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# CLIMATE CHANGE IMPACT ON THE AIR QUALITY: THE PORTUGUESE CASE

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## ABSTRACT

The changes in greenhouse gases and aerosols emissions are expected to lead to regional and global changes in temperature, precipitation, and other climate variables. The degree to which human conditions and the natural environment are vulnerable to the potential effects of climate change is a key concern for governments and the environmental science community. Regional differences in climate change and its impacts have recently been identified as current gaps in the present scientific knowledge. Air quality regional impacts of global climate change, namely the effects on photochemical production, are not a common subject of scientific studies. The main objective of this paper is to provide a basis of scientific information for policy makers and public use by the assessment of the vulnerability of Portuguese air quality to climate change. A General Circulation Model was applied in order to provide initial and driving meteorological boundary conditions, assuming a present climate situation and a scenario of double carbon dioxide concentration in the atmosphere, for higher resolution mesometeorological and photochemical models. Results emphasise a possible significant impact of the climate change scenario on the photochemical pollution, namely at noon.

**KEY WORDS:** Climate change, air quality, general circulation model, dynamical downscaling, mesoscale model, photochemical pollution.

## INTRODUCTION

Since the beginning of the industrial age concentrations of greenhouse gases (GHG) have been increasing substantially. Combustion of fossil energy, land uses changes and, in recent years, the use of chlorofluorocarbons, are the main activities responsible for this increase. Actual concentrations are about 25 % greater than those at the beginning of the Industrial Revolution. If current trends continue, concentrations will double from pre-industrial levels before the end of the next century and, if unchecked, continue to rise thereafter (IPCC, 1990). These increases lead to a net energy input to the lower atmosphere resulting in additional warming of the earth's surface. A warming trend of about 0.5°C has been detected over the last 150 years (Houghton, 1994). In particular, the 80s and early 90's of the XX century were among the warmest on the record, with 1995 heading the higher values ever registered on temperature (MetOffice, 1997). The evidence that human activities have affected concentrations, distributions and life cycles of GHG is clear and the human induced climate warming has become an important issue.

The changes in GHG and aerosols emissions are expected to lead to regional and global changes in temperature, precipitation, and other climate variables. Analysis on the temperatures trends for the last century indicates a warming in the south-western part of Europe, Iberian Peninsula and south-central part of France, of 2 °C (IPCC, 1998). The degree to which human conditions and the natural environment are vulnerable to the potential effects of climate change is a key concern for governments and the environmental science community. Regional differences in climate change and its impacts, as well as the economic and social effects in the various countries, have recently been identified as current gaps in the present scientific knowledge.

In order to foreseen the regional impacts of changes on climate system it is necessary to apply numerical algorithms to estimate climate variability. General Circulation Models (GCM) are the state-of-art tool for understanding the Earth's present climate, and to estimate the effects on past and future climate of various natural and human factors. The best climate models currently available are global, coupled ocean atmospheric and their solution are in relatively good agreement with present climate observed data. However, the horizontal resolution of present coupled atmosphere-ocean models is still too coarse to capture the effects of local and regional forcing in areas of complex surface physiography and to provide information suitable for many impact assessment studies (IPCC, 1996). Downsizing the spatial resolution of the models thus constitutes a major challenge for climate modellers and different techniques were developed (IPCC, 1998): (i) empirical approaches, (ii) semi-empirical approaches, and (iii) modelling technique. Within the modelling, the one-way nested modelling technique has been increasingly applied to climate change studies in the last few years. This technique consists in the use of output from GCM simulations to provide initial and driving lateral meteorological boundary conditions for high-resolution Regional Climate Model (RegCM) simulations, with no feedback from the RegCM to the driving GCM. From the validation of these simulations, the most important results allowed to verify (IPCC, 1998):

- Increase of temperature bias as the size of the region decreases;
- The performance of regional climate models is strongly affected by the quality of the driving GCM outputs;
- The performance of regional climate models is improved with higher resolution of GCM;
- When compared with GCM results, regional climate models produce more realistic regional details of surface climate;
- A very large amount of surface data is necessary to validate these models.

