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OFFLINE AND ONLINE COUPLING OF REGIONAL CLIMATE MODEL WITH CHEMISTRY TRANSPORT MODEL

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Abstract: An offline and online coupled system consisting of regional climate model RegCM and chemistry transport model CAMx was developed at Charles University to study the interactions between climate and atmospheric chemistry. In the framework of the EC FP6 project CECILIA, focus was given on investigation of the impact of climate change on air pollution. In fact, even at regional and local scale, especially the impact on the photochemical smog formation conditions can be significant when expecting, e.g., more frequent appearance of heat waves, or more precipitation resulting in elevated wet scavenging rates. Off-line one way coupling was applied for the simulation of surface distribution of pollutants over 1991-2001 in very high resolution of 10 km. Its results are compared to the EMEP/AIRBASE observations for the area of Central Europe. Simulations driven by boundary conditions for time slices 1991-2000, 2041-2050 and 2091-2100 are presented to show the effect of climate change on the air quality in the region. Online coupling of the two models is also developed to investigate the feedbacks of chemistry on climate. Tropospheric ozone has been coupled and preliminary results are presented here. Coupling of atmospheric aerosols will be addressed in future work.

Key words: *regional climate modelling, chemistry transport models, air quality, coupling, radiative feedbacks.*

INTRODUCTION

Recently there has been a high demand for detailed information on the impact of climate change on regional and even local scale. To address this issue, a more sophisticated representation of the climate system is required in today's climate models. One of the elements of this system that needs to be considered is the atmospheric chemistry and aerosols.

It is now well established that atmospheric chemistry and aerosols are strongly linked to climate. First of all, the spatial and temporal distribution of atmospheric gases and aerosols is dependent on the governing meteorological conditions. Secondly, gases and particle matter may participate in the Earth's radiation balance causing heating and/or cooling of the atmosphere (direct effect). Moreover, aerosols are capable of participating in the cloud and precipitation formation thus changing microphysical properties and amount of clouds which leads to different cloud radiative effect (indirect effect).

During the last several years, a great development in meteorology-chemistry or climate-chemistry models is evident (Zhang, Y., 2008; Baklanov, A. *et al.*, 2007; Baklanov, A. and U. Korsholm, 2008). A new concept of "chemical weather forecasting" was introduced by Baklanov, A. (2010) which emphasises the importance of integrating meteorology and chemistry into one modelling system.

In general, to establish a coupling of climate and atmospheric chemistry and aerosols, one can follow two approaches. In the first one, a module is developed within the climate model that calculates the chemistry and aerosol processes. This approach has great advantage in the fact that this chemistry module has continual access to driving meteorological fields from the climate model, and on the other hand, the chemistry module provides real time species concentrations to calculate the radiative or microphysical effects mentioned above.

The second way to connect the climate system and atmospheric chemistry/aerosols takes the advantage of already existing state-of-the-art chemistry transport models (CTM). These models provide a sophisticated calculation of the concentration of atmospheric gases and particle matter. A connection of a climate model with an already existing CTM can be established using a coupling interface, which ensures the continual data flow between the two models.

We will follow the second approach and in the presented work, we introduce a modelling system consisting of the regional climate model RegCM3 and chemistry transport model CAMx. An offline and later online coupling of these two models was developed. In the first case, only the species concentrations were driven by the meteorology from the regional climate model but no radiative feedbacks were considered, as is done in the online version of this couple.

In the first part of this study, we used the offline couple of RegCM3 and CAMx to investigate the impact of the climate change on air quality. Already, numerous studies dealt with future air quality projections on global scale using coupled climate-chemistry models. Most of them were global scale studies focusing on ozone (Hauglustaine, D.A. *et al.*, 2005; Stevenson, D.S. *et al.*, 2006; Racherla, P. N. and P. J. Adams, 2006, 2008), while Hedegaard, G. B. *et al.* (2008) provides results also for sulphur and nitrogen dioxide (SO_2 and NO_2). Fewer studies focus on regional and local scale air quality changes (Szopa, S. *et al.*, 2006; Meleux, F. *et al.*, 2007; Nolte, C. G. *et al.*, 2008).

