SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	EC-EARTH: developing a European Earth System model based on ECMWF modelling systems
Computer Project Account:	SPNLTUNE
Start Year - End Year :	2015 - 2017
Principal Investigator(s)	Dr. Ralf Döscher
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Other Researchers (Name/Affiliation):	Dr. Souhail Bousetta (ECMWF) and Dr. Glenn Carver (ECMWF)

The following should cover the entire project duration.

Summary of project objectives
(10 lines max)

The integration, testing and tuning of components in EC-Earth 3 are representing a major effort in the development of the model in the framework of this project. Main objectives were

- to complete the model with features and forcing necessary for CMIP6. Here we focus on effects of aerosol, albedo of ice sheets, orbital forcing, atmospheric nudging and variable land use.
- to test and tune the atmosphere-standalone model based on the IFS cyc 36 and EC-Earth-specific modifications in climate model. This work was done in the expected standard resolution, which is planned for most applications in the CMIP6 project. The goal was to reduce biases and at the same time maintain a stable model suitable also for coupled applications.
- tune different versions and Earth system model configurations of the model and to finalize features and forcing necessary for CMIP6.

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

We did not experience major technical problems with the computing environment. Challenges exist concerning the EC-Earth tuning. Those are addressed in the summary of results.

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

Application and reporting went smoothly

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.)

During the three years of the project

- we investigated the sensitivity of the EC-Earth radiative fields and performance indexes to a number of parameters that affects convection, entrainment rates, precipitation, and other various water-cycle-related features.
- we implemented and tested several parameterizations
- we tuned several versions of EC-Earth 3 atmosphere-standalone, GCM configurations and ESM configurations
- We implemented, debugged and tested various forcing functions provided and updated by CMIP6.

Model development

Significant work has been performed since the beginning of this special project for developing EC-Earth v3 (based on IFS cy36r4 and NEMO 3.6), with aim to reach a well-tuned Earth-System-Model, suitable for performing CMIP6 simulations and addressing a wide range of scientific questions. Almost 200 issues have been opened and addressed on the EC-Earth development portal, accompanied by the necessary numerical experiments, since the beginning of this SP in 2015. A tight schedule of model releases has been included EC-Earth 3.2.1 in December 2016 (used for AMIP tuning) and EC-Earth 3.2.2 in March 2017 (used to test and tune the coupled model). Resources provided by this SP have been essential to achieve the final goal, with a final, greatly improved, release of EC-Earth v3 suitable for CMIP6 and other projects during 2018.

Another important component of the SP usage was the implementation and testing of CMIP6 forcing functions into the different components and configurations of the ESM. Below we show selected exampled of specific tuning and testing work.

Sensitivity tests:
We have tested the sensitivity of the EC-Earth radiative fields and performance indexes (PIs) to 12 different parameters that affects convection, entrainment rates, precipitation, and other various water-cycle-related features. Tuning experiments were carried out in atmosphere-standalone mode. We were successfully able to reduce the net top-of-the-atmosphere (TOA) long wave (LW) and short wave (SW) fluxes, and this can be achieved in different ways. Most efficient tuning buttons are RPRCON (controls the rate of conversion of cloud water to rain) and RVICE (regulates fall speed of ice particles), since they operate on high cloud cover. Supplementary tuning is likely needed for optimal results once the model will be run in coupled mode.

Development and tuning of EC-Earth version 3.2 with coupling to TM5
Activities with TM5 at KNMI have largely been focused on the development and tuning of the EC-Earth version with coupling to the atmospheric composition module TM5. After the EC-Earth version 3.2-beta was released in late 2015, it has been merged with the multi-component branch, which includes the interactive coupling with TM5. With this model configuration, a number of short atmosphere-only simulations have been performed with one-way and two-way coupling to TM5. The analysis has focused on the simulation of tropospheric aerosols.
Three lines of development were followed:

- Analysis of aerosol direct radiative effects
- Development and tuning of atmospheric nudging for tropospheric composition simulations
- Tuning of the dust emission source in free climate simulations

Analysis of aerosol direct radiative effects

The radiative effects due to direct aerosol-radiation interactions was analyzed using atmosphere-only simulations for present-day conditions with prescribed sea-surface temperatures and sea ice

