerical methods in the different sub-models and, thus, to reduce considerably the computational work by exploiting better the specific properties of each sub-model.

Assume that the space domain is discretized by using a grid with $\mathbf{N_x} \times \mathbf{N_y} \times \mathbf{N_z}$ grid-points, where $\mathbf{N_x}$, $\mathbf{N_y}$ and $\mathbf{N_z}$ are the numbers of the grid-points along the grid-lines parallel to the $\mathbf{Ox}$, $\mathbf{Oy}$ and $\mathbf{Oz}$ axes. Assume further that the number of chemical species involved in the model is $\mathbf{N_s} = \mathbf{q}$. Finally, assume that the spatial derivatives are discretized by some numerical algorithm (it must be mentioned here that different numerical algorithms can be applied in the different sub-models). Then the three systems of PDEs represented by (2)–(4) will be transformed into three systems of ODEs (ordinary differential equations):

$$\frac{\mathbf{d\,g^{(1)}}}{\mathbf{d\,t}} = \mathbf{f^{(1)}}(\mathbf{t}, \mathbf{g^{(1)}}), \qquad \frac{\mathbf{d\,g^{(2)}}}{\mathbf{d\,t}} = \mathbf{f^{(2)}}(\mathbf{t}, \mathbf{g^{(2)}}), \qquad \frac{\mathbf{d\,g^{(3)}}}{\mathbf{d\,t}} = \mathbf{f^{(3)}}(\mathbf{t}, \mathbf{g^{(3)}}). \tag{5}$$

The components of functions $\mathbf{g^{(m)}}(\mathbf{t}) \in \mathbf{R^{N_x \times N_y \times N_z \times N_s}}$, $\mathbf{m} = \mathbf{1}, \mathbf{2}, \mathbf{3}$, are approximations at time $\mathbf{t}$ of the concentrations at all spatial grid-points and for all species. The components of functions $\mathbf{f^{(m)}}(\mathbf{t}) \in \mathbf{R^{N_x \times N_y \times N_z \times N_s}}$, $\mathbf{m} = \mathbf{1}, \mathbf{2}, \mathbf{3}$, depend both on quantities involved in the right-hand-side of (1) and on the particular numerical algorithms that are used in the discretization of the spatial derivatives.

A simple linear finite element method is used to discretize the spatial derivatives in (2) and (3). The spatial derivatives can also be discretized by using other numerical methods as, for example, a pseudo-spectral discretization, a semi-Lagrangian discretization (which can be used only to discretize the first-order derivatives, i.e. the advection part should not be combined with the diffusion part when this method is to be applied) and methods producing non-negative values of the concentrations.

It is necessary to couple the three ODE systems given in (5). The simplest coupling procedure is closely related to the time-integration of these systems. Assume that the values of the concentrations (for all species and at all spatial grid-points) have been found for some $\mathbf{t} = \mathbf{t_n}$. These values can be considered as components of a vector-function $\mathbf{g}(\mathbf{t_n}) \in \mathbf{R^{N_x \times N_y \times N_z \times N_s}}$. The next time-step, time-step $\mathbf{n} + \mathbf{1}$ (at which approximations of the concentrations are found at $\mathbf{t_{n+1}} = \mathbf{t_n} + \Delta\mathbf{t}$ where $\Delta\mathbf{t}$ is some increment), can be performed by integrating successively the three systems. The values of $\mathbf{g}(\mathbf{t_n})$ are used as an initial condition in the solution of the first ODE system in (5). The solution of the first system in (5) is used as an initial condition of the second ODE system in (5). Finally, the solution of the second ODE system in (5) is used as an initial condition of the third ODE system in (5). The solution of the last ODE system in (5) is accepted as an approximation to $\mathbf{g}(\mathbf{t_{n+1}})$. In this way, everything is prepared to start the calculations in the next time-step, step $\mathbf{n} + \mathbf{2}$.

The first system of ODEs in (5) can be solved by using many classical time-integration methods. The well-known $\boldsymbol{\theta}$-method is currently used in UNI-DEM.

Predictor–corrector (PC) methods with several different correctors, which are discussed in [3], are used in the solution of the second ODE system in (5). The correctors are carefully chosen so that the stability properties of the method can be enhanced. If the code judges the time-stepsize to be too large for the currently used PC method (and may lead to unstable computations), then it switches to a more stable (but also more expensive, because more corrector formulae are used to obtain stability) PC scheme. On the other hand, if the code judges that the stepsize is too small for the currently used PC method, then it switches to not so stable but more accurate PC scheme (which is using less corrector formulae and, therefore is less expensive). In this way the code is trying both to keep the same stepsize and to optimize the performance. More details about this strategy can be found in [3].

The solution of the third system in (5) is much more complicated, because this system is both time-consuming and very stiff. Often the QSSA (Quasi-Steady-State-Approximation) method is used in this part of the model. It is simple and relatively stable but not very accurate (therefore, it has normally to be run with a small time-stepsize). An improved QSSA method

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Table 1
Scenarios run by using UNI-DEM. Normal biogenic emissions are produced by applying ideas proposed in [23,24] as implemented in [22]. Increased biogenic emissions are produced by applying ideas from [25]. Scenario 2010 and Scenario MFR (Maximal Feasible Reductions) were prepared by multiplying the anthropogenic EMEP emissions [26,27] by the reduction factors given in [28].

Scenario	Meteorology	Anthropogenic emissions	Biogenic emissions
Basic	EMEP and NERI	EMEP and NERI	Normal (as in [22])
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 Basic	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

was recently implemented in UNI-DEM. The classical numerical methods for stiff ODE systems (such as the Backward Euler Method, the Trapezoidal Rule and Runge–Kutta algorithms) lead to the solution of non-linear systems of algebraic equations (which have to be treated, for example, by the Quasi-Newton Iterative Method) and, therefore, their computational cost per time-step is normally more expensive. On the other hand, these methods can be incorporated with an error control and perhaps with larger time-steps. Partitioning can also be used. Some convergence problems related to the implementation of partitioning have been studied in [4].

The particular numerical methods and the splitting procedures, which are used when the system of PDEs (1) is handled, are described in detail in [16,5,29]. Optimizing the code for parallel computations on high-speed computers is discussed in [1,5].

3. Development of appropriate scenarios

UNI-DEM was run with 14 scenarios. These scenarios are listed in Table 1 (not all of them will be used in this study, but the full description and many results are given in [12]; see also [3,8,13,19]). Each scenario was run on a time-period consisting of sixteen consecutive years (from 1989 to 2004).

Mainly results obtained by the Basic Scenario and Scenario Climate 3 will be used in this paper, but also results from some of the other scenarios are shortly discussed. The Basic Scenario for a given year $\mathbf{N}$ where ($\mathbf{N} \in [\mathbf{1989}, \mathbf{2004}]$) is obtained by using emissions inventories and meteorological data for the selected year, which were prepared either at EMEP, European Monitoring and Evaluation Programme [26,27] or at the Danish National Environmental Research Institute, some details can be found in [30].

The predictions of the increase in the annual temperatures in Europe according to the *IPCC Scenario SRES A2* as well as several other conclusions, which are related to the climatic changes in Europe and which are discussed in [31,32], were used in order to prepare the three climatic air pollution scenarios mentioned in Table 1. The rules, which were actually used in the development of these scenarios, are sketched below.

Climate Scenario 1. The predicted in *IPCC Scenario SRES A2* annual changes of the temperature, see [31,32], were used to produce this climatic scenario. The changes of the temperature in Europe, which result from the *IPCC Scenario SRES A2*, are shown in Fig. 1. Consider any cell of the grid used to create the plot shown in Fig. 1 and assume that this cell is located in a region in Fig. 1 where the increase of the temperature is in the interval $[\alpha, \beta]$. The temperature in each cell at an arbitrary hour $\mathbf{k}$ (i.e. $\mathbf{k}$ being any hour in the interval from the beginning of 1989 to the end of 2004) is increased by an amount $\alpha + \gamma(\mathbf{k})$, where $\gamma(\mathbf{k})$ is randomly generated in the interval $[\mathbf{0}, \beta - \alpha]$ so that the mathematical expectation of the increase of the annual mean of the temperature at any cell of the space domain is $(\beta - \alpha)/2$. This means that (a) only temperatures are varied in this scenario and (b) *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 Scenario SRES A2*.

Climate Scenario 2. The extreme cases will become even stronger in the future climate; see Table 9.6 on p. 575 in [32]. It is expected that: (a) there will be higher maximum temperatures and more hot days over the land areas, (b) there will be higher minimum temperatures, fewer cold days and fewer frost days over nearly all land areas and (c) 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 the annual means of the changes remained the same, at all cells, as those in the first climatic scenario (i.e. as those prescribed in the *IPCCS Scenario SRES A2*). We also reduced (by 10%) the cloud covers over land during the summer periods.

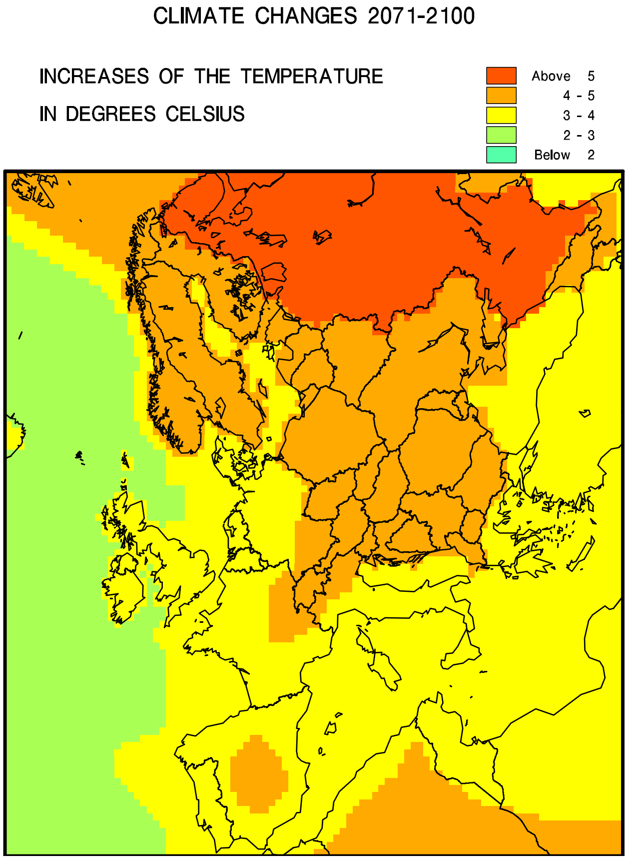

Fig. 1. Future changes of the temperatures in Europe and its surroundings according to *IPCC Scenario SRES A2* compare to 1989 from [32].

