SPECIAL PROJECT FINAL REPORT

Project Title:	Modelling interactions between atmospheric composition and climate changes with the Earth system model EC-Earth
Computer Project Account:	spnlcece
Start Year - End Year :	2012 - 2014
Principal Investigator(s)	Dr. T.P.C. van Noije
Affiliation/Address:	Royal Netherlands Meteorological Institute (KNMI)
Other Researchers (Name/Affiliation):	Dr. M. van Weele, Dr. B. Monge-Sanz, N. Banda MSc, C.D. Chuwah MSc, Dr. Ph. Le Sager

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

This project focused on the simulation of changes in the atmospheric composition and interactions between atmospheric chemistry and climate. The modelling system that has been used is the Earth system model EC-Earth with online coupling to the atmospheric chemistry and transport model TM5. Simulations have been performed in the context of a number of projects funded by national or international research programs. The national projects are two PhD projects part of the program 'Feedbacks in the climate system' of the Netherlands Organisation for Scientific Research (NWO). The international projects are the CLIMBAIR Marie Curie Fellowship that was granted to Dr. B. Monge-Sanz, and the Ozone_cci project carried out in the framework of the Climate Change Initiative of the European Space Agency.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

The simulations for the Ozone_cci and CLIMBAIR projects have not been carried out within this Special Project.

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

The application and reporting procedures are reasonable.

Summary of results

(This section should comprise up to 10 pages and can be replaced by a short summary plus an existing scientific report on the project.)

The research that has been carried out within this special project is related to different scientific projects. Below we summarize the main results related to model development, future climate simulations with TM5, methane simulations with EC-Earth, and the EC-IMAGE project.

Model development

TM5

Activities related to the development of TM5 were to large extent aimed at improving the computational performance of the model, in order to make it suitable for long climate simulations when coupled to EC-Earth. Previously, the MPI implementation in TM5 used parallellisation over both vertical layers and tracers, depending on the process the model is simulating. The swapping between the two parallel configurations and the related MPI broadcast operations significantly added to the computational costs. Moreover, because of the limited number of both vertical levels and tracers, it also resulted in a poor scalability. Using computing resources provided by this special project, we changed the MPI implementation of the model to a regular domain decomposition in the horizontal plane. Initially, the maximum number of processor units that could be used was limited to the number of grid points in the latitudinal direction divided by 2. This was related to the model's reduced number of grid cells in the polar regions. Further development activities have removed this limitation. The maximum number of processors is now given by the number of grid columns divided by 4. Initial tests at the ECMWF Cray supercomputer showed optimal performance using around 90 cores (see Figure 1). Work to improve the scalability is ongoing.

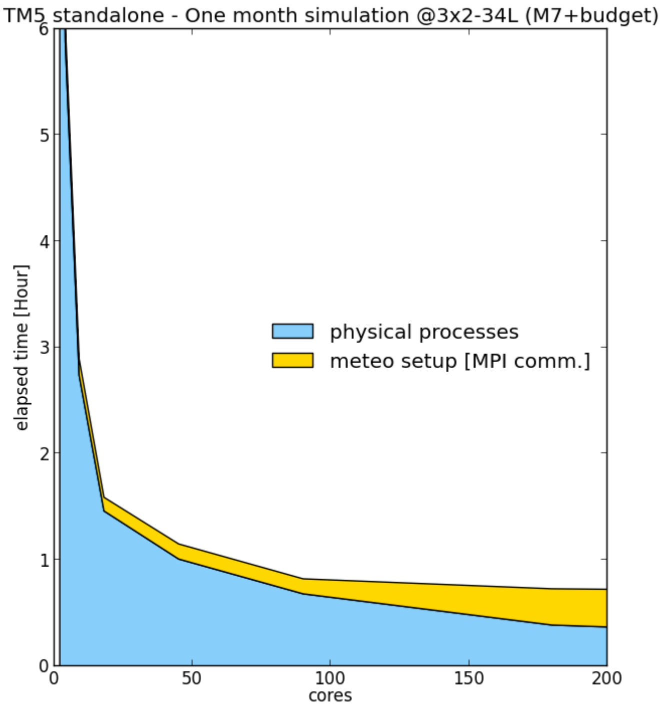

Figure 1. Performance of the new massively parallel version of TM5 versus the number of processor units used, on the ECMWF Cray computer (cca).