Therefore, the performance of the RegCM is strongly dependent on the performance of the GCM.

Global warming will lead to different temperature gradients, the primary factor of atmospheric circulation changes. Different flow patterns will affect air pollutant transport and dispersion and thus air quality. It is expected (IPCC, 1998) that summer conditions will lead to more stable anticyclonic conditions, which may favour ozone ground level formation. Climate change plays also an important role in the formation of secondary atmospheric pollutants, due to the dependency of kinetic constants on temperature.

The main objective of this work was to evaluate the impact of a climate change scenario on the air quality of an urban region in Portugal, where the weather is strongly affected by the position and strength of the Anticyclone of the Azores, especially in summer. The chosen approach was based on the dynamical downscaling technique. Nested simulations through GCM and mesoscale models were performed to estimate the photochemical pollutants, namely ozone ($O_3$), concentration fields, for control and double carbon dioxide ($CO_2$) climate simulations.

## THE MODELS

A GCM and a mesoscale model were used to dynamically downscale the atmospheric circulation and to evaluate the impact of a double $CO_2$ concentration on the air quality of an urban region in Portugal, Lisbon.

### GCM model - the NCAR Community Climate Model

The NCAR Community Climate Model (CCM3)

is a spectral global climatic model. The standard horizontal resolution of the model is T42 (triangular truncation in the 42nd wave number, which is equivalent to 2.8° latitude x 2.8° longitude resolution) with 18 vertical levels. The vertical implemented co-ordinate system is hybrid. This model version applies a semi-implicit temporal integration scheme, leapfrog, a spectral transformation representing the dry dynamics, a bi-harmonic horizontal diffusion operator and a semi-Lagrangian scheme to represent the water vapour transport. The standard time-step is 20 minutes. The longwave and short wave fluxes and the cloud radiation processes are hourly calculated and these values are kept constants in that period of time (Kiehl *et al.*, 1998).

The CCM3 includes the version 1 of the NCAR Land Surface Model (Bonan, 1998). This model fully treats all the processes that are developed by the soil. It considers the ecological differences amongst the different types of vegetation, the hydraulic and thermal differences related with distinct soils and allow the inclusion of different types of surfaces in the same cell (including lakes and wetlands). It is an unidimensional model for the calculation of energy, momentum, water and $CO_2$ exchange between atmosphere and surface. The standard CCM3 configuration uses a prescribed distribution of the sea surface temperatures, which can be either, observed monthly temporal series or climate averages repeated annually. Sometimes, certain applications require a model representing the ocean surface in an interactive way. Hence, in the CCM3 there is also a simple layer ocean model. This model assumes values for mixing layer and for the heat ocean fluxes (which vary with the geographical position and the season). A multilayer thermodynamic model calculates the sea ice.

This model was included in the Atmospheric Model Intercomparison Project and its performance was evaluated (IPCC, 1996). The Atmospheric Model Intercomparison Project results allowed to come to the conclusions that global circulation model's supplies realistic results of the phase and amplitude of the seasonal changes of large scale distribution of pressure, temperature and circulation (IPCC, 1996). Errors are greater over higher latitudes. Statistical evaluation of the simulated mean sea level pressure in the Northern Hemisphere showed that the errors calculated for the CCM3 model are around 0.3 in the normalised error in time-mean and almost 45 % in the temporal variability. The better performance was obtained with the GCM of the Max Planck Institute for Meteorology, with values of less than 0.15 and 15 % for normalised error in time-mean and in temporal variability, respectively (IPCC, 1996).

### Mesoscale model system - the MEMO/MARS

Two major models, a meteorological and a photochemical one, compose the mesoscale model system MEMO/MARS, which is part of the EUMAC Zooming model structure. Figure 1 presents a scheme of the MEMO/MARS system.