Climate Scenario 3. It is also expected, as shown in Table 9.6 on p. 575 in [32], that there will be more intense precipitation events but 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 (by 10%), 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 changes of the temperature is the same as the predictions made in the *IPCC Scenario SRES A2*.

A remark about the *great computational complexity* of problem handled in this study should be given here. The task of running 14 scenarios over a time-period of 16 years on a fine grid ($480 \times 480 \times 10$ cells resulting in systems of 80 640 000 equations that are to be handled in 209 664 time-steps per year) is extremely demanding even when powerful modern computers are available. Therefore, the task of running so many scenarios over such a long time-period can be successfully solved only if at least four requirements are simultaneously satisfied: (a) fast but also sufficiently accurate numerical methods are to be implemented in the model, (b) the cache memories of the available computers have to be efficiently utilized, (c) codes which can be run in parallel have to be developed and used and (d) reliable and robust splitting procedures have to be implemented. The solution of sub-tasks (a)–(d) is discussed in detail in [1,5]. It must be emphasized here that at present it is *impossible* to handle the 14 scenarios over a time-period of 16 years on the available super-computers if the sub-tasks (a)–(d) are not efficiently solved. Even when this was done, it took more than two years to compute the needed output data from all 2688 runs (14 scenarios $\times$ 16 years $\times$ 12 months) carried out for this study. This fact illustrates the great computational difficulties that are related to the investigation of various impacts of climatic changes on pollution levels. The storage requirements (the need for huge input and output files) are also enormous.

The main purpose with the climatic scenarios developed and used in this paper can be described as follows. It is desirable to compare directly the pollution levels obtained by using the predicted future temperatures with the present state of the corresponding levels. To achieve this we fixed the transport and varied (in the developed climatic scenarios) only the temperatures and the emissions as well as some other closely related quantities. For the sake of simplicity, assume temporally that only the temperature is varied. Then the approach discussed in this paper has the advantage that it allows us to compare directly the present pollution levels with corresponding pollution levels obtained with the increased temperature fields. Since the temperature is the only parameter that is varied all changes of the considered pollution levels

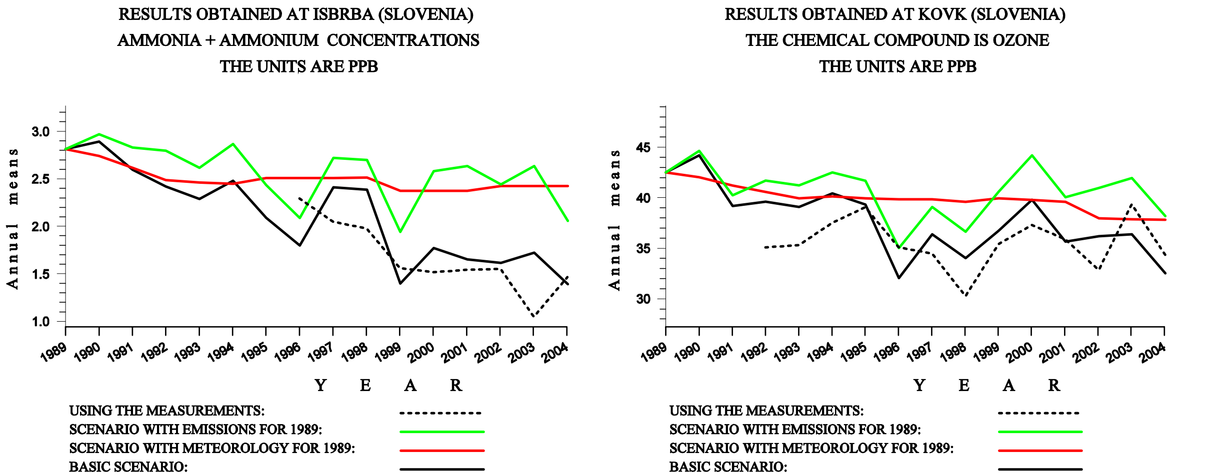

Fig. 2. Comparison of the Basic Scenario with the scenarios where either the meteorological conditions or the emissions are kept constant (as in year 1989). Some measurement results are also given.

are clearly due to the increased temperature levels. It is obvious that similar conclusions can be drawn if the emissions and some other parameters are also varied (the important issue being to keep the transport the same as that in the Basic Scenario).

It is also possible to include all meteorological parameters in the set of scenarios (first and foremost the wind fields). However, this would require running a climatic model. Moreover, it is not very clear in advance how to compare the results found when a climatic model is used with the results obtained with the Basic Scenario, because the changes will be caused both by the increased temperature and by the different transport. It will nevertheless be possible to draw useful conclusions by performing runs over sufficiently long time-periods. The major problem is that the computational difficulties would be enormous when the fine discretization (10 km $\times$ 10 km surface cells) used in this paper should be preserved.

Finally, the problem will become even more challenging if the air pollution model is to be fully coupled with a climatic model in an attempt to study directly also the feed back from the increased pollution levels to the climatic changes. At present it is not possible to resolve computationally this problem on the whole European domain when *fine spatial resolution* is to be used. However, the computers are becoming more and more powerful and it will hopefully be possible to resolve the last two difficult problems in the near future.

Many more details connected to the topics discussed in this section can be found in [19,5]. Some other studies on future impacts of climate changes on air pollution can be found for example in [33–35] (see also the references given there).

4. Inter-annual variations of the concentrations of several pollutants

Several issues, which are not connected very strongly to the climatic changes, are studied in this section. The results presented in the next three sub-sections explain clearly (a) why it is necessary to run the model on a long time interval (Section 4.1), (b) what kind of results should be expected if concentrations only are compared (Section 4.2) and (c) why the model should be run on a large spatial domain (Section 4.3).

4.1. *Constant meteorology versus constant emissions*

The Basic Scenario is compared (a) with the scenario in which the emissions are kept constant (the emissions for year 1989 were used in all sixteen runs) and (b) with the scenario in which the meteorological conditions are kept constant (the meteorological conditions for year 1989 are used also for the remaining fifteen years). Some typical results are presented in Fig. 2. Measurement results are also given in Fig. 2.

The results obtained by using the Basic Scenario show clearly that (a) there are very considerable inter-annual variations of the concentrations and (b) there is a slight trend for decreasing of the concentrations at the end of the time-interval. The inter-annual variations are preserved also when the scenario with constant emissions is used, but the decreasing trend vanishes. The inter-annual variations disappear when the scenario with constant emissions is used, but the decreasing trend is preserved. It should be noted here that similar results were reported in [12,13,8].

The results that are presented in this sub-section as well as in the references given above show clearly that it is necessary to run the model on a long time interval in order to preserve both the inter-annual variations and the long-term trends.

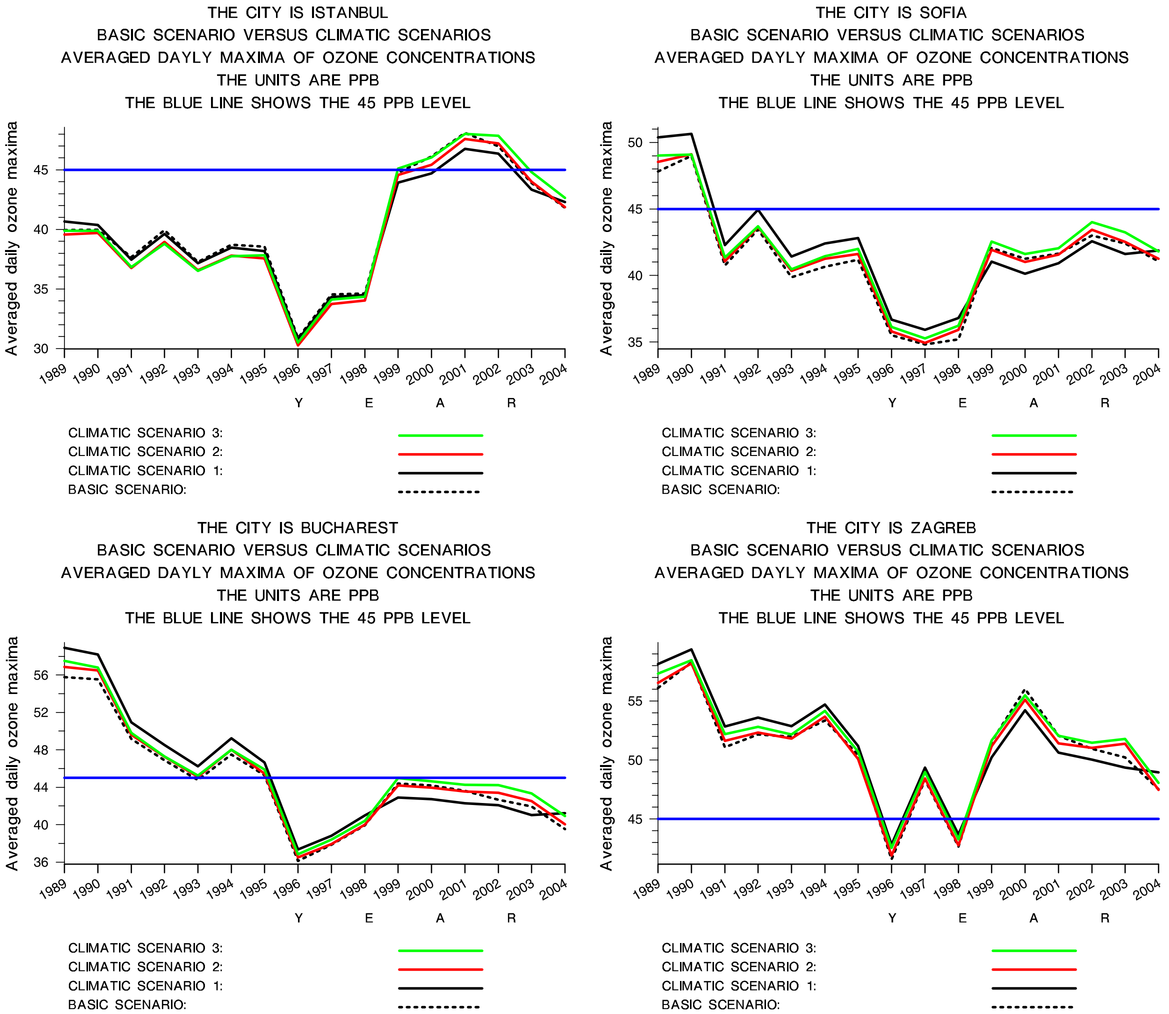

Fig. 3. Comparison of the Basic Scenario with the three climatic scenarios when averaged (for the period from April 1 to September 30) daily maxima of the ozone concentrations are studied.