TM5 v4 was officially released in September 2013. Since then, development has been continued. An option has been included to use convective fluxes from ERA-Interim instead of computing them from temperature, relative humidity and wind using the Tiedkte scheme. Also, the CBM4 chemistry scheme has been updated to CB05, and major updates of the heterogeneous chemistry and photolysis scheme have been implemented and tested. Furthermore, various new emission datasets have been included (e.g. MACCity, MEGAN) and a daily cycle for NOx emissions from biomass burning has been added. In the stratosphere, there is now an option to nudge CO concentrations as well as the HNO_3:O_3 ratio using a climatology from ODIN instead of UARS.

EC-Earth

Regarding the development of the EC-Earth climate model, we were instrumental in releasing version 2.4 of the EC-Earth climate model in February 2013, which included TM5 v3 and the LPJ-Guess dynamic vegetation model. We later updated it to TM5 v4, and made it work with the new MPI domain decomposition. More recently, the focus of the work has shifted toward the development of EC-Earth v3. We have coupled TM5 v4 to IFS through the new OASIS3-MCT interface, and included the feedback of aerosols concentrations and optical properties and ozone and methane concentrations from TM5 to IFS. In particular, we coupled the relevant TM5 fields with the shortwave and longwave radiation scheme of IFS.

We also contributed to the development of a carbon cycle in EC-Earth v3. As TM5 will be used to transport the CO_2 in the atmosphere, we created and tested a single-tracer TM5 version that ingests the historical and future anthropogenic CO_2 emission estimates as provided to the Coupled Model Intercomparison Project phase 5 (CMIP5).

Future climate simulations with TM5

Next to the online integration of TM5 into EC-Earth, we also developed a software interface that enables running TM5 in standalone mode driven by model-level output from the EC-Earth climate model. The preprocessing of the meteorological data is done in a similar way as for other offline meteorological datasets, such as ECMWF's operational forecasts and reanalysis data. Before the start of this special project, this pre-processor was used to carry out decadal simulations for both present day (2000-2009) and the near future (2026-2035) using EC-Earth output from one of the future scenario simulations carried out within the Coupled Model Intercomparison Project (CMIP5). Specifically, we used a simulation for the Representative Concentration Pathway RCP4.5, which corresponds to a radiative forcing target of 4.5 W/m^2 in 2100. In TM5 the emissions from anthropogenic activities and biomass burning were also prescribed according to this scenario. Thus in the future simulation both the climate and the emissions changed at the same time.

To separate the climate change signal, a new decadal simulation was done at the start of this project with future meteorological fields from EC-Earth, but with present-day emissions. From this simulation we were able to estimate the climate feedbacks related to the response of the CH_4 lifetime and the tropospheric ozone burden to the imposed climate change. In our simulations both responses resulted in small, but significant negative climate feedback. It was also found that the production of NO_x from lightning in the model decreased in the warmer climate, contrary to what we expected based on other studies. This behaviour could be traced back to a bug in the calculation of the lightning NO_x production, which was corrected.

Methane simulations with EC-Earth

TM5 is one of the models participating in the Atmospheric Tracer Transport Model Intercomparison (TransCom) project. Forward simulations of CH_4 carried out in this project showed that TM5 driven by offline ECMWF meteorological data such as ERA-Interim overestimates the interhemispheric gradient in the CH_4 concentration (Patra et al., Atmos. Chem. Phys., 11, 12813-12837, 2011). As simulations with C-IFS produced smaller gradients, we repeated the experiment using EC-Earth with online coupling to TM5. The simulation was carried out for the years 2000-2003. The results showed that EC-Earth indeed produces a more realistic interhemispheric gradient than the TM5 model driven by offline meteorological fields. A number of multi-annual sensitivity simulations have subsequently been performed, to analyse the differences between the offline and online simulations. This work was carried out in collaboration with Dr. S. Houweling from the Netherlands Institute for Space Research (SRON).

“Feedbacks between climate and human systems assessed with a coupled integrated assessment – climate modeling system” (EC-IMAGE)

EC-IMAGE is a 4-year research project funded by NWO, in which KNMI collaborated with the Netherlands Environmental Assessment Agency (PBL). The simulations included here are part of the PhD project of C.D. Chuwah, who is supervised by dr. T. van Noije, prof. W. Hazeleger (KNMI/Wageningen University) and prof. D. van Vuuren (PBL/Utrecht University). The project started in August 2010.

In recent years there is increasing interest in coupling different disciplines involved in climate research (e.g. Van Vuuren et al., 2012). In this project, we attempted to make a closer connection between natural and human model components by coupling EC-Earth to the integrated assessment model IMAGE (Bouwman et al., 2006). IMAGE describes socio-economic, physical and biological factors to make projections of future changes of the world economy, agriculture, land use, emissions, climate and ecological values. Different types of simulations were performed within this project.