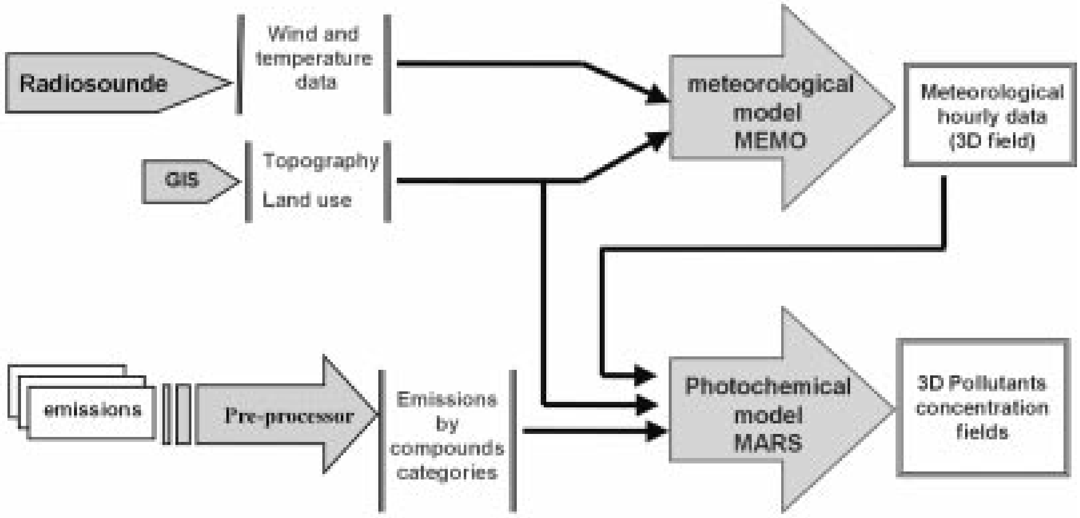


*Figure 1*: The used mesoscale system.

This system was successfully applied to some regions in Southern Europe, namely Athens (Moussiopoulos *et al*., 1995), Barcelona (Baldasano *et al*., 1993), Madrid (San José *et al*., 1997) and Lisbon (Borrego *et al*., 1998a). The MEMO/MARS system applied in this study uses a set of pre-processors in a Geographical Information System (GIS) base. They are important for the format and compatibility of the input data needed by the models, related with orography, land use and emissions.

### *The mesometeorological model MEMO*

MEMO is a non-hydrostatic prognostic mesoscale model (Moussiopoulos, 1990), which describes the atmospheric boundary layer for unsaturated air. The atmospheric physical phenomena is simulated by the numerical resolution of a set of equations, including continuity, the momentum and some equations for the transport of scalar quantities, such as energy, water vapour, kinetic turbulent energy, in terrain-following co-ordinates.

The parameterisations of the physical processes, including turbulence, together with the radiative processes, are very important. Turbulence is calculated by the application of the turbulence closure based on the K-theory. Concerning the radiative budget, the parameterisation of long wave radiation is based on the emissivity method as the short wave radiation transfer is described with an implicit multilayer method.

### *The mesoscale photochemical model MARS*

The MARS model simulates numerically photo-oxidants formation considering the chemical transformation process of pollutants together with its transport in the atmospheric boundary layer (Moussiopoulos *et al*., 1995). The model solves the parabolic differential concentration transport equation system in terrain-following co-ordinates, with the meteorological variables calculated by the mesometeorological model (wind speed and wind direction, temperature, turbulent kinetic energy, surface roughness, Monin-Obukhov length and friction velocity), e.g., the mass conservation equations are driven by the momentum equation.

The chemical mechanism used was the KOREM. This mechanism combines the inorganic reactions of the CERT mechanism with the compact mechanism proposed by Bottenheim and Strausz (1982). The KOREM mechanism considers 20 reactive species (Table 1) and 39 reaction equations.

