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Improvement and extension of the coupling between RACMO2 and LOTOS-EUROS
Technical report

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1 Introduction

Air quality is very sensitive to meteorology, as the transport, dilution, wet and dry deposition and chemical reactions of aerosol species in the atmosphere are to a large extent controlled by weather related processes. In return, the radiative balance is sensitive to aerosol concentrations, through direct scattering and through the effect of aerosol on cloud formation and cloud radiative properties. To investigate the impact of climate change on air quality a common approach is to couple a climate model and a chemistry transport model and perform (long-term) simulations (e.g. the overview by Jacob and Winner, 2009). Within the Climate change Spatial Planning (CcSP) and Knowledge for Climate (KIC) projects a one-way coupling between the KNMI regional climate model RACMO2 and the chemistry transport model LOTOS-EUROS was established. LOTOS-EUROS was furthermore adapted to be operated in parallel mode to facilitate the performance of multi-annual simulations (Manders et al. 2011). Results from a transient one-way coupled climate chemistry simulation (1970-2060) have been used to estimate the potential impact of climate change on air quality (Manders et al. 2012). Already during CcSP also a two-way coupling was realized (De Martino et al. 2008; Ten Brink et al., 2012) and applied in present-day and future climate (van Meijgaard et al. 2012). This version was used to quantify the role of the first indirect aerosol effect: the impact of aerosol on number of cloud condensation nuclei.

In the present project, the coupled system was improved and extended. The model output of RACMO2 and LOTOS-EUROS was made compliant with NetCDF-CF conventions, which are accepted as an international standard. Thus, the model output becomes more accessible for visualization and can more readily be used by other models. Also the scripts for transferring information between the two models have been improved. Example model output was stored on an OPeNDAP server (http://OPeNDAP.nmdc.eu/knmi/thredds/nmdc.html) so that it is more generally accessible. In addition, the two-way coupling was extended to include the first direct aerosol effect: the impact of aerosol on radiation. The technical details regarding two-way coupling are also included in the present report, whereas the physical considerations of this two-way coupling and results of the two-way coupled run are described in a separate report (Savenije et al. 2012).

This report contains basic model descriptions of RACMO2 and LOTOS-EUROS. The information which is exchanged between the models is documented and the coupling procedure is described. The report finishes with conclusions and recommendations.

2 Description of models

2.1 RACMO2

RACMO2 is the regional atmospheric climate model of KNMI (Lenderink et al, 2003; van Meijgaard et al., 2008). It consists of the ECMWF physics package embedded in the semi-Lagrangian dynamical kernel of the numerical weather prediction model HIRLAM and a few routines to link the dynamics and physics parts.
Within the EU-PRUDENCE project RACMO2 did participate in an ensemble study with other regional climate models (RCMs) (Christensen et al., 2007), which showed that the regional models were capable of reproducing the large-scale circulation of the global driving model, albeit with biases, and that RACMO2 was not one of the extreme models. More recently, within the EU-ENSEMBLES project, RACMO2 was objectively assessed to be the best performing RCM among 14 RCMs in representing climate features of temperature and precipitation on the European scale (Christensen et al., 2010) RACMO2 is driven by lateral and surface boundary conditions provided by a reanalysis or transient run of a global climate model (e.g. ERA Interim, ECHAM, MIROC).

RACMO2 employs a rotated longitude-latitude grid to ensure that the distance between neighboring grid points is more or less the same across the entire domain. For the coupled run a RACMO2 domain was configured just encompassing the standard LOTOS-EUROS domain (see Figure 1). It has a horizontal resolution of 0.44° with 114 points distributed from 25.04°W to 24.68°E longitude and 100 points from 11.78°S to 31.78°N latitude in the rotated grid. The South Pole of the rotated coordinate frame is positioned at 47° S and 15° E with respect to the geographical coordinate frame. In the vertical, 40 pressure levels are used. At this resolution RACMO2 uses a model time step of 15 minutes and output for coupling with LOTOS-EUROS is generated every three hours. The analysis of atmospheric parameters is limited to the interior of the RACMO2 domain, obtained by omitting information from the lateral boundary zone.