First, a number of time slice simulations were performed using TM5 in stand-alone mode driven by offline meteorological fields from the European Centre’s ERA-Interim reanalysis. In these simulations TM5 was applied to calculate future concentrations of reactive gases and aerosols using input on emission scenarios from IMAGE. Emissions were provided for reactive gases (methane, carbon monoxide, non-methane volatile organic compounds, nitrogen oxides, ammonia, and sulfur dioxide), as well as for primary aerosols (black carbon and particulate organic matter).

The scenarios we applied in our simulations are variants of the Representative Concentration Pathways (RCPs) used in the Coupled Model Intercomparison Project (CMIP5) and the IPCC Fifth Assessment Report (AR5). We used IMAGE to produce climate policy scenarios similar to the RCP3-PD and RCP6.0 scenarios. The original RCP3-PD is based on an earlier version of IMAGE, but in this project we used the updated version used for the OECD Environmental Outlook to 2050. In terms of short-lived air pollutants, the RCPs are based on the assumption that economic development will lead to the implementation of more stringent air pollution control in the coming decades. As a consequence, the RCPs generate much lower emissions of ozone and aerosol precursors than in other commonly used scenarios, e.g. from the Special Report on Emissions Scenarios (SRES) and the International Institute of Applied Systems Analysis (IIASA). We therefore made two variants for both RCPs, an RCP-like standard one with low emissions of air pollutants and another one with much higher pollutant emissions.

For these scenarios we performed time-slice simulations for a number of discrete years, including 2005, 2020 and 2050. All simulations have been carried out with meteorological fields for the year 2005. To assess the implications of the different assumptions regarding both climate policy and air pollution control, we analysed surface concentrations of ozone and various aerosol types as well as the differences in radiative forcings. The results have been published in Chuwah et al. (2013).

Activities in the second year focused on the further analysis and evaluation of the simulated surface ozone fields in terms of a number of indices (M7, M12, AOT40) commonly used to describe ozone effects on vegetation. Additional data on plant sensitivies of various crop types were collected from the literature and used to convert the ozone fields from our present-day and future scenario simulations into global maps of relative yield loss factors for the crop types used in the IMAGE model. These maps were implemented into the crop growth module of the IMAGE model. A number of new scenario simulations were carried out to estimate the impact of the projected ozone changes on global crop yields and the related CO_2 uptake. Results are described in Chuwah et al. (2015).

Finally, we calculated the long-term climate response to future aerosol changes using EC-Earth. We used the model in CMIP5 configuration with aerosol concentrations prescribed based on output from the CAM model. The alternative aerosol scenarios were implemented by scaling the CAM concentration values based on the TM5 scenario estimates of the burdens of sulphate, black carbon and organic aerosol. Time slices were performed with present-day conditions for 2005 and for our IMAGE variants of the RCP6.0 scenario for 2050, assuming both high and low air pollution control policies. Additional simulations were performed to estimate the effect of individual aerosol components. For each case the model was run for ~180 years, sufficiently long to reach a steady state and produce statistically significant differences among the simulations. The results have been analysed with focus on the effects the different aerosol concentrations have on the radiation balance and the global and regional climate (Chuwah et al., under review). As an example Fig. 1 shows the mean difference in the net shortwave radiation at the surface between the high and the low air pollution scenario.

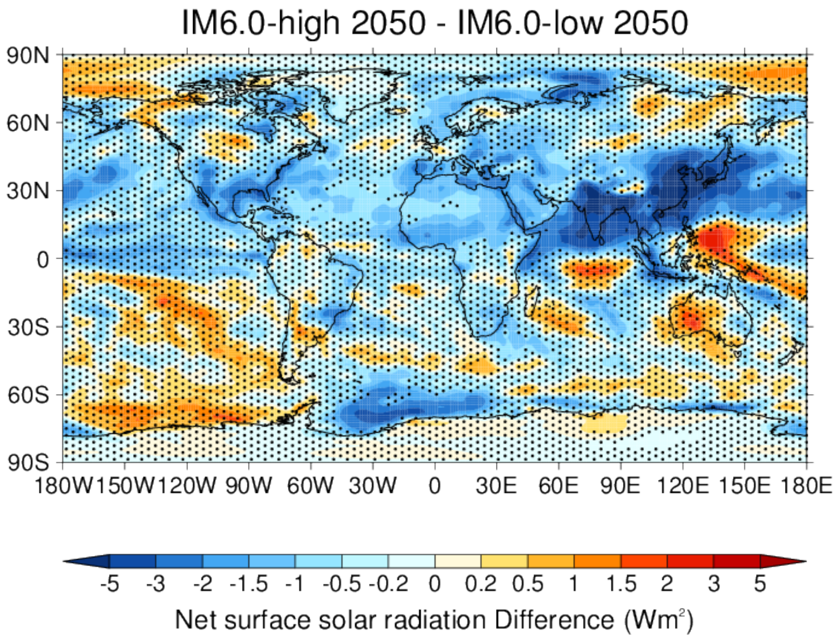

Figure 1. The difference in the net shortwave radiation at the surface in EC-Earth due to differences in aerosol concentrations between the high and low air pollution variants of RCP6.0, produced with the IMAGE integrated assessment model.