The considered species in the emission inventory for the application of the KOREM mechanism are: nitrogen oxides (NO and $NO_2$), carbon monoxide (CO) and volatile organic compounds (VOC) emissions, which should be aggregated in 5 classes:

1. Methane, including species such as $C_nH_{2n+2}$, n ≤ 3;
2. Alkanes, including species as $C_nH_{2n+2}$, n ≥ 4;
3. Alkenes, including all the species as $C_nH_{2n}$;
4. Aromatics, including benzene, toluene and other superior aromatics;
5. Aldheydes, including formaldheyde and superior ones.

It is possible to take into account temporal variation of emissions.

## THE METHODOLOGY

The chosen methodology, which is illustrated in Figure 2, is based on the dynamical downscaling technique, from a GCM to a mesoscale meteorological model and from this to a photochemical pollution model.

Three different study cases were used for mesoscale circulation simulation over Portugal: a typical summer day (the 4th of August 1992) (Coutinho *et al*., 1994), a control case with actual $CO_2$ concentration, and a double $CO_2$ scenario.

*Table 1*: Reactive species considered in the KOREM mechanism.

| | | | |
|---|---|---|---|
| $NO_2$ | $HO_2$ | $N_2O_5$ | $CH_4$ |
| NO | $HNO_4$ | RCHO | Alkanes |
| $O_3$ | $H_2O_2$ | $RO_2$ | Alkenes |
| OH | CO | $RCO_3$ | Aromatics |
| HONO | $NO_3$ | PAN | $RO_2NO_2$ |

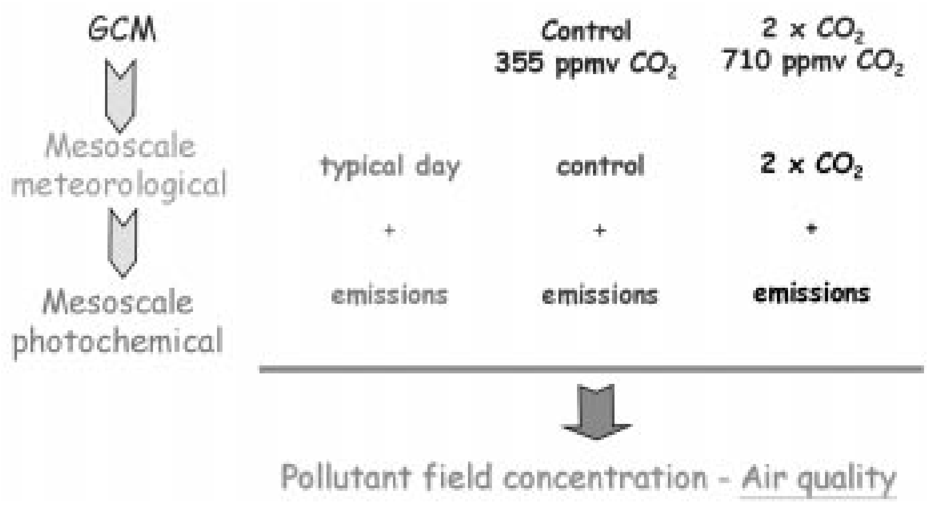


*Figure 2*: Schematic representation of the methodology.

### Meteorological boundary and initial conditions

Two GCM simulations were made: a control one with an actual $CO_2$ concentration value (355 ppmv) and a double $CO_2$ concentration (710 ppmv). The integration period was 36 years, with a 20 minutes time-step, for a T42 resolution. An average of the vertical temperature and wind components variation considering 3 grid GCM cells was made for each simulation (between the 25 of July and the 13 of September). These cells are located at (Figure 3): (8.4° W, 40.5° N); (8.4° W, 37.7° N) and (5.6° W, 37.7° N). They have been chosen in order to obtain a better characterisation of the GCM vertical results above the mesoscale domain of interest. Hence, the cells climatic data were introduced as vertical meteorological information in the mesoscale model. Averaged values of surface water temperature estimated with the GCM were also introduced in the mesoscale model as initial and to update the boundary conditions.