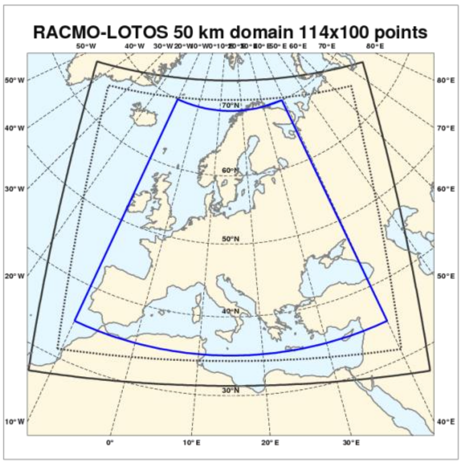

Figure 1 RACMO2 domain (black, solid), with the interior domain (dashed) closely encompassing the LOTOS-EUROS domain. The area between the solid black and dashed lines is the boundary zone.

The RACMO2 model can deliver many different output variables (2D and 3D fields, Table 1), and also some statistical output is readily available (totals, extreme values, etc.). Model input and output is done via ASIMOF files which is the HIRLAM flavour of GRIB-1. From these ASIMOF files many products are derived by means of different tools. Time series output at selected points only is directly exported as NetCDF for specific use in single column models. However, this type of output is not used in this project. The script **asim2cdf** is a post-processing tool to convert ASIMOF data into NetCDF format, reorganize data from single time step/multi-parameter into time series of one parameter, and to perform simple operations (*e.g.* calculate mean, total, max, min) for given intervals and accumulation times. With this tool (with about 200 presets) a large community can be served with RACMO2 model output

In addition, the RACMO version used in the coupling was updated. In previous projects RACMO2.2 was used, which is based on cy31r1 of the ECMWF physics package, however, for this NMDC project the coupled system was updated to RACMO2.3, based on cycle 33r1. To this end also the coupling scripts and import routines have been revised.

Table 1 RACMO2 meteorological output fields. Fields that are not used by LOTOS-EUROS are in italic.

2D fields:	3D fields:
sensible heat flux [W m-2]	density [kg m-3]
cloud base height [m]	height of layer top from surface [m]
cloud top height [m]	*liquid water path [kg m-2]*
boundary layer height [m]	*mass flux updrafts [kg m-2 s-1]*
low cloud cover [0-1]	relative humidity [0-1]
1 / Monin-Obukhov length [m-1]	temperature [K]
precipitation [kg m-2 3hr-1]	zonal wind speed [m s-1]
2 meter relative humidity [0-1]	meridional wind speed [m s-1]
Snow cover fraction [0-1]	
incoming surface short wave radiation [W m-2]	
skin temperature [K]	
2 meter temperature [K]	
friction velocity (u) [m s-1]*	
10 meter wind speed [m s-1]	

2.2 LOTOS-EUROS

LOTOS-EUROS is a Eulerian chemistry transport model on the European domain. It has participated in model intercomparison studies (Vautard et al. 2007, Van Loon et al. 2007) and is well evaluated for PM10 in the Netherlands (Manders et al. 2009). It is used for the daily air quality forecast in the Netherlands and part of the MACC ensemble (www.gmes-atmosphere.eu). Modelled species are ozone, nitrogen oxides, sulfur dioxide, ammonia, primary PM2.5 and black carbon, primary PM10 (excluding PM2.5 and black carbon), sulfate, nitrate, ammonium and sea salt and species relevant as precursors or reservoir (peroxy-acetylnitrate, volatile organic carbon). Total PM is defined as PM10=PPM25+PPM10_coarse+BC+$NO3^-$ +$NH4^+$+$SO4^{2-}$+sea salt (fine and coarse). Sodium is used as a tracer for sea salt, sea salt =3.26*Na.

The horizontal model domain is 10˚W-40˚E, 35-70˚N on a 0.5x0.25˚ regular longitude-latitude grid. In the vertical 5 dynamical vertical layers up to 5 km are used, representing a surface layer, a mixing layer and reservoir layers.
For (photo)chemical gas reactions the CBM IV scheme is used, for secondary inorganic aerosol formation EQSAM is used. Friction velocity and u* could be taken from RACMO2 but are recalculated internally in LOTOS-EUROS for consistency with the grid size and land use in LOTOS-EUROS.