4.2. Comparisons of the Basic Scenario with the three climatic scenarios

The Basic Scenario was extensively compared with the three climatic scenarios that were discussed in Section 3. Some results from this comparison are presented in Fig. 3. Many more results can be found in [12,13,8].

It is seen that (a) the averaged daily maxima of the ozone concentrations obtained when the climatic scenarios are used are often (but not always) greater than those obtained by the climatic scenarios and (b) the differences (between the averaged daily maxima of the ozone concentrations obtained with the climatic scenarios and those obtained with the Basic Scenario) are rather small. It will be shown in the next three sections that the second statement, (b), is not necessarily true when some quantities which might cause damages on plants, animals and human beings are considered instead of averaged concentrations. In the latter case the differences can be considerably larger.

The main conclusion is that it is much more relevant to consider not the annual means of the concentrations but directly the quantities (AOT40C, AOT40F and "bad days") which can be dangerous for our environment and, furthermore, to establish whether the critical levels for these quantities, which are established by the EU Directive [36], are exceeded or not.

4.3. Influence of the European emissions on the concentration levels in the Balkan Peninsula

The influence of the European emissions on the pollution levels in the Balkan countries was studied by performing two series of runs: (a) runs with the Basic Scenario where all European emission sources, including the emission sources in the Balkan Peninsula, are used and (b) runs in which all emission sources in the Balkan countries are set to zero. Let us mentioned

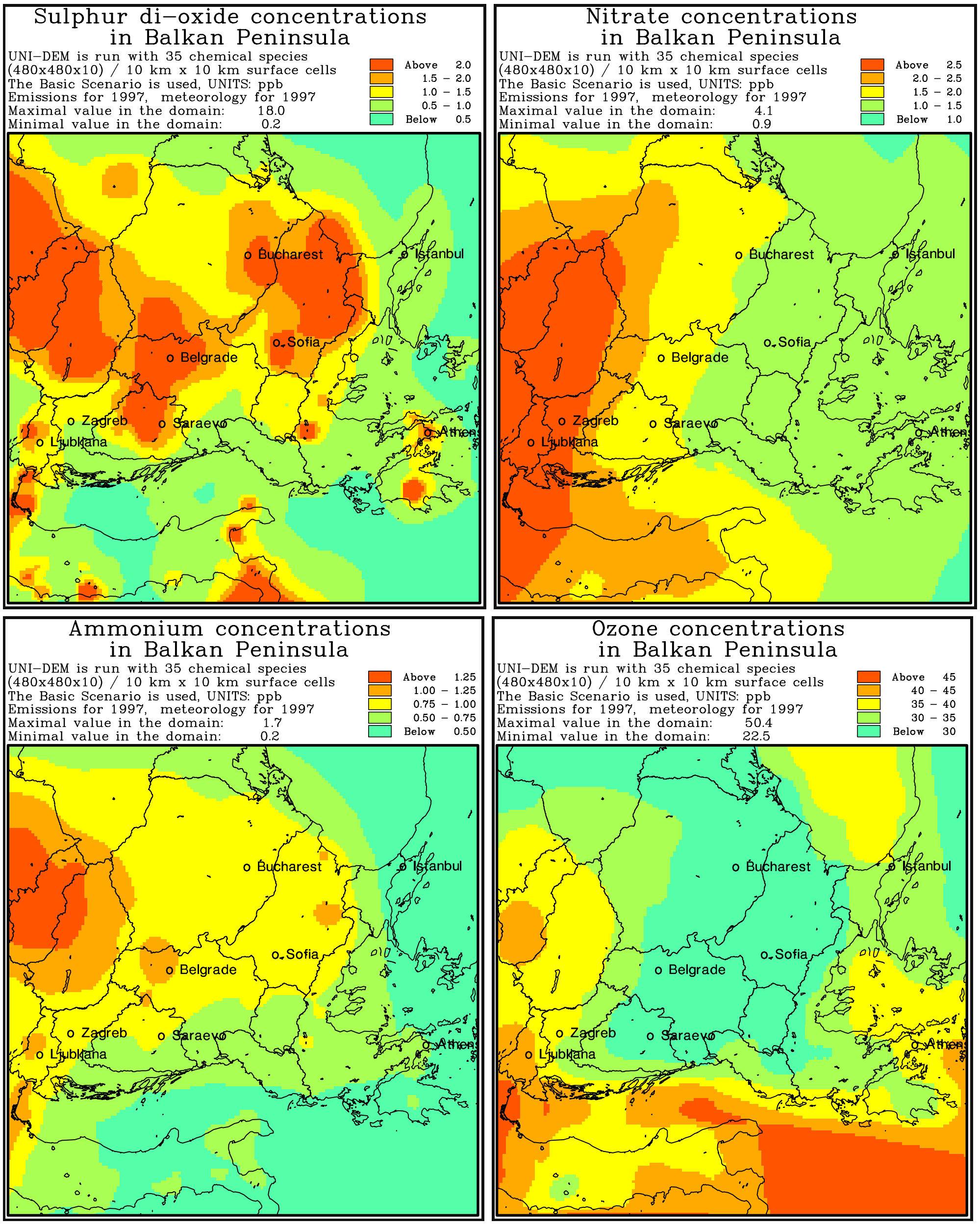

Fig. 4. Distribution of the concentrations of sulphur di-oxide (upper left-hand-side plot), nitrate (upper right-hand-side plot), ammonium (lower left-hand-side plot) and ozone (lower right-hand-side plot) in the Balkan Peninsula. The units are ppb.

some other studies of the climate change impact on pollution levels in Bulgaria had been performed in the last few years (see e.g. [37–40,14]).

The distribution of the concentrations of sulphur di-oxide, nitrate, ammonium and ozone in the studied in this paper area are given in Fig. 4. It is seen that while the sulphur di-oxide levels are rather high (especially in Bulgaria), the nitrate, ammonium and ozone levels in the Balkan Peninsula are relatively low.

The influence of the European emission sources on the pollution levels in the Balkan countries is shown in Fig. 5. The changes are given in percent. Denote by **A** the result at a given grid-point in the case where the scenario without emission sources from the Balkan countries is used. Denote by **B** the corresponding result from the Basic Scenario. Then the quantities **100 A**/**B** are given in the plots in Fig. 5.

Three important conclusions can be drawn from the plots in Fig. 5:

- The influence of the European emission sources on the sulphur di-oxide levels is relatively small. This is not a big surprise because the sulphur di-oxide levels in the Balkan Peninsula are rather high.

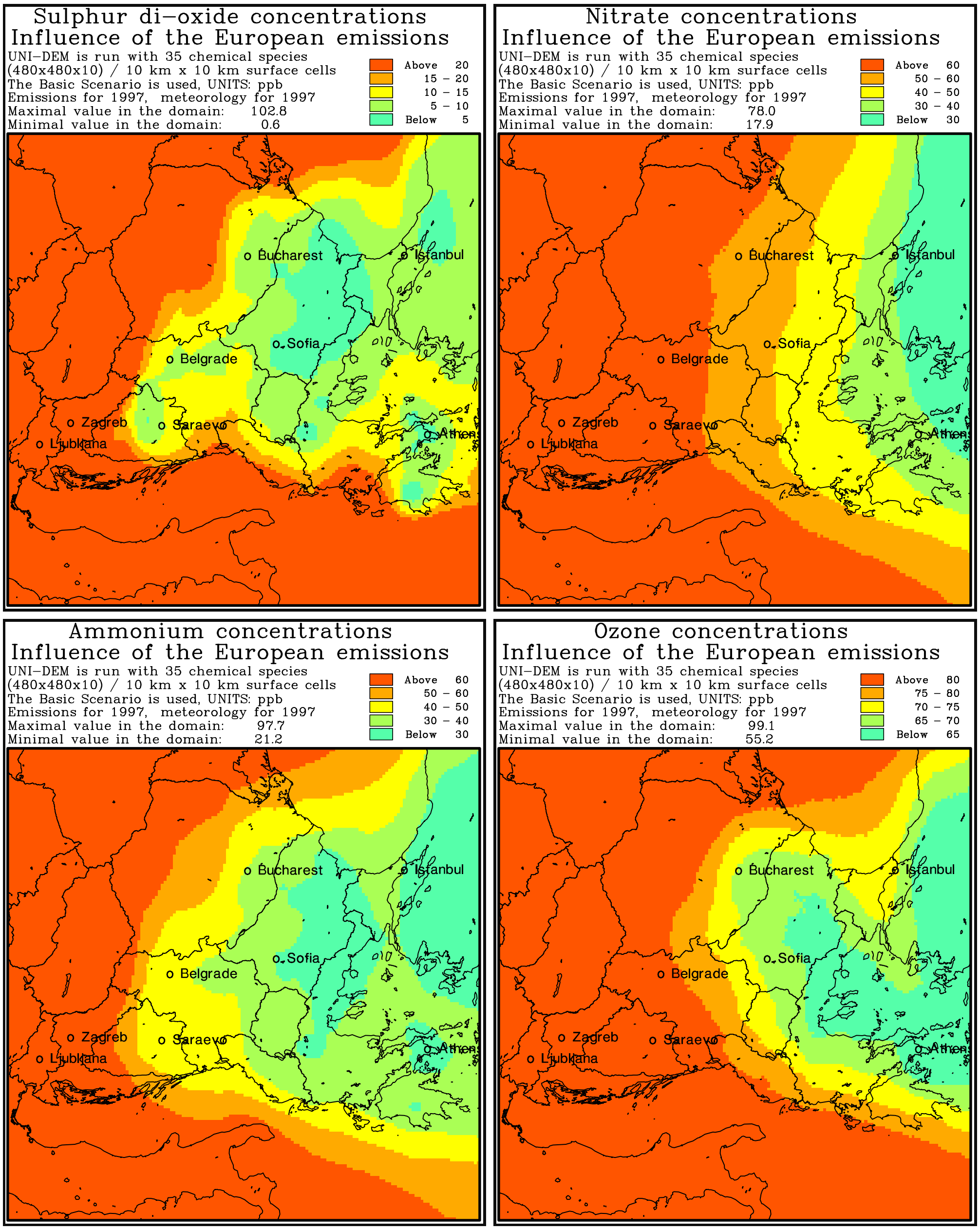

Fig. 5. Contributions of the European emission sources to the concentration levels of sulphur di-oxide (upper left-hand-side plot), nitrate (upper right-hand-side plot), ammonium (lower left-hand-side plot) and ozone (lower right-hand-side plot) in the Balkan Peninsula. The units are percent.