Using models RegCM3 and CAMx coupled offline we will assess the present and future air quality on a regional scale focusing on the area of Central and Eastern Europe. We do not intend to give climatic projections for air pollution for the future, but to investigate how the different meteorological conditions brought by the expected climate change will affect the chemical processes in the troposphere. The study focuses mainly on surface change of ozone, although, we evaluated also SO_2, NO_2 and particulate matter. Nevertheless, results for the latter are not presented here. Simulations for three decades were performed: 1991-2000, 2041-2050 and 2091-2100. The first decade served as a validation period for the presented

modelling system while the other two served to evaluate the climate induced tropospheric chemistry changes. To exclude potential air quality impacts resulting from different anthropogenic emissions in the future, we kept emissions at the present level during all the simulations.

In the second part of the study, we implemented the online couple of RegCM3 and CAMx. In the first stage, only tropospheric ozone is coupled and results are provided only for this case. Online coupling of aerosols will be addressed in future work. Annual runs for year 2004 were performed with the couple switched on and off and the surface temperature and radiation response has been examined.

MODELS AND EXPERIMENTAL SET-UP

For the regional climate simulations RegCM Version 3 (Pal, J. S. *et al.*, 2007) regional climate model was used. RegCM was originally developed by Giorgi, F. *et al.* (1993a,b) and has undergone a number of improvements described in Giorgi, F. *et al.* (1999). The dynamical core of the RegCM is equivalent to the hydrostatic version of the meso-scale model MM4 (Anthes, R. A. *et al.*, 1987) and uses terrain following σ-levels. Surface processes are represented via the Biosphere-Atmosphere Transfer Scheme (BATS) and boundary layer physics is formulated following a non-local vertical diffusion scheme (Giorgi F. *et al.*, 1993a). Resolvable scale precipitation is represented via the scheme taken from Pal *et al.* (2000), which includes a prognostic equation for cloud water and allows for fractional grid box cloudiness, accretion and re-evaporation of falling precipitation. Convective precipitation is represented using a mass flux convective scheme detailed by Giorgi F. *et al.* (1993b) while radiative transfer is computed using the radiation package of the NCAR Community Climate Model, version CCM3 (Giorgi F. *et al.*, 1999). This scheme describes the effect of different greenhouse gases, cloud water, cloud ice and atmospheric aerosols. Cloud radiation is calculated in terms of cloud fractional cover and cloud water content, and the fraction of cloud ice is diagnosed by the scheme as a function of temperature.

Chemistry calculations in this study were performed by model CAMx. It is a Eulerian photochemical dispersion model developed by ENVIRON Int. Corp. (http://www.camx.com). CAMx can use environmental input fields from a number of meteorological models (e.g. MM5, RAMS, CALMET) and emission inputs from many emissions processors. CAMx includes the options of two-way grid nesting, multiple gas phase chemistry mechanism options (CB-IV, CB-V, SAPRC99), evolving multisectional or static two-mode particle size treatments, wet deposition of gases and particles, plume-in-grid (PiG) module for sub-grid treatment of selected point sources, Ozone and Particulate Source Apportionment Technology, mass conservative and consistent transport numerics, parallel processing. It allows for integrated "one-atmosphere" assessments of gaseous and particulate air pollution (ozone, PM2.5, PM10, air toxics) over many scales ranging from sub-urban to continental.

To drive dispersion, chemical reactions and removal of pollutants by dry/wet deposition in the troposphere, a preprocessor utility was developed that converts RegCM generated meteorological field into CAMx input format. Fields required by CAMx and not available directly in RegCM's output are calculated using diagnostic tools. Pressure is computed using the known location of the σ-levels, the distribution of the surface pressure and the constant top model pressure. Geopotential height is obtained from the hydrostatic formula using the average temperature and humidity of each layer. The precipitation rates and the vertical profile of temperature and humidity are used to compute the cloud/rain water content and cloud optical depth and finally, the vertical diffusion coefficients are calculated following O'Brien, J. J. (1970).