Chemical boundary conditions were not changed for climate simulations. Anthropogenic emissions for 2005 (MACC 2005 emissions, Denier van der Gon et al. 2010) are used, but other emissions sets are available as well. . Natural emissions of sea salt and isoprene emissions by trees are calculated online, they depend on wind speed (sea salt, Monahan et al. 1986) and temperature (isoprene, Guenther et al. 1993). Dust emissions, forest fire emissions and secondary organic aerosols were not included since they are either too uncertain (secondary organic aerosols), mainly fall outside the domain (dust) or cannot be modelled in a realistic way in a climate run (fire emissions).

For the coupled simulations version 1.6 was used, this version was adapted to the new output conventions.

3 Set-up of a coupled simulation

3.1 Structure of the coupling

To couple RACMO2 and LOTOS-EUROS a rather simple, but yet effective approach has been taken. In fact the models run completely separately, but synchronize and exchange several fields at specified timesteps (3 hours is typically used) by means of NetCDF files. This solution is possible because the amount of interaction between the models is limited. A major advantage is that model development on the two models can continue independently. The structure of the coupling is visualized in Fig. 2

When executing a coupled run RACMO2 will create the meteorological fields needed by LOTOS-EUROS and in return LOTOS-EUROS will create (among other output) the aerosol concentrations RACMO2 uses for both direct and indirect aerosol effects. Practically the models run intermittently for one (coupling) timestep, one after the other. The coupling scripts described below take care of the synchronization and conversion issues.

While RACMO2 can be driven by different boundary conditions (*e.g.* ERA re-analysis data, future climate scenarios), LOTOS-EUROS currently has fixed emissions and boundary conditions in a year-to-year respect.

Output for coupling is generated every three hours for both models. The models are completely disconnected (cold coupling) and the models use their own internal time step (15 minutes for RACMO, 10 minutes for LOTOS-EUROS for the present set-up) and the model fields are exchanged by NetCDF files. Both models run intermittently for 3 (model) hours. A coupling script synchronizes the models by use of lock files and further scripts take care of the horizontal and vertical interpolation to transform the domains. First RACMO calculates the meteorological fields for a given three-hour period (say 00:00 to 03:00) and the fields are converted for LOTOS-EUROS. LOTOS-EUROS then calculates the aerosol concentrations during these three hours (00:00 – 03:00) using the RACMO meteo fields and the concentrations at the end of this three-hour period are used to by RACMO to calculate the next three hours (03:00 – 06:00). In the calculation by RACMO the aerosol concentrations during a three-hour period are kept constant.

Current calculation speed at ECMWF of the coupled run is one model year per 36 hours.