- The influence of the European emission sources on the nitrate and ammonium levels is considerably larger, while the influence on the ozone concentrations is very high.
- The influence of the European emission sources is greater in the Western and Northern parts of the Balkan Peninsula.

The fact that the influence of the European emission sources on the pollution levels is very big for some chemical species indicates that *the long-range transport* should properly be taken into account. This explains why it is always more preferable to use a large spatial domain also when limited areas of this domain are of interest.

5. Variations of the AOT40 values 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 [6]):

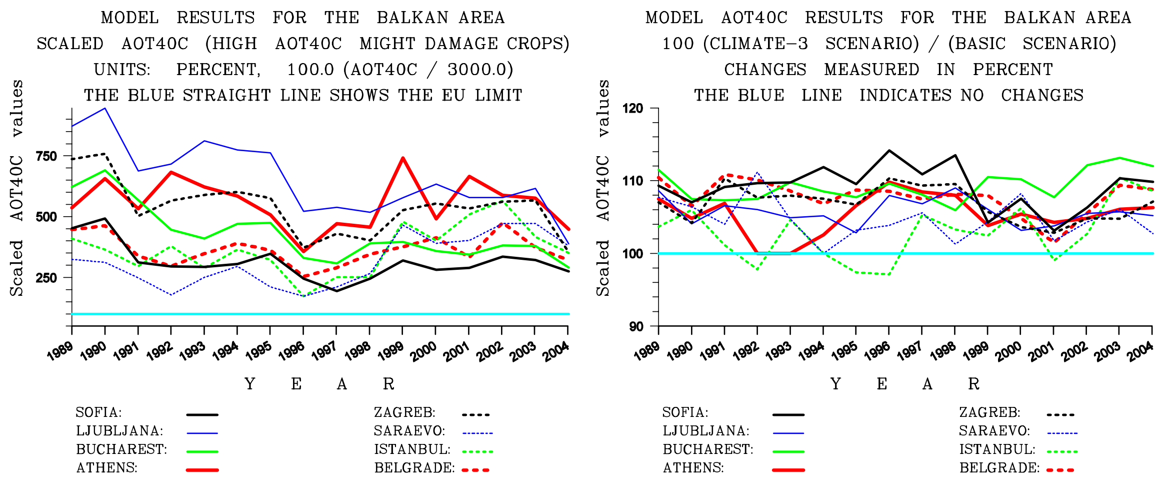

Fig. 6. Variations of AOT40C values at eight major cities in the Balkan Peninsula computed by UNI-DEM: (a) when the Basic Scenario is used (the left-hand-side plot) and (b) changes when the Climate 3 Scenario is applied instead of the Basic Scenario (the right-hand-side plot).

$$AOT40C = \sum_{\mathbf{i=1}}^{\mathbf{N}} \mathbf{max}\,(\mathbf{c_i} - \mathbf{40}, \mathbf{0})\ , \tag{6}$$

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 $\mathbf{i} \in \{\mathbf{1},\ \mathbf{2}, \ldots, \mathbf{N}\}$.

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, [36].

Some results are presented in Fig. 6. In the left-hand-side plot of Fig. 6 it is shown by how many percent the critical level for AOT40C is exceeded in the neighborhood of eight major cities in the Balkan Peninsula. The increases of the AOT40C values (in percent) when the Climatic Scenario 3 is used instead of the Basic Scenario are given in the right-hand-side plot of Fig. 6.

Several conclusions can be drawn from the results presented in Fig. 6 (similar results were obtained in many other comparisons):

- The AOT40C values exceed very substantially the limit prescribed in the EU Directive [36] (by factors up to nine).
- The application of the Climate 3 Scenario leads in general to an increase of the AOT40C values. Only in Istanbul were decreases obtained for a few years. However, the decreases are very small (the greatest one being only 2.8%).
- The increases of the AOT40C values are not very large, but still considerable (the greatest increase being 14.1%).

Results for the whole studied area are given in Fig. 7. These results are for 2004, but rather similar results for all other years were obtained (see [12,8,5]).

The following conclusions can be drawn from Fig. 7:

- The EU critical levels are exceeded in the whole Balkan Peninsula (see the upper left-hand-side plot in Fig. 7). The AOT40C levels are greatest in the Western and Southern parts of the area.
- The application of the Climate 3 Scenario leads in general to an increase of the AOT40C levels in comparison with the Basic Scenario (see the lower left-hand-side plot in Fig. 7). The increases are greatest in the Eastern part of the area.
- The scenario with increased biogenic emissions (which are discussed in detail in [22] and are based on the statements of some scientists that the presently used biogenic emissions are strongly underestimated; see, for example, [41,42]) leads to a very considerable increase of the AOT40C values (see the upper right-hand-side plot in Fig. 7). The increases of the AOT40C levels (when the scenario with increased biogenic emissions is compared with the Basic Scenario) are greater than 15% in nearly all areas of the Balkan Peninsula; excluding only (a) some narrow areas that are close to the Adriatic Sea, (b) the Southern part of Greece and (c) the area around the metropolitan city of Istanbul.
- Also the combined application of the Climatic 3 Scenario and the scenario with increased biogenic emissions leads to big additional increases of the AOT40C levels in the Balkan Peninsula (compared again with the Basic Scenario). The increases are greater than 15% in a large part of the studied domain (see the lower right-hand-side plot in Fig. 7). However the areas where the increases are less than 15% are greater than the corresponding areas when the scenario with increased biogenic

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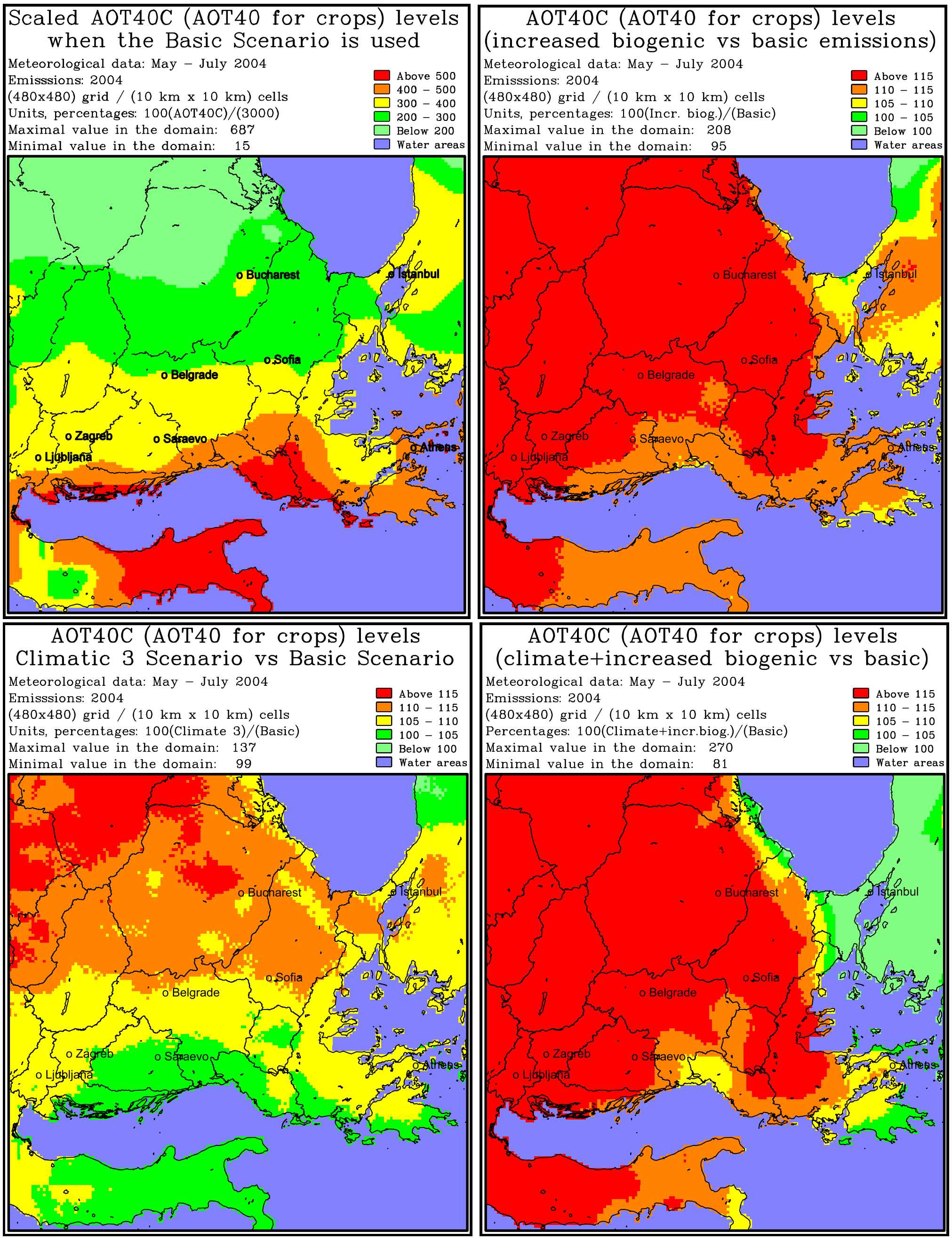

Fig. 7. AOT40C levels in the Balkan Peninsula computed by using different scenarios. The fact that the AOT40C values exceed the established critical levels is shown in the left-hand-side plot. The changes of the AOT40C levels in percent are given in the other three plots when three scenarios are compared with the Basic Scenario.

emissions is compared with the Basic Scenario (compare the upper and the lower right-hand-side plots in Fig. 7). In a few areas of the Balkan Peninsula the AOT40C values are even decreased when the combination of the Climatic 3 Scenario and the scenario with increased biogenic emissions is used instead of the Basic Scenario.