List of publications/reports from the project with complete references

Bândă, N., M. Krol, M. van Weele, T. van Noije, and Thomas Röckmann, Analysis of global methane changes after the 1991 Pinatubo volcanic eruption, Atmos. Chem. Phys., 13, 2267-2281, 2013.

Bândă, N., M. Krol, T. van Noije, M. van Weele, J. Williams, P. Le Sager, U. Niemeier, L. Thomason, and Thomas Röckmann, The effect of stratospheric sulfur from Mount Pinatubo on tropospheric oxidizing capacity and methane, J. Geophys. Res., 120, 1202-1220, 2015.

Bândă, N., M. Krol, M. van Weele, T. van Noije, and Thomas Röckmann, Can we explain the observed methane variability after the Mount Pinatubo eruption?, Atmos. Chem. Phys. Discuss., submitted.

Bândă, N., Variations in the atmospheric methane budget after the Mount Pinatubo eruption, PhD thesis, Utrecht University, 2015.

Chuwah, C., T. van Noije, D.P. van Vuuren, W. Hazeleger, A. Strunk, S. Deetman, A. Mendoza Beltrán, and J. van Vliet, Implications of alternative assumptions regarding future air pollution control in RCP-like scenarios, Atmos. Environ., 79, 787-801, 2013.

Chuwah, C., T. van Noije, D. van Vuuren, E. Stehfest en W. Hazeleger, Global impacts of surface ozone changes on crop yields and land use, Atmos. Environ., 106, 11-23, 2015.

Chuwah, C., T. van Noije, D.P. van Vuuren, P. Le Sager and W. Hazeleger, Climate impacts of future aerosol mitigation in an RCP6.0-like scenario, under review.

Lauwaet, D., P. Viaene, E. Brisson, T. van Noije, A. Strunk, S. Van Looy, B. Maiheu, N. Veldeman, L. Blyth, K. De Ridder, and S. Janssen, Impact of nesting resolution jump on dynamical downscaling ozone concentrations over Belgium, Atmos. Environ., 67, 46-52, 2013.

Lauwaet, D., P. Viaene, E. Brisson, T. van Noije, A. Strunk, S. Van Looy, B. Maiheu, N. Veldeman, L. Blyth, K. De Ridder, and S. Janssen, The effect of climate change and emission scenarios on ozone concentrations over Belgium: a high resolution model study for policy support, Atmos. Chem Phys., 14, 5893-5904, 2014.

Naik, V. A. Voulgarakis, A.M. Fiore, L.W. Horowitz, J.-F. Lamarque, M. Lin, M. J. Prather, P. J. Young, …, T.P.C. van Noije, et al., Preindustrial to present-day changes in tropospheric hydroxyl radical and methane lifetime from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP), Atmos. Chem. Phys., 13, 5277–5298, 2013.

Stevenson, D.S., P.J. Young, V. Naik, J.-F. Lamarque, D.T. Shindell, A. Voulgarakis, …, T.P.C. van Noije, et al., Tropospheric ozone changes, radiative forcing and attribution to emissions in the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP), Atmos. Chem. Phys., 13, 3063-3085, 2013.

Van Noije, T.P.C., P. Le Sager, A.J. Segers, A. Strunk, M.C. Krol, and W. Hazeleger, Simulation of tropospheric chemistry and aerosols with TM5 coupled to the climate model EC-Earth, Geosci. Model Dev., 7, 2435-2475, 2014.

Van Vuuren, D.P., L. Batlle Bayer, C. Chuwah, L. Ganzeveld, W. Hazeleger, B. van den Hurk, T. van Noije, B. O'Neill, and B.J. Strengers (2012), A comprehensive view on climate change: coupling of earth system and integrated assessment models, Environ. Res. Lett., 7, doi:10.1088/1748-9326/7/2/024012, 2012.

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

Application for a new Special Project will depend on the computing resources we will have available to participate in CMIP6 satellite projects, in particular AerChemMIP.