As referred in the overview, calculations of the RegCM3/CAMx offline couple were performed on three distinct periods. Decade 1991-2000 gives a picture about the present day air quality conditions, decades 2041-2050 and 2091-2100, "near" and "far future" decades, serve to capture climate change impact in two different future time slices. The RegCM3 10 km resolution run for the first decade 1991-2000 was forced by RegCM3 25 km runs covering time period 1960-2002 on a domain containing most of Europe, which were performed at the ICTP (International Centre for Theoretical Physics) in the framework of the EU project ENSEMBLES. These runs were forced by either the ERA40 reanalysis (Uppala, S. M. *et al.*, 2005) or by the global climate model ECHAM5 which is a widely used and well established global circulation model adapted in the Coupled Model Intercomparison Project (CMIP) simulations used in the IPCC 4th Assessment Report. The ERA40 forced RegCM3 10 km run (through the 25 km ENSEMBLES runs) is referred as a "perfect boundary condition" run which serves for model system validation. On the other hand, the ECHAM5 forced RegCM3 10 km run (through the corresponding 25 km ENSEMBLES runs) is referred to as the "control" run which is the basis for comparison with future model runs.

For the online coupled runs, where the radiative feedback of ozone was studied, we set up a different domain at 50 km x 50 km spatial resolution. To assess how the consideration of the radiative effects of ozone will affect surface air temperatures and radiation, year 2004 was chosen to carry out the test runs.

For all the experiments, UNECE/EMEP data for the year 2000 and 2004 (Vestreng, V. *et al.*, 2007) were used as anthropogenic emissions. These data provide annual sums of emission of NOx , CO, non-methane volatile organic compounds (NMVOCs), SO_2 , NH_3 , fine particles (<2.5 µm) and coarse particles (2.5 µm to 10 µm) on a 50 km x 50 km grid. Emissions are divided into eleven activity sectors. For each sector, temporal disaggregation factors taken from Winiwarter, W. and J. Zueger (1996) were applied to resolve hourly emissions. These factors represent different distributions of emissions for months, days of the week and hours of the day, depending on the activity sector. In the offline coupled runs, EMEP emissions were combined with the 5 km x 5 km emission database for Central Europe to increase resolution on the targeted domain (Winiwarter, W. and J. Zueger, 1996). Calculation of biogenic emissions for isoprene and monoterpenes follows Guenther, P. *et al.* (1993). They are dependent on landuse category, foliar density, temperature at 2 m and global radiation. The chemistry scheme used in the simulations was the Carbon Bond IV (CB-IV) scheme.

OFFLINE COUPLE OF REGCM3 AND CAMX

Using an offline couple, we examined the effect of climate change on air quality. Here, results for ozone will be shown, although nitrogen dioxide, sulphur dioxide and particle matter were also investigated.

First, we evaluated the average winter and summer surface ozone change and results for the far future decade 2091-2100 are presented. Figure 1 shows that the surface ozone change in the far future will decrease in winter. In summer, regions with ozone increase up to 1 ppbv are present in Central Europe. Even larger increase occurs in Northern Italy, up to 2.5 ppbv.

The number of days with 8-hour ozone greater than 120 $\mu g.m^3$ for far future shows large increase (Figure 2). Northern Italy will suffer the most, affected by an increase of 6-20 days per year, but influenced areas are also southern Germany (4-6 days) and the Czech Republic (2-4 days). Comparing with the absolute values these changes are very large in relative sense, often reaching 100 %.