The last conclusion was a little surprising (greatest increases were expected when the Climatic 3 Scenario and the scenario with increased biogenic emissions was applied). However note that the greatest increase in the studied domain is higher when the combination of the Climatic 3 Scenario and the scenario with increased biogenic emissions is used instead of the scenario where the biogenic emissions are increased the values being 270 and 208 respectively.

The most important conclusion from the results presented in the two lower plots of Fig. 7 is that the sensitivity of the AOT40C values to changes of the biogenic emissions is considerably greater than that due to the climatic changes. Therefore,

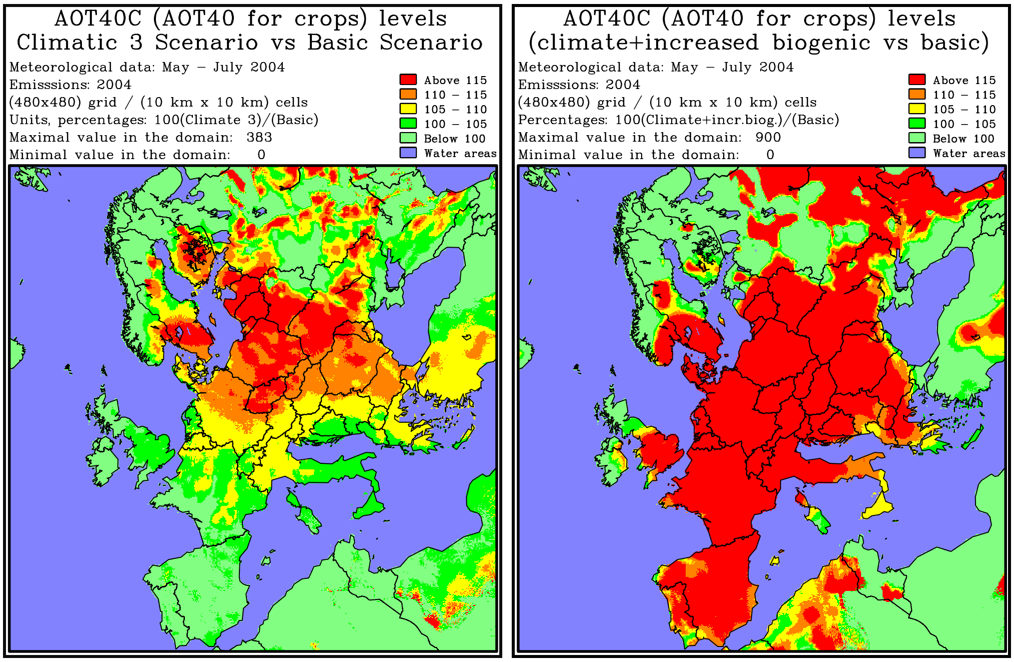

Fig. 8. Ratios of AOT40C values in Europe that are computed by comparing different scenarios. Scenario Climate 3 is compared with the Basic Scenario in the left-hand-side plot. Scenario Climate 3 combined with increased biogenic emissions is compared again with the Basic Scenario in the right-hand-side plot.

it is reasonable to ask whether this tendency holds not only for the Balkan Peninsula, but also for the whole of Europe. The results, which are shown in Fig. 8, indicate that this is precisely the case for nearly the whole of Europe (excluding the Northern parts of Scandinavia as well as some areas in Eastern Europe and Northern Africa).

6. Variations of the AOT40 values 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 [12,22,5]):

$$AOT40F = \sum_{\mathbf{i}=\mathbf{1}}^{\mathbf{N}} \mathbf{max}\left(\mathbf{c_i} - \mathbf{40}, \mathbf{0}\right), \tag{7}$$

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 $\mathbf{i} \in \{\mathbf{1}, \mathbf{2}, \ldots, \mathbf{N}\}$.

If AOT40F exceeds 10 000 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 [36].

Some results are given in Fig. 9. In the left-hand-side plot of Fig. 9 it is shown by how many percent the critical level for AOT40F is exceeded in the neighborhood of eight major cities in the Balkan Peninsula. The increases of the AOT40F values (in percent) when the Climatic Scenario 3 is used instead of the Basic Scenario are given in the right-hand-side plot of Fig. 9.

Several conclusions can be drawn from the results presented in Fig. 9 (similar results were obtained in many other comparisons):

- The AOT40F values exceed rather substantially the limit prescribed in the EU Directive [36] (by not as much as the AOT40C values; compare the plots in Fig. 9 with the plots in Fig. 6).
- The application of the Climate 3 Scenario leads also in this case to an increase of the AOT40F values. Only in Istanbul were decreases obtained for some years. However, the decreases are very small (compare again the plots in Fig. 9 with the plots in Fig. 6).
- The increase of the AOT40F values is not very large when the Climatic Scenario 3 is used, but it is still considerable.

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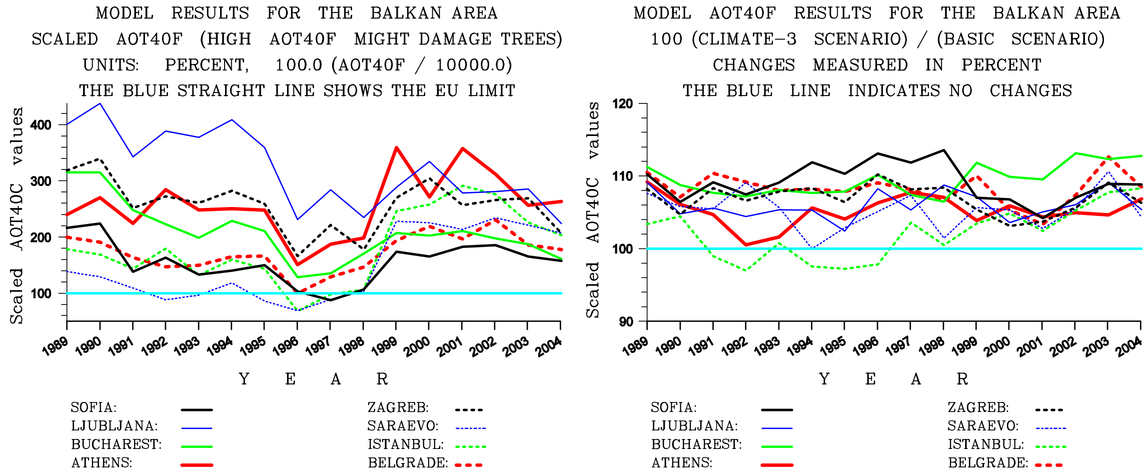

Fig. 9. Variations of AOT40F values at eight major cities in the Balkan Peninsula computed by UNI-DEM: (a) when the Basic Scenario is used (the left-hand-side plot) and (b) changes when the Climate 3 Scenario is applied instead of the Basic Scenario (the right-hand-side plot).

Results for the whole studied area are given in Fig. 10. These results are for 2004, but rather similar results for all other years were obtained (see [12,8,5]).

The conclusions, which can be drawn from Fig. 10, are nearly identical to those drawn in the previous section. There is no need to repeat all these conclusions. It is quite sufficient to emphasize the two most important of them:

- The sensitivity of the AOT40F levels to changes of the biogenic emissions is considerably greater than the sensitivity of these levels to the climatic changes.
- The EU critical values for AOT40F are not exceeded as much as the critical values for AOT40C. This is not a very great surprise because the critical value for AOT40F (10 000 ppb.hours) is more than three times greater than the corresponding values for AOT40C (3000 ppb.hours), while the length of the time-period is only doubled.

In connection with the first of these two important conclusions, it is again worthwhile to check whether this conclusion holds not only for the Balkan Peninsula, but also for the whole of Europe. The results shown in Fig. 11 indicate that indeed the sensitivity of the AOT40F values to changes of the biogenic emissions is considerably greater than those due to the climatic changes for the most of Europe (excluding, as in the previous section, the Northern parts of Scandinavia as well as some areas in Eastern Europe and Northern Africa).

7. Variations of the numbers of “bad days”

Assume that $\mathbf{c}_{\mathbf{max}}$ 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 **A**. If the condition $\mathbf{c}_{\mathbf{max}} > \mathbf{60}$ 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 **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 2002 [36]:

- *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).

Some results are presented in Fig. 12. In the left-hand-side plot of Fig. 12 the numbers of “bad days” in the neighborhood of eight major cities in the Balkan Peninsula are shown. The increases of the numbers of “bad days” (in percent) when the Climatic Scenario 3 is used instead of the Basic Scenario are given in the right-hand-side plot of Fig. 12.

Several conclusions can be drawn from the results presented in Fig. 12 (similar results were obtained in many other comparisons):

- The numbers of “bad days” exceed rather substantially the limit prescribed in the EU Directive [36] (up to nearly three times at some sites).
- The application of the Climate 3 Scenario leads in general to some increase of the numbers of “bad days”. Only in Sarajevo and Istanbul decreases were obtained for some years. However, the decreases are relatively small.
- The increase of the numbers of “bad days” is in general not very large when the Climatic Scenario 3 is used, but it can still be rather considerable (up to 30% in some cases).