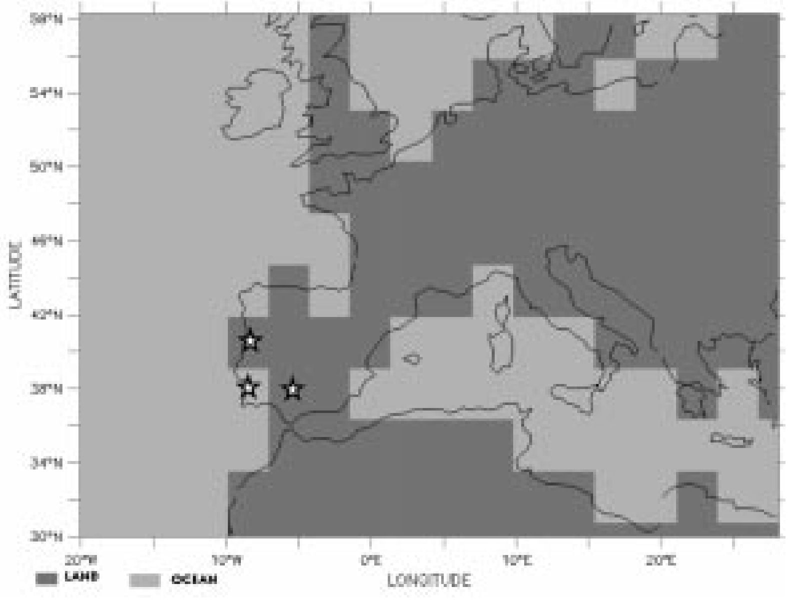


*Figure 3*: Location of the 3 cells considered for driven initial and boundary mesoscale meteorological data.

The mesoscale results calculated with the boundary conditions driven by the GCM were compared with a mesoscale simulation initialised with data from measurements acquired during a typical summer day.

### Lisbon airshed region

The domain simulated by the mesoscale system agrees with the Lisbon airshed region (GLA), covering an area of 200 km x 200 km, with 4 km x 4 km horizontal resolution. The GLA, because of its industrial and urban importance and high emissions levels, is one of the Portuguese regions where the knowledge concerning impact of climate change in the atmospheric environment is fundamental. This region has about 3.5 millions inhabitants, which represents 35 % of the Portuguese population.

In spite of its size, this region is not climatically uniform. The domain coastline suffers the Atlantic Ocean influence and due to that fact, temperature is not severe. But, just along shoreline, and above Lisbon city, it can be observed mountains chains oriented perpendicularly to the dominant wind direction inducing a dryer and hotter air in the east part of the domain.

### Emission rates

Concerning emissions the work of Borrego *et al.* (1998b) presenting the development of an emissions inventory for urban areas in Portugal, which was elaborated applying ‘bottom-up’ and ‘top-down’ approaches was used. Considered emission sources for the control scenario simulation included point, line and area sources from the aforesaid inventory. The emission scenario for the double $CO_2$ simulation needed some assumptions based on the Kyoto Protocol. Portugal, within the global commitment made by the European Union, assumed a 40 % limit on the increase of $CO_2$ emissions, until 2010, and having as baseline the 1990 year. Therefore, anthropogenic emissions were enhanced by a "factor" of 40%. Biogenic emissions, which depend on the land cover and on the meteorological parameters, namely on temperature, were estimated considering no changes on the land cover data but recalculated for the new temperature matrix, calculated by the mesoscale model on a future climate, with double $CO_2$ concentration.

## RESULTS

The pollutants transport and dispersion are strongly related with vertical structure of meteorological parameters, especially the temperature. For this reason the simulated results of temperature vertical data and ozone concentration fields were analysed.

### Temperature Profiles

The vertical temperature profiles were obtained from the outputs of GCM corresponding to the two grid cells that covers Portugal, located at (8.4°W; 40.5°N) and (8.4°W; 37.7°N). Those profiles refer to two different types of locations (please, see figure 3): above land, in the North part of Portugal, and in the South part of Portugal considered by the GCM as sea. They were compared with radiossounding measurements of the typical summer day, over Lisbon. Figure 4 presents the obtained temperature profiles, at 00H00 and 12H00.