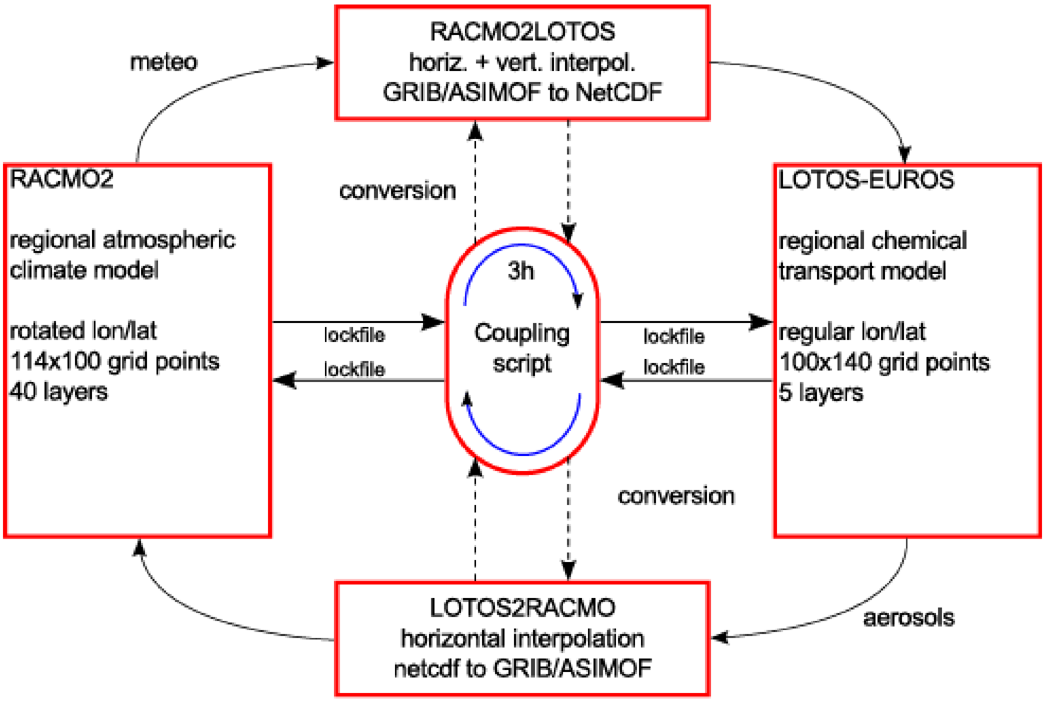

Figure 2 Schematic showing the coupled run.

3.2 Scripts for coupling

For the two-way coupling **nc2asim** was developed to translate LOTOS-EUROS output in NetCDF to GRIB used by RACMO2. LOTOS-EUROS' output is in the NetCDF format and consists of aerosol concentrations on the LOTOS-EUROS model grid. Nc2asim performs a horizontal remapping and also initializes the profiles. The output format of Nc2asim is GRIB/ASIMOF, which is used as the primary IO format for RACMO2. The number of aerosol species handled is extended to nine: nitrate, sulfate, ammonium, black carbon, primary PM2.5, sodium (both fine and coarse mode) and dust (both fine and coarse mode).

Special attention has been given to the 2-way coupled version of RACMO2 and LOTOS-EUROS. In this setup the two models actually run separately and exchange information intermittently via the use of (NetCDF) files. A master coupling script takes care of the synchronization between the models, and initiating the two different conversions needed: The '**Racmo2Lotos**' conversion extracts a number of fields (mostly meteorological parameters) from the standard ASIMOF files and performs both a horizontal and vertical interpolation to the LOTOS-EUROS grid, and stores the interpolated data in a NetCDF file. In table 1 the contents of this file are listed. For the '**Lotos2Racmo**' a reverse process takes places, converting NetCDF files with aerosol fields on the LOTOS_EUROS grid to ASIMOF files on the RACMO2 grid.