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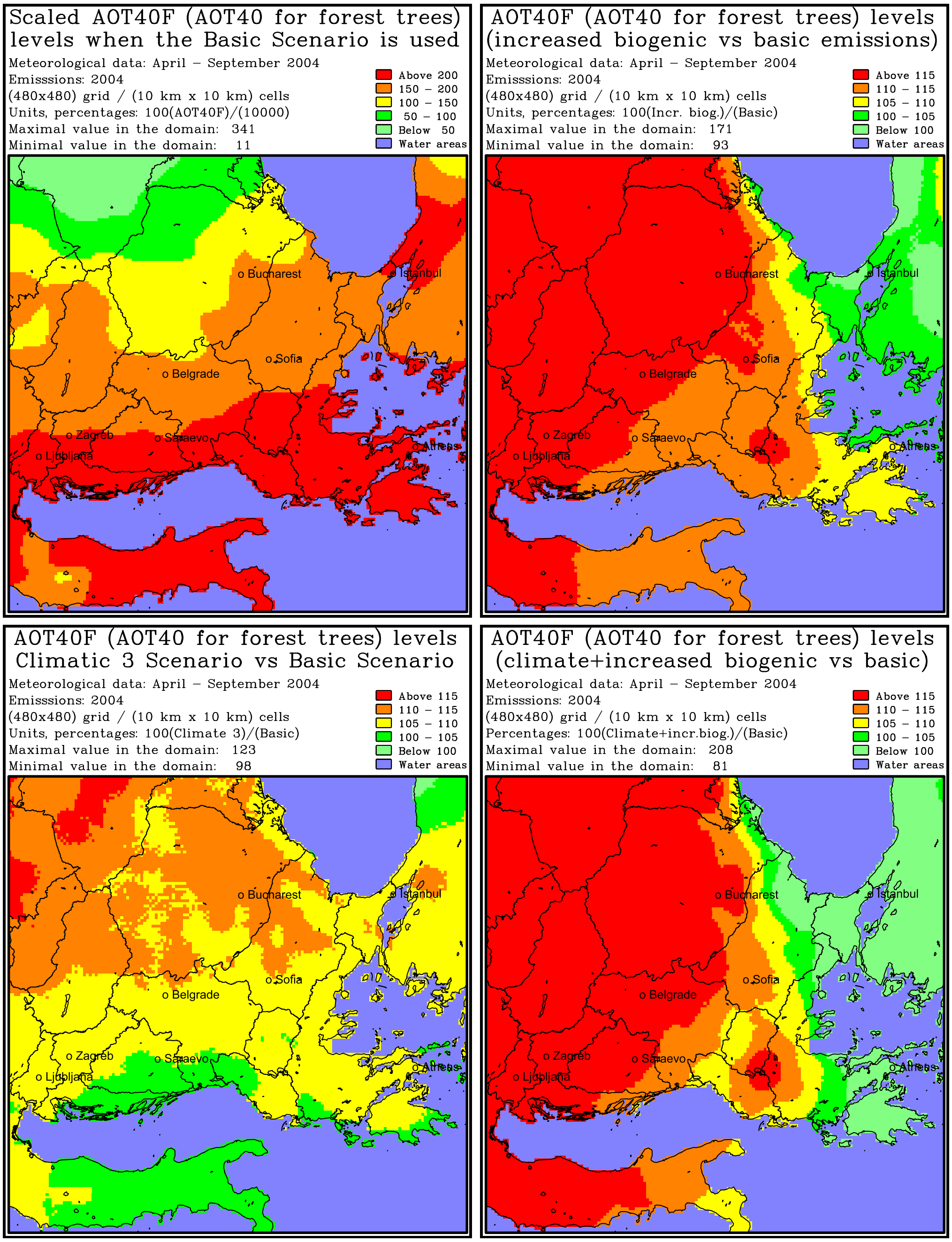

Fig. 10. AOT40F levels in the Balkan Peninsula computed by using different scenarios. The fact that the AOT40F values exceed very often the established critical levels is shown in the left-hand-side plot. The changes of the AOT40F levels in percent are given in the other three plots when three scenarios are compared with the Basic Scenario.

Results for the whole studied area are given in Fig. 13. These results are for 2004, but rather similar results for all other years were obtained (see [12,8,5,19]).

The conclusions, which can be drawn from Fig. 13, are rather similar to the corresponding conclusions in the previous two sections:

- The EU critical levels are exceeded in nearly the whole Balkan Peninsula, excluding parts of Romania and Bulgaria (see the upper left-hand-side plot in Fig. 13). The numbers of "bad days" are greatest in the Western and Southern parts of the area as well as in the domain around Istanbul.
- The application of the Climate 3 Scenario leads in general to an increase of the numbers of bad days (see the lower left-hand-side plot in Fig. 13). The increases are greatest in the Eastern part of the area.

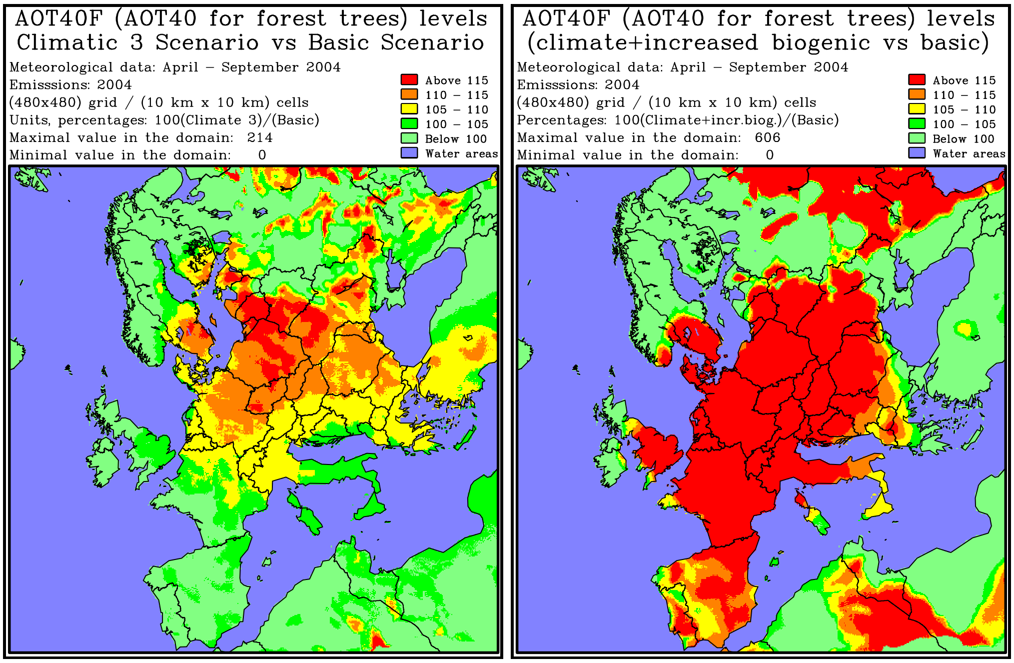

Fig. 11. Ratios of AOT40F values in Europe, which are computed by comparing different scenarios. Scenario Climate 3 is compared with the Basic Scenario in the left-hand-side plot. Scenario Climate 3 combined with increased biogenic emissions is compared again with the Basic Scenario in the right-hand-side plot.

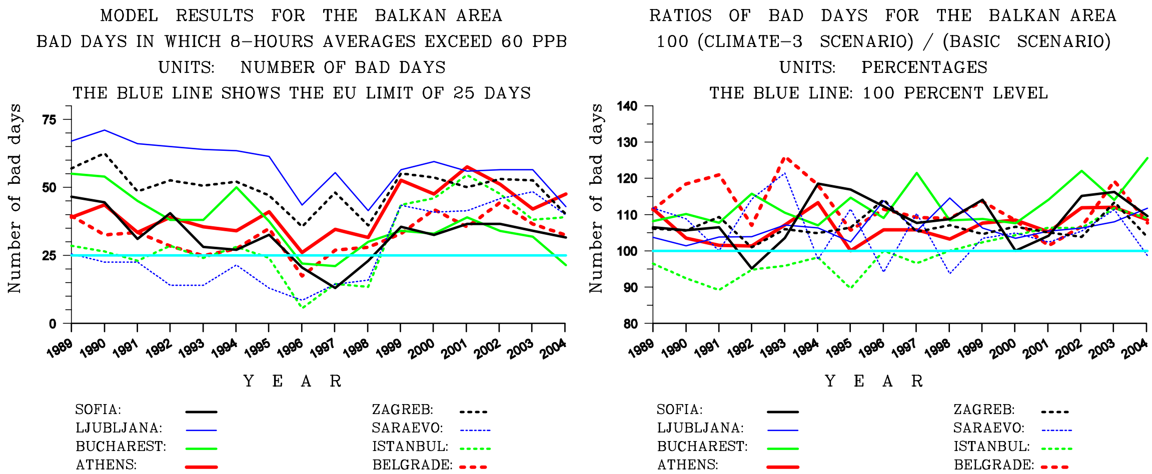

Fig. 12. Variations of "bad days" at eight major cities in the Balkan Peninsula computed by UNI-DEM: (a) when the Basic Scenario is used (the left-hand-side plot) and (b) changes (given in percent) when the Climate 3 Scenario is applied instead of the Basic Scenario (the right-hand-side plot).

- The scenario with increased biogenic emissions leads to a very considerable increase of the numbers of bad days (see the upper right-hand-side plot in Fig. 13). The increases of the numbers of bad days (when the scenario with increased biogenic emissions is compared with the Basic Scenario) are greater than 15% in nearly all areas of the Balkan Peninsula (see again the upper right-hand-side plot in Fig. 13).
- Also the combined application of the Climatic 3 Scenario and the scenario with increased biogenic emissions lead to big additional increases of the numbers of bad days in the Balkan Peninsula (compared again with the Basic Scenario). The increases are greater than 15% in a large part of the studied domain excluding some areas in the Southern and Eastern part of the Balkan Peninsula (see the lower right-hand-side plot in Fig. 13), where the increase is not as big as those shown in the upper right-hand-side plot in Fig. 13.

The last conclusion was a little surprising (greatest increases were expected when the Climatic 3 Scenario and the scenario with increased biogenic emissions was applied). The results, which are presented in Fig. 14, show clearly that in many areas of the remaining part of Europe the increases of the numbers of bad days when the climatic scenario is combined with