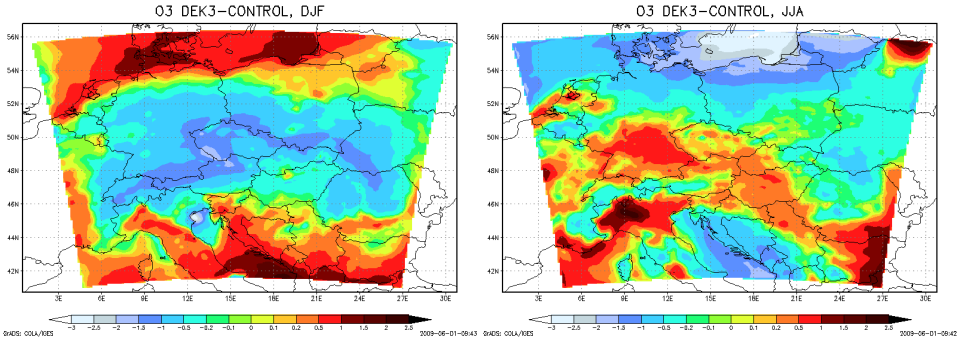

Figure 1. Climate change impact on average surface ozone in decade 2091-2100 compared to decade 1991-2000 during winter (left) and summer (right) season in ppbv.

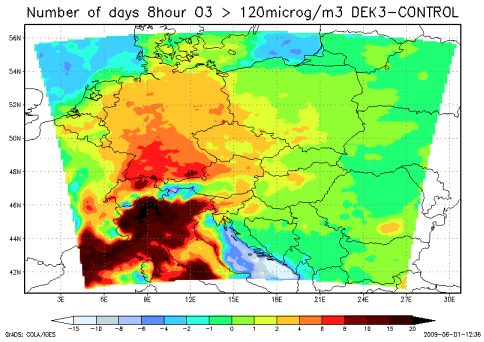

Figure 2. Climate change impact on ozone exceedances in decade 2091-2100 compared to decade 1991-2000 as the average number of days per year when 8hour ozone maxima exceed 120 $\mu g.m^3$.

ONLINE COUPLE OF REGCM3 AND CAMX

The online couple of RegCM3 and CAMx was implemented with an online access technique. We have established a time period (3 or 6 hour) during which the species concentrations are kept constant and the regional climate model is run using these concentrations in its radiation code. After this time period, the chemistry model is run again (as a restart), the species concentrations are updated, the regional model is restarted and run for another 3 or 6 hours.

As the first stage, we coupled tropospheric ozone. The difference in monthly mean surface temperature between runs with online coupled ozone and run with ozone not coupled is presented in Figure 3. Significant impact on temperature is modelled when ozone radiative effects are considered. Large areas of temperature increase occur (up to 3 K). Nevertheless, due to nonlinearity of the climate system, temperature changes occur in both directions.

The difference in surface downward long wave radiation pattern is very similar to temperature pattern reflecting the radiative impact of tropospheric ozone (Figure 4).

Finally, we point out the non-linear character of the climate system. Indeed, by adding online coupled ozone, the meteorology within the climate model will in general evolve in a different way. This may cause very large variations of the meteorological parameters in the end. In Figure 5, left, the temperature difference can be seen for selected points while on the right, the domain maximum and minimum difference is shown. Although the radiative effect of realistic ozone might not be large compared to average ozone already predefined in RegCM3, due to these non-linearities in the system, small variations can rise into significant differences in the end.

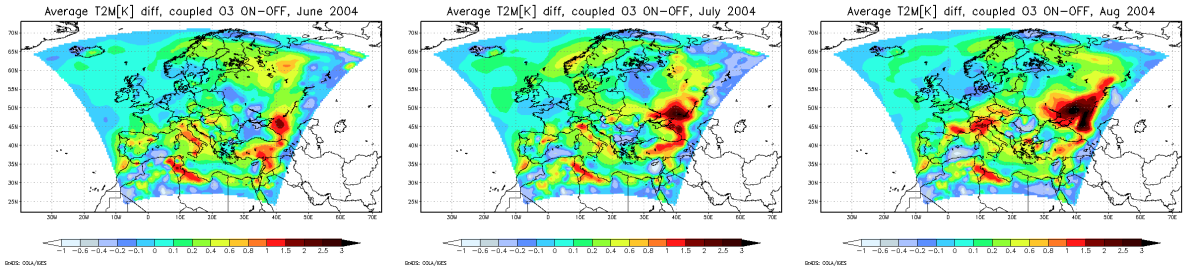

Figure 3. Monthly average 2 m temperature difference between run with online coupled ozone and without coupled ozone for June, July and August 2004.