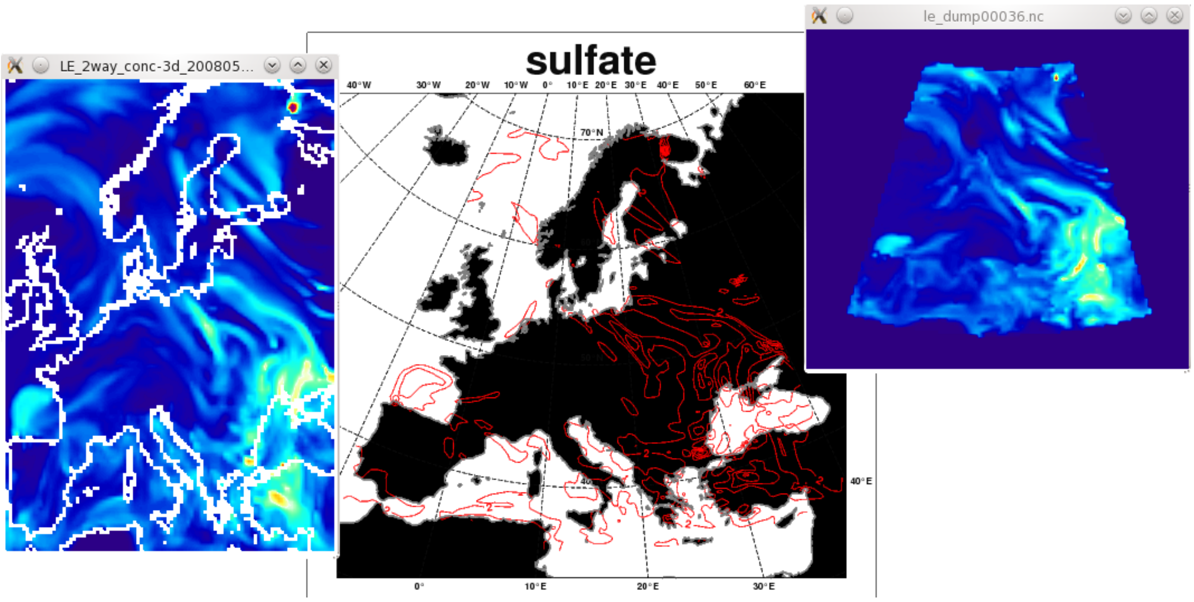

Figure 3 Stages in conversion process from NetCDF to GRIB.

4 Model output storage and exchange

Currently, the models are run together at ECMWF, making use of the processors and storage of the ECMWF. The output of RACMO2 and LOTOS-EUROS was in NetCDF format and was slightly modified to comply with CF conventions. Thus, the output of both models can easily be visualized and used by other models. Example data were made available through KNMI's OPeNDAP server (http://OPeNDAP.nmdc.eu/knmi/thredds/nmdc.html). As the data is readily available at the OPeNDAP server, also WebGIS applications have access to data (see Fig. 4 for an example). At this server, also examples of a header of a RACMO2 and a LOTOS-EUROS NetCDF output file can be viewed. An example of ncBrowse is shown (Fig. 5), this tool can be used to visualize NetCDF files from both local sources and from and OPeNDAP.

Besides the files exchanged by RACMO2 and LOTOS-EUROS, also the more general output of RACMO2 by the *asim2cdf* tool has been adapted. The NetCDF compliance has been improved and standard names have been added. Special attention has been given to the precise mapping and projection parameters for use in GIS systems. Most of the model output that is available in RACMO2 can be processed with asim2cdf .In Van Meijgaard et al. (2008) a complete list can be found.