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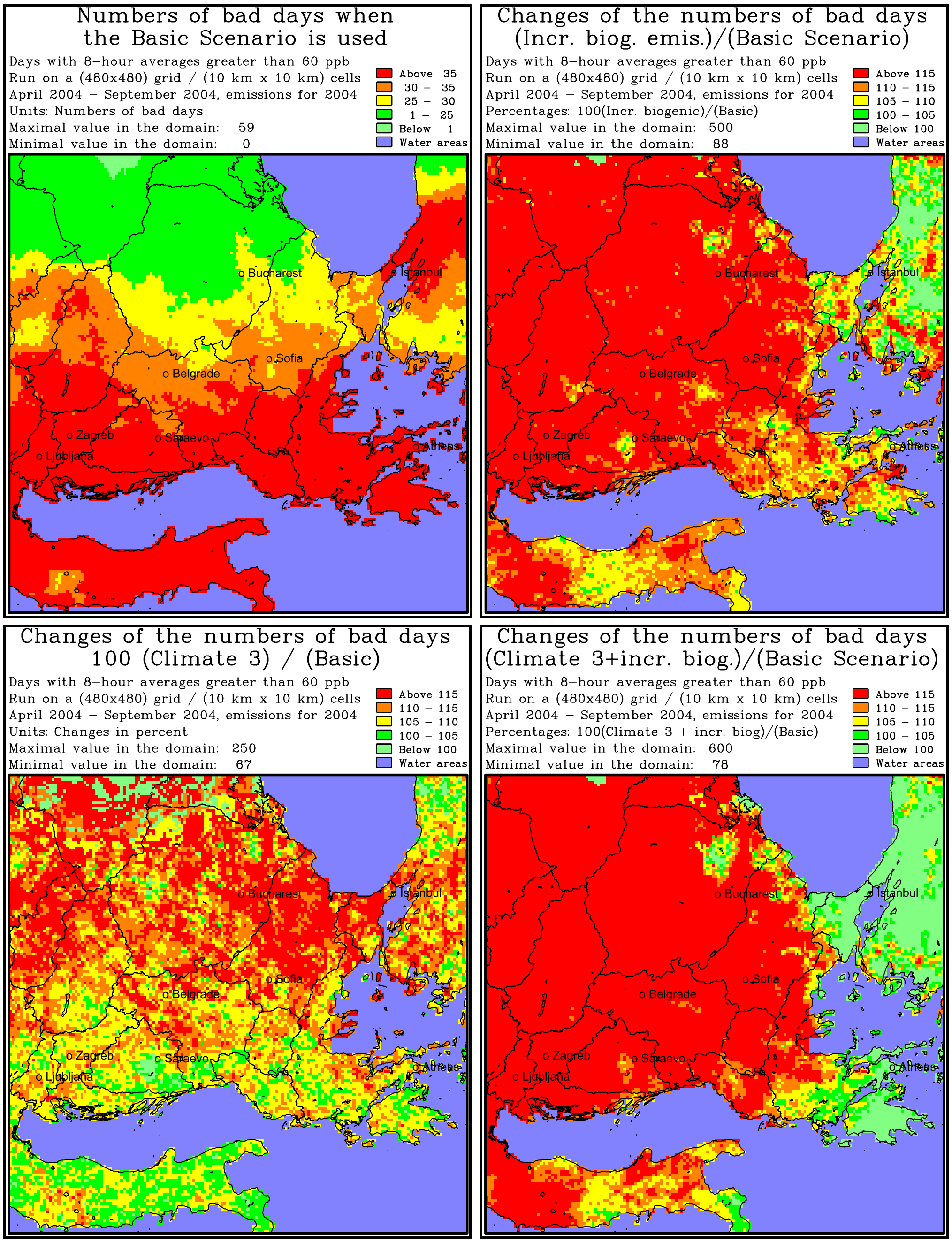

Fig. 13. Information about numbers of bad days in the Balkan Peninsula computed by using different scenarios. The numbers of the bad days obtained with the Basic Scenario are shown in the left-hand-side plot. The changes of the numbers of bad days are given (in percent) in the other three plots when three scenarios are compared with the Basic Scenario.

the scenario with increased biogenic emissions are much bigger than the corresponding numbers obtained when only the climatic scenario is applied.

8. Concluding remarks and plans for future research

Many conclusions were drawn in the previous sections immediately after presenting the results. It is necessary to emphasize two general conclusions here:

- The prescribed by the EU directives critical levels (as, for example, the directive in [36]) are exceeded in nearly all countries of the Balkan Peninsula.

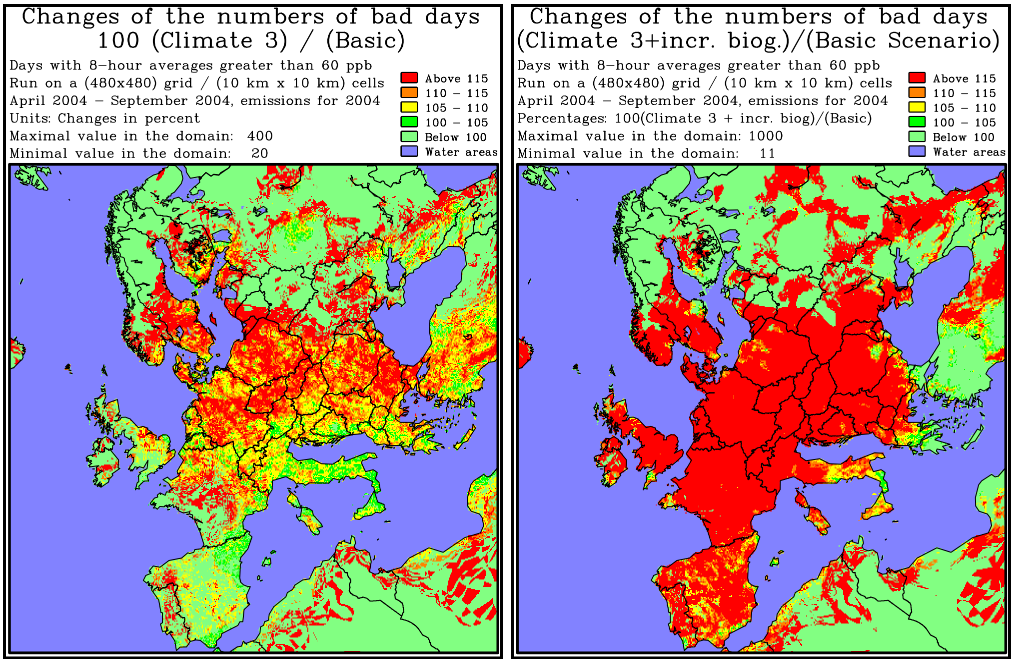

Fig. 14. Ratios of numbers of bad days in Europe that are computed by comparing different scenarios. Scenario Climate 3 is compared with the Basic Scenario in the left-hand-side plot. Scenario Climate 3 combined with increased biogenic emissions is compared again with the Basic Scenario in the right-hand-side plot.

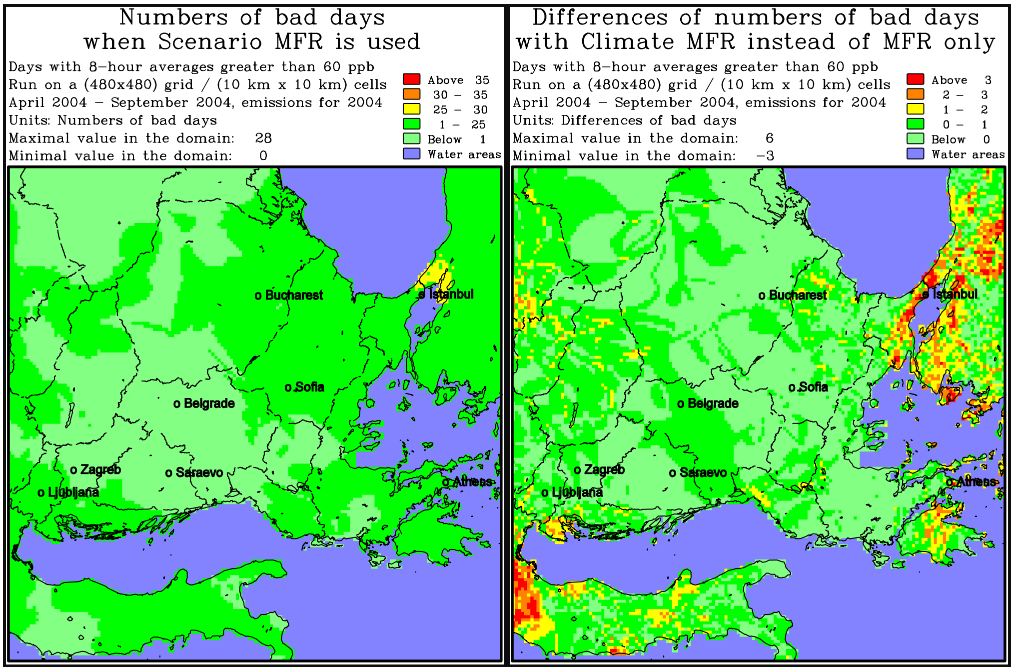

Fig. 15. Numbers of "bad days" in the Balkan Peninsula, which are computed by using the IIASA MFR (Maximum Feasible Reductions) Scenario proposed in [28]. Numbers of "bad days" are given on the left-hand-side plot. Differences (numbers of "bad days obtained by the Climatic Scenario 3 combined with the MFR Scenario) minus (numbers of "bad days" obtained only by the MFR scenario) are given in the right-hand-side plot.

- The policy-makers should take into account the global warming effect during the preparation of strategies for keeping the pollution levels under the prescribed critical levels.

Reductions of the human-made (anthropogenic) emissions are normally suggested as a means for decreasing the pollution levels. Therefore, it is interesting to find the answer of the following question: *By how much should the amount of the anthropogenic emissions be reduced in order to keep the pollution levels under the prescribed in* [36] *critical levels?* Some experiments indicate that the reductions proposed in the IIASA MFR (Maximum Feasible Reductions) Scenario would give an answer to this question. Some results obtained by using this scenario are given in Fig. 15.

The numbers of "bad days" are reduced to zero (i.e., the long-term aim in the EU Directive is satisfied) in a very large part of the Balkan Peninsula when the IIASA MFR Scenario from [28] is used (see the left-hand-side plot in Fig. 15). Also the differences between the numbers of "bad days" obtained by using the combination of the Climatic Scenario 3 and the IIASA MFR Scenario (instead of the IIASA MFR Scenario alone) are rather small, not greater than six (see the right-hand-side plot in Fig. 15). Moreover, in many areas of the Balkan Peninsula the use of the combined scenario leads in fact to some reductions (very small) of the numbers of "bad days".

The results in Fig. 15 indicate that the IIASA MFR Scenario seems to be very efficient (at least for the area of the Balkan Peninsula) in the attempts to reduce some ozone pollution levels. However, the reductions of the human-made (anthropogenic) emissions made in the development of this scenario are perhaps too big. For example, the $\mathbf{NO}_x$ emissions in Slovenia for 1990 are decreased by 87%, while the corresponding **VOC** emissions are reduced by 78% when this scenario is used. The authors of the Seventh Interim Report [28] called this scenario "Maximum Feasible Reduction", but it is not very clear whether such big reductions are really feasible (they may become feasible only if some very great technological achievements are made in the near future).

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References

[1] V. Alexandrov, W. Owczarz, P.G. Thomsen, Z. Zlatev, Parallel runs of large air pollution models on a grid of SUN computers, Mathematics and Computers in Simulation 65 (2004) 557–577.