On Figure 4, it can be seen that for (8.4°W; 40.5°N) location the vertical structure of temperature obtained with both control and double $CO_2$ simulations present similar values under approximately 1500 m height. Above this height slopes for the two temperature profiles present a ~5°C lag, e.g. at the same height, the temperature is greater for the double $CO_2$ simulation. On the cell (8.4°W; 37.7°N) vertical temperature profiles also have similar values, but in this case only until few meters above surface. This similarity in the lower troposphere may be due to the ocean proximity (for the (8.4°W; 40.5°N) location) and because the (8.4°W; 37.7°N) cell is considered as water surface in the GCM. The vertical temperature profiles measured in Lisbon at 4th of August 1992 are characterised by an inversion in altitude at 00H00 and 12H00. In the (8.4°W; 40.5°N) location, under approximately 3000 m height, the measured temperature profile presents higher temperatures than the two simulated GCM scenarios. Attending to the fact that vertical temperature was measured in Lisbon and that the cell (8.4°W; 40.5°N) covers the North part of Portugal, the described differences could be expected. On the contrary, measured temperature values above 4500 m are near the results of the GCM output control simulation, which can also be verified in the other GCM grid location. At (8.4°W; 37.7°N) for the lower troposphere, the measured temperature is between the temperatures simulated for both global climatic scenarios.