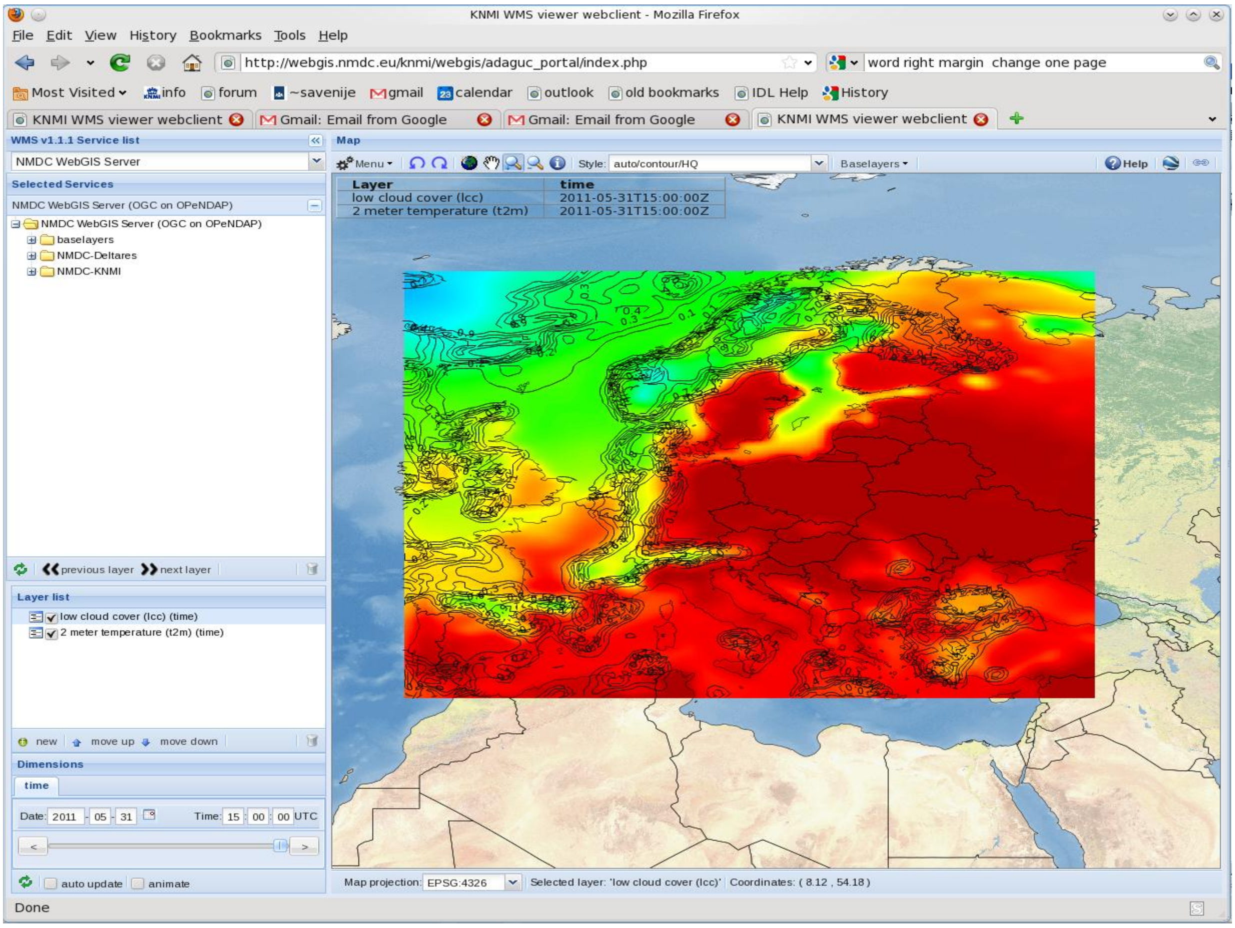

Figure 4 Screenshot of a WebGIS application showing the 2-metre temperature and cloud cover from a RACMO2 output file for LOTOS-EUROS.