[2] M. Roemer, M. Beekman, R. Bergsröm, G. Boersen, H. Feldmann, F. Flatøy, C. Honore, J. Langner, J.E. Jonson, J. Matthijsen, M. Memmesheimer, D. Simpson, P. Smeets, S. Solberg, D. Stevenson, P. Zandveld, Z. Zlatev, Ozone trends according to ten dispersion models, GSF—National Research Center for Environment and Health, International Scientific Secretariat, ISS, EUROTRAC-2, Münich, 2004. Available also at: http://www.mep.tno.nl/eurotrac/EUROTRAC-trends.pdf.

[3] Z. Zlatev, Impact of future climate changes on high ozone levels in European suburban areas, Climatic Change 101 (2010) 447–483.

[4] Z. Zlatev, I. Dimov, Tz. Ostromsky, G. Geernaert, I. Tzvetanov, A. Bastrup-Birk, Calculating losses of crops in Denmark caused by high ozone levels, Environmental Modeling and Assessment 6 (2001) 35–55.

[5] Z. Zlatev, D. Syrakov, A fine resolution modelling study of pollution levels in Bulgaria. Part 1: SO_x and NO_x pollution, International Journal of Environment and Pollution 22 (1–2) (2004) 186–202.

[6] Z. Zlatev, D. Syrakov, A fine resolution modelling study of pollution levels in Bulgaria. Part 2: high ozone levels, International Journal of Environment and Pollution 22 (1–2) (2004) 203–222.

[7] Z. Zlatev, Computer Treatment of Large Air Pollution Models, Kluwer, Academic Publishers, Dordrecht, Boston, London, 1995.

[8] Z. Zlatev, L. Moseholm, Impact of climate changes on pollution levels in Denmark, Environmental Modelling 217 (2008) 305–319.

[9] S. Abdalmogith, R.M. Harrison, Z. Zlatev, Intercomparison of inorganic aerosol concentrations in the UK with predictions of the Danish Eulerian model, Journal of Atmospheric Chemistry 54 (2006) 43–66.

[10] C. Ambelas Skjøth, A. Bastrup-Birk, J. Brandt, Z. Zlatev, Studying variations of pollution levels in a given region of Europe during a long time-period, Systems Analysis Modelling Simulation 37 (2000) 297–311.

[11] A. Bastrup-Birk, J. Brandt, I. Uria, Z. Zlatev, Studying cumulative ozone exposures in Europe during a 7-year period, Journal of Geophysical Research 102 (1997) 23917–23935.

[12] P. Csomós, R. Cuciureanu, G. Dimitriu, I. Dimov, A. Doroshenko, I. Faragó, K. Georgiev, Á. Havasi, R. Horváth, S. Margenov, Tz. Ostromsky, V. Prusov, D. Syrakov, Z. Zlatev, Impact of climate changes on pollution levels in Europe, Final Report for a NATO Linkage Project, Grant 980505, 2006. Available at: http://www.cs.elte.hu/~faragois/NATO.pdf, http://www2.dmu.dk/atmosphericenvironment/Climate%20and%20Pollution, http://www.umfiasi.ro/NATO.pdf, http://www.personal.rdg.ac.uk/~sis04itd/MyPapers/climatic_scenarios_NATO.pdf, http://www.softasap.net/ips/climatic_scenarios_NATO.pdf, http://www.meteo.bg/bulair/NATO.pdf.

[13] I. Dimov, G. Geernaert, Z. Zlatev, Impact of future climate changes on high pollution levels, International Journal of Environment and Pollution 32 (2) (2008) 200–230.

[14] Z. Zlatev, Application of predictor–corrector schemes with several correctors in solving air pollution problems, BIT 24 (1984) 700–715.

[15] Z. Zlatev, Massive data sets issues in air pollution modelling, in: J. Abello, P.M. Pardalos, M.G.C. Resende (Eds.), Handbook on Massive Data Sets in Science and Engineering, Kluwer, Academic Press, Dordrecht, Boston, London, 2002, pp. 1169–1220.

[16] Z. Zlatev, I. Dimov, Computational and Numerical Challenges in Environmental Modelling, Elsevier, Amsterdam, 2006.

[17] Á. Havasi, L. Bozó, Z. Zlatev, Model simulation on transboundary contribution to the atmospheric sulfur concentration and deposition in Hungary, Időjárás 105 (2001) 135–144.

[18] Á. Havasi, Z. Zlatev, Trends of Hungarian air pollution levels on a long time-scale, Atmospheric Environment 36 (2002) 4145–4156.

[19] Z. Zlatev, Á. Havasi, I. Faragó, Influence of climatic changes on pollution levels in Hungary and its surrounding countries, Atmosphere 2 (2011) 201–221.
[20] R.M. Harrison, Z. Zlatev, C.J. Ottley, A comparison of the predictions of an Eulerian atmospheric transport chemistry model with experimental measurements over the North Sea, Atmospheric Environment 28 (1994) 497–516.
[21] H. Hass, M. van Loon, C. Kessler, R. Stern, J. Mathijsen, F. Sauter, Z. Zlatev, J. Langner, V. Foltescu, M. Schaap, Aerosol modelling: results and intercomparison from European regional-scale modelling systems, GSF—National Research Center for Environment and Health, International Scientific Secretariat, ISS, EUROTRAC-2, Münich, 2004. This report is also available at: http://www.trumf.fu-berlin.de/veranstaltungen/events/glream/GLOREAM_PMmodel-comparison.pdf.
[22] G. Geernaert, Z. Zlatev, Studying the influence of the biogenic emissions on the AOT40 levels in Europe, International Journal of Environment and Pollution 23 (1–2) (2004) 29–41.
[23] B. Lübkert, W. Schöpp, The OECD-map emission inventory for, and in Western Europe, Report No. WP-89-082, International Institute for Applied Systems and Analysis, IIASA, Laxenburg, Austria, 1989.
[24] D. Simpson, A. Guenther, C.N. Hewitt, R. Steinbrecher, Biogenic emissions in Europe: I. Estimates and uncertainties, Journal of Geophysical Research 100 (1995) 22875–22890.
[25] C. Anastasi, L. Hopkinson, V.J. Simpson, Natural hydrocarbon emissions in the United Kingdom, Atmospheric Environment, Part A 25 (1991) 1403–1408.
[26] EMEP: Emission Data: Status Report, EMEP/MSC-W Report 1/99, July 1999, Meteorological Synthesizing Centre-West, Norwegian Meteorological Institute, P.O. Box 43-Blindern, N-0313 Oslo 3 Norway, 1999.
[27] EMEP Home Web-page: http://www.emep.int/index_data.html, 2006.
[28] M. Amann, I. Bertok, J. Cofala, F. Gyarfas, C. Heyes, Z. Klimont, M. Makowski, W. Schöpp, S. Syri, Cost-effective control of acidification and ground-level ozone, Seventh Interim Report, International Institute for Applied System Analysis, IIASA, A-2361 Laxenburg, Austria, 1999.
[29] Z. Zlatev, Partitioning ODE systems with an application to air pollution models, Computers and Mathematics with Applications 42 (2001) 817–832.
[30] O. Hertel, C. Ambelas Skjøth, L.M. Frohn, E. Vignati, J. Frydendall, G. de Leeuw, U. Schwarz, S. Reis, Assessment of the atmospheric nitrogen and sulphur inputs into the North Sea using a Lagrangian model, Physics and Chemistry of the Earth 27 (2002) 1507–1515.
[31] Climate Change: The Physical Science Basis. Contribution of the Working Group I to the Fourth Assessment Report of IPCC (Intergovernmental Panel on Climate Change), Cambridge University Press, Cambridge, New York, Melbourne, Madrid, Cape Town, 2007.
[32] J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, C.A. Johnson (Eds.), Climate Change 2001: The Scientific Basis, Cambridge University Press, Cambridge, New York, Melbourne, Madrid, Cape Town, 2001.
[33] M.L. Bell, R. Goldberg, C. Hogrefe, P.L. Kinney, K. Knowlton, B. Lynn, J. Rosenthal, C. Rosenzweig, J.A. Patz, Climate change, ambient ozone, and health in 50 US cities, Climatic Change 82 (2007) 61–76.
[34] A. Carvalho, A. Monteiro, S. Solman, A.I. Miranda, C. Borrego, Climate-driven changes in air quality over Europe by the end of the 21st century, with special reference to Portugal, Environmental Science and Policy 13 (2010) 445–458.
[35] M.Z. Jacobson, On the causal link between carbon dioxide and air pollution mortality, Geophysical Research Letters 35 (2008) L03809. http://dx.doi.org/10.1029/2007GL031101.
[36] European Parliament Directive 2002/3/EC of the European Parliament and the Council of 12 February 2002 relating to ozone in ambient air, Official Journal of the European Communities L67 (2002) 14–30.
[37] D. Syrakov, M. Prodanova, N. Miloshev, K. Ganev, G. Jordanov, V. Spiridonov, A. Bogatchev, E. Katragkou, D. Melas, A. Poupkou, K. Markakis, Climate Change Impact Assessment of Air Pollution Levels in Bulgaria, in: LNCS, vol. 5910, Springer, 2009, pp. 538–546.
[38] D. Syrakov, V. Spiridonov, K. Ganev, M. Prodanova, A. Bogachev, N. Miloshev, K. Slavov, First Results of SEE-GRID-SCI Application CCIAQ, in: LNCS, vol. 6046, 2010, pp. 215–223.
[39] D. Syrakov, K. Ganev, M. Prodanova, N. Miloshev, G. Jordanov, G. Gadjev, A. Todoriva, Climate change impact assessment of air quality over Bulgaria, SEE-GRID-SCI USER FORUM, Istanbul, December 2009, pp. 95–103. ISBN: 978-975-403-510-0.
[40] D. Syrakov, V. Spiridonov, M. Prodanova, K. Ganev, A. Bogatchev, K. Slavov, N. Miloshev, G. Jordanov, Model estimates for the regional climate changes and its impact on the air quality in Bulgaria, Bulgarian Journal of Meteorology and Hydrology 16 (1) (2011) 17–29.
[41] V.S. Bouchet, R. Laprise, E. Torlaschi, J.C. McConnel, Studying ozone climatology with a regional climate model, 1. Model description and evaluation, Journal of Geophysical Research 104 (1999) 30351–30371.
[42] V.S. Bouchet, R. Laprise, E. Torlaschi, J.C. McConnel, D.A. Plummer, Studying ozone climatology with a regional climate model, 2. Climatology, Journal of Geophysical Research 104 (1999) 30373–30385.