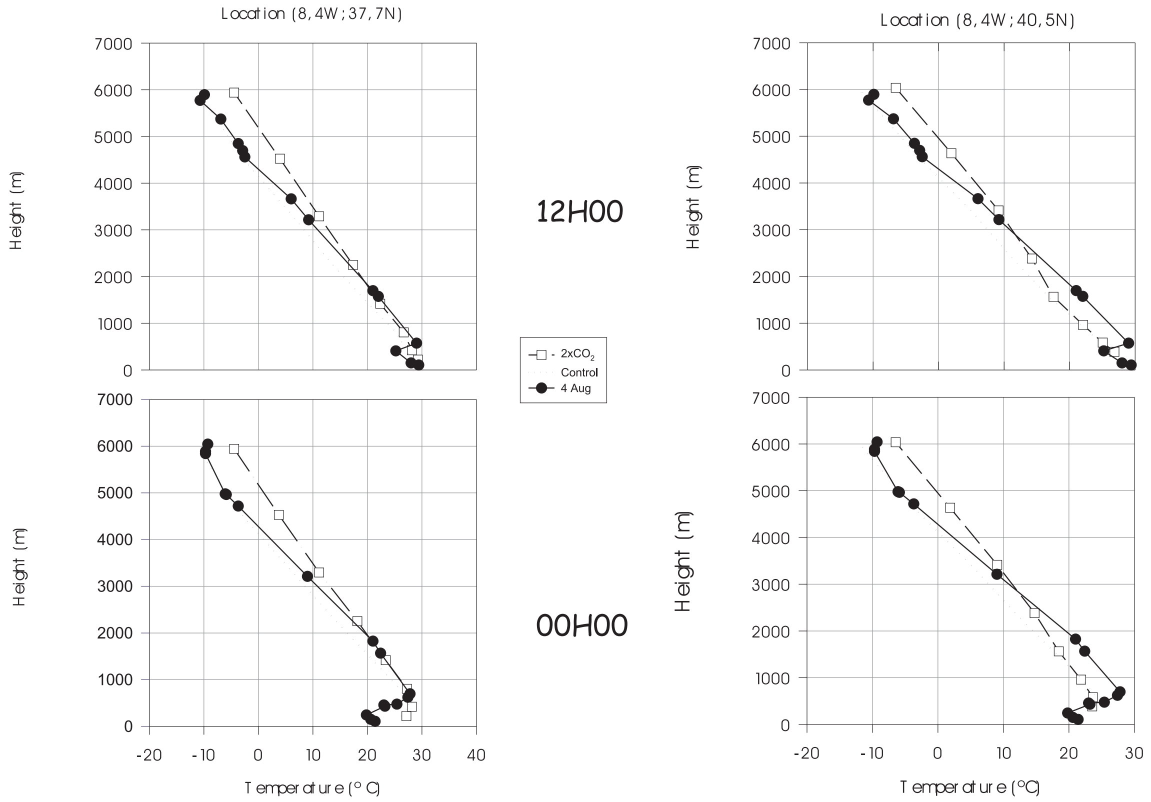


*Figure 4*: GCM results of temperature vertical profiles for the two considered locations, and radiossonde data measured at Lisbon, at 00H00 and 12H00.

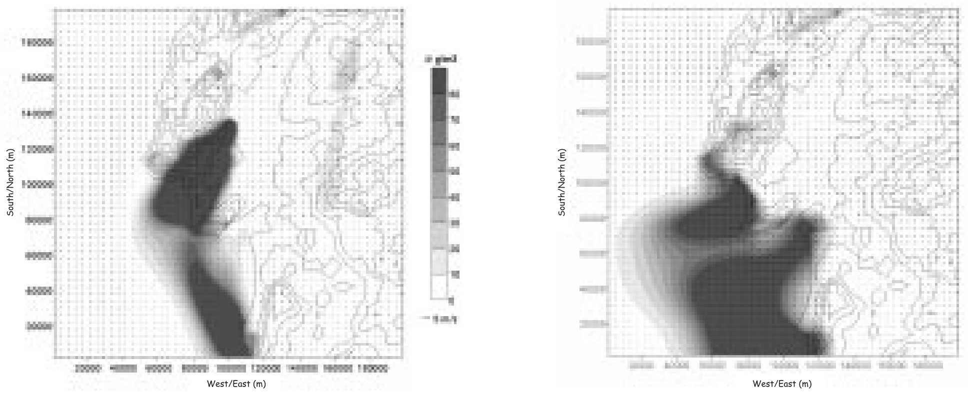
## Surface Ozone Concentration Fields

Figure 5 shows ozone concentrations and wind fields, for the 4th of August 1992 at 12H00 (fig. 5a) and 17H00 (fig. 5b). The reason for the choice of these two instants is due to the fact that, generally over Lisbon, at 12H00 the ozone concentration is increasing and at 17H00 is near the maximum value (Borrego *et al.*, 1998a). In the early morning, the ozone precursors emitted in Lisbon are transported offshore by the local circulation established in the Tagus Valley. At 12H00 the ozone plume is very thin. It starts over Lisbon City and is transported along the coastline. At 17H00 the ozone plume is larger. At this time, the sea breeze is formed, the winds are stronger, and the combination of these factors is responsible for the plume entering into land Southwest. During the afternoon the ozone concentrations in the Southwest part are gradually enhanced by the sea breeze transport.

Figures 6 and 7 present, respectively, the obtained results at 12H00 and 17H00, both for control and double $CO_2$ simulations. At 12H00, $O_3$ concentration reaches 50 $\mu$g m$^{-3}$ in both presented situations. For the control simulation the plume is transported by the land breeze and the estuary wind flow oriented NE-SW. The double $CO_2$ simulation indicates a displacement of the plume along the coastline, due to the breakdown of the land breeze.

At 17H00 the $O_3$ plume estimated with the control scenario remains near the coast and is extended in a thong shape into the Atlantic Ocean. Concentration values obtained with the double $CO_2$ simulation are always under 10 $\mu$g m$^{-3}$.