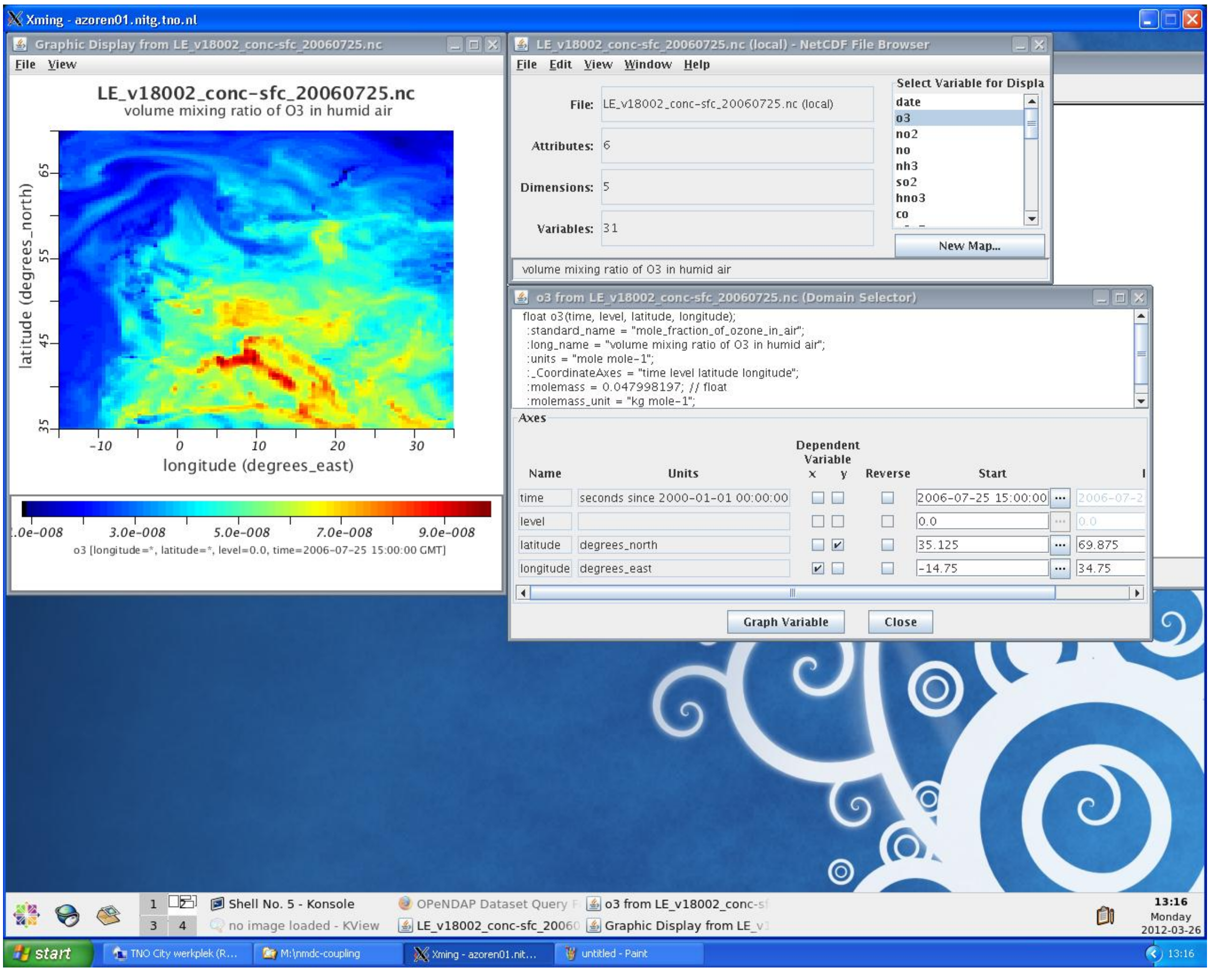

Figure 5 Screenshot of an ncBrowse application showing ozone concentrations at surface level from a LOTOS-EUROS output file.

5 Synopsis and outlook

Within this NMDC project the model output of RACMO2 and LOTOS-EUROS has been standardized according to the CF1.4 convention. This facilitates the exchange between both models and makes it easier for other researchers to analyse the data or use them in their own models. As a proof-of-principle the model data have been transferred to an OPeNDAP server, which can be accessed freely. For a coupled model run, data are not yet exchanged through this OPeNDAP. OPeNDAP is useful if the models are run subsequently, but for the tight connection between RACMO2 and LOTOS-EUROS it would yield a delay.

The updated version of the RACMO2-LOTOS-EUROS coupled system is linked to the ‘Air quality and external safety’ NMDC project in which the direct aerosol effect was implemented (Savenije et al. 2012). In addition a parameterization for the effect of aerosols on precipitation has been developed within past projects and it is planned to implement this parameterization in RACMO2 as well. The adapted version will be used to further determine the impact of aerosols on the climate and vice versa.
There is also an interest to investigate the impact of aerosols on climate changes in the past within the framework of the KNMI’next climate scenarios, however the feasibility of this research topic is not yet clear.

6 Recommendations

In the future, the coupling system could be further optimized. In a two-way coupled run RACMO and LOTOS-EUROS run alternately and have to wait for each other to receive the data for the next model steps. LOTOS-EUROS is the slowest model due to its parallelization structure. RACMO has been parallelized using MPI. Its model domain is decomposed into subdomains and each core performs calculations for a separate subdomain. This means that as long as the domain is sufficiently large model speed increases when more cores are used. LOTOS-EUROS on the other hand, uses OpenMP parallelization and rapidly saturates when the number of cores is increased. For platforms on which the performance was tested the elapsed time hardly decreased anymore when more than 8 CPUs where used. This means that when operated on the latest supercomputers the LOTOS-EUROS component is becoming the bottleneck in performing two-way coupled runs. For long climate runs it would be desirable to improve the parallelization of LOTOS-EUROS and if possible use both MPI and OpenMP or switch to MPI completely.

If this improvement would be achieved then the coupling scripts are likely to become the next bottleneck, in a relative sense.. These scripts and related programs are executed on a single core and and their processing cannot be easily parallelized. However, the largest amount of time is spent on the horizontal interpolation from the RACMO to the LOTOS-EUROS grid and vice-versa. This step could be avoided by running both models on the same horizontal grid .

If both improvements could be achieved, the elapsed time of runs with the two-way coupled RACMO-LOTOS-EUROS system becomes much shorter and carrying out (an ensemble of) long climate runs might become within reach.

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8 Signature

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