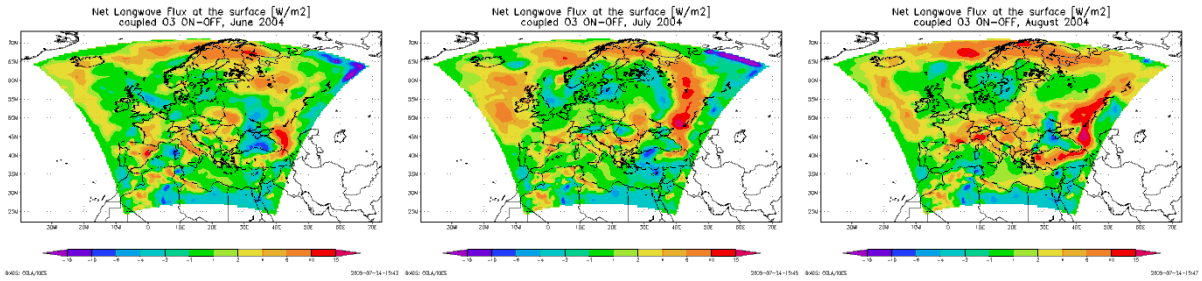

Figure 4. Monthly average surface incident long wave radiation difference between run with online coupled ozone and without coupled ozone for June, July and August 2004.

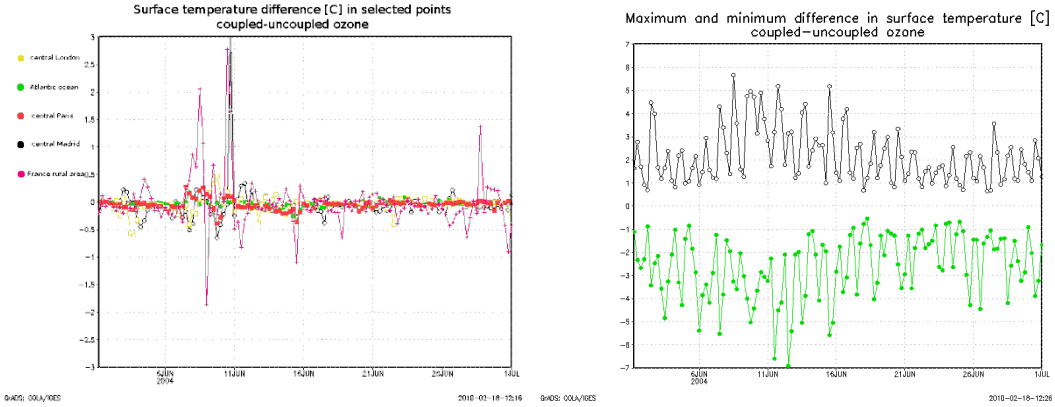

Figure 5. The impact of the non-linear effects due to coupled ozone. On the left, temperature difference at selected points. On the right, the absolute domain maximum and minimum difference between online and offline coupled ozone, again for 2 m temperature.

CONCLUSIONS

An integrated system consisting of regional climate model RegCM3 and chemistry transport model CAMx was introduced here and applied. In offline regime, when only the species concentrations are driven by the meteorology fields provided by the climate model, we looked at the impact of climate change on near surface air quality. We found large effect on ozone, especially at the end of the 21st century. Not only the average values are affected, but significant increase occurs in exceedances.

Considering the radiative feedbacks of ozone, we carried out experimental runs for year 2004 and showed that the coupling brings modified average temperatures and has large impact on radiation. However, these changes may be a result of non-linear effects so caution is needed in interpreting these results. For instance, when evaluating the radiative forcing of a particular gas/aerosol, we need to perform longer simulations so the non-linear fluctuations are eliminated.

Online coupling of aerosols (mainly sulphate and black carbon) will be addressed in future work.

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