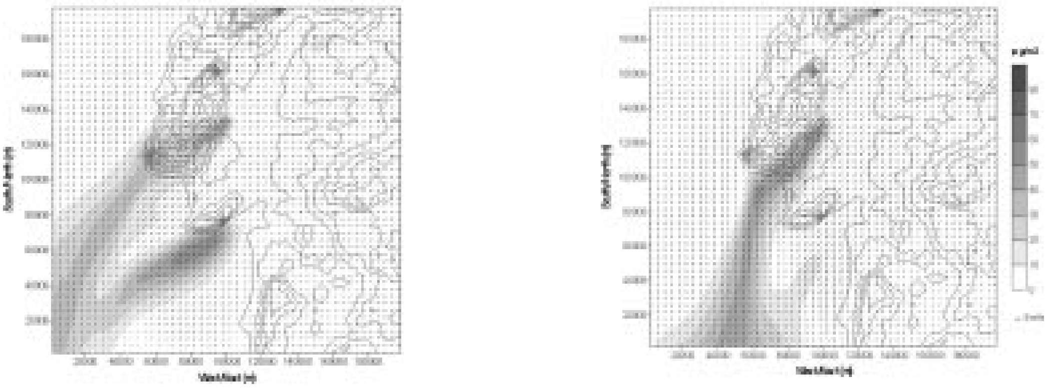
At 12H00, the $O_3$ concentration field resulting from the control situation present lower maximum values than the results from the simulation of the 4th of August 1992. The reason for this difference relays on different vertical temperature structures. In the case of the control scenario, the vertical mixture is enhanced by a greater vertical instability. The "comparison" between the typical summer day simulation and the mesoscale results produced by the driven GCM simulations, shows that the GCM model was unable to produce the particularity of the inversion in altitude at 12h00 in the Lisbon region.



a. Ozone concentration field at 12H00

b. Ozone concentration field at 17H00

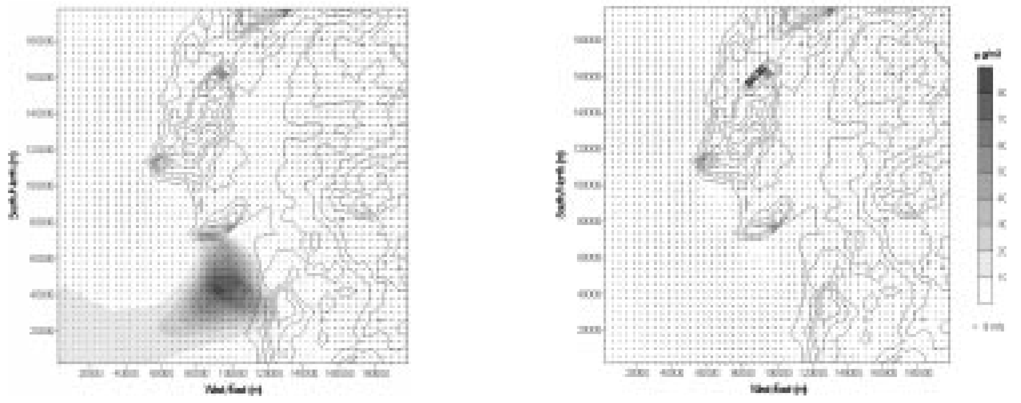
*Figure 5*: Ozone concentration and wind fields for the Lisbon airshed region, simulation of the 4th of August 1992.



a. control

b. 2 x $CO_2$

*Figure 6*: Ozone concentration and wind fields for the Lisbon airshed region, at 12H00.



a. control

b. 2 x $CO_2$

*Figure 7*: Ozone concentration and wind fields for the Lisbon airshed region, at 17H00.

## CONCLUSIONS

An important conclusion reached in this work is that more studies in the same issue are needed to overcome the differences between the control and the typical simulations day. These studies may be focused on getting a better knowledge of the vertical atmosphere structure over the Lisbon region based on the existent radiossounding measurements. Also, regional climatic model results must be tried as mesoscale initial boundary conditions in order to get more consistencies on the physical processes in the atmosphere. Concerning the photochemical part of the mesoscale system, it is necessary to obtain information on future emissions scenarios.

In spite of these future developments of the work and concerning the impact of climate change on the air quality in Lisbon airshed under the simulated conditions, it seems that the disturbed wind circulation will induce greater $O_3$ concentration over Lisbon at noon. However, in the afternoon these values will be considerably lower and there will be no problems of photochemical pollution.

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