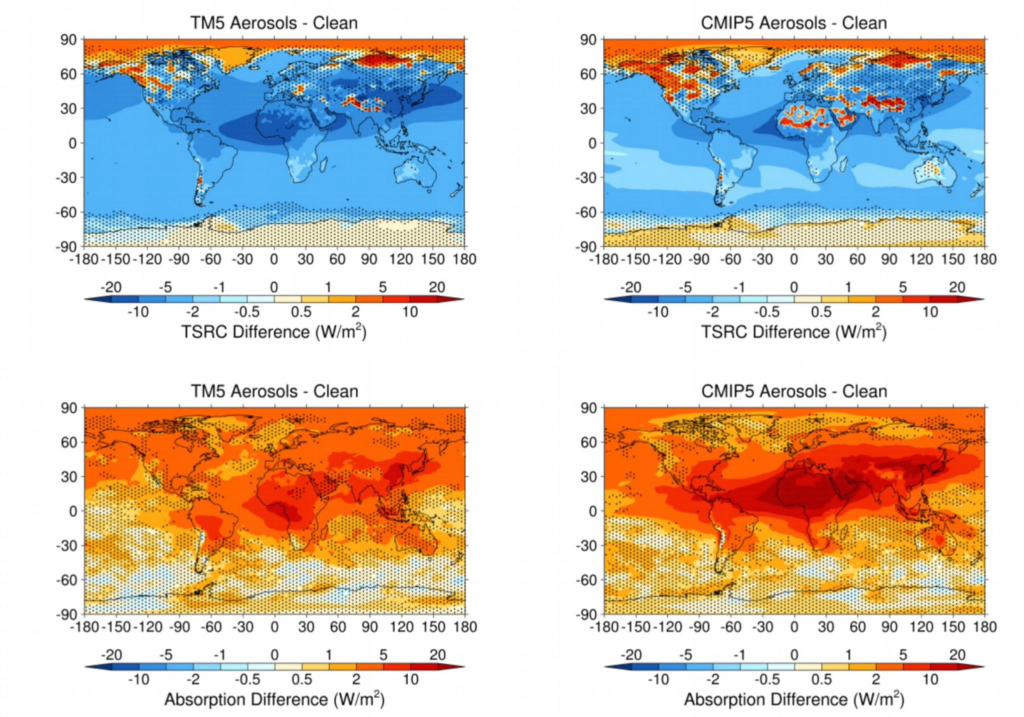

Figure 1. Aerosol direct radiative effects on the clear-sky flux at the top of the atmosphere (top) and on the atmospheric absorption (bottom), for the cases with interactive (left) and prescribed (right) aerosols. The flux perturbations shown are annual means based on the first two simulated years. The stippled areas indicate regions where the aerosol effects are statistically insignificant at the 5% level.

The simulation with interactive aerosols gives qualitatively similar flux perturbation patterns as the simulations with prescribed CMIP5 aerosols. It should be noted that the model has been improved in several aspects after completion of these simulations. For instance, the snowfall contribution was missing in the large-scale and convective precipitation fields that IFS sent to TM5, reducing the wet removal at high latitudes. Also, the calculation of dust emissions in the interactive simulations has been revised (see below).

Development and tuning of atmospheric nudging for tropospheric composition simulation

Code for nudging of atmospheric fields was ported to EC-Earth 3.2-beta, and merged with the multi-component branch, allowing to do atmospheric composition simulations with nudging of IFS towards ERA-Interim fields. A large number of two-year simulations have been performed in atmosphere-only configuration with interactive coupling to TM5, for various combinations of the nudging coefficients applied for the different variables. In this way, we assessed the possibility to reproduce the results from the standalone TM5 model driven by ERA-Interim meteorological fields. Our preliminary conclusion is that the best agreement is obtained using a nudging time scale of around 6 hours for vorticity, divergence, temperature and surface pressure, with nudging of specific humidity and cloud variables switched off. With these settings, the nudged EC-Earth simulation produces quite similar aerosol concentrations and optical depths as the standalone model, although differences remain due to differences in model physics (e.g. the convective parameterization) and resolution between the IFS version used in EC-Earth (T255L91) and ERA-Interim (T159L60). In Figure 2 we compare the simulated aerosol optical depth from the standalone and nudged simulations for boreal summer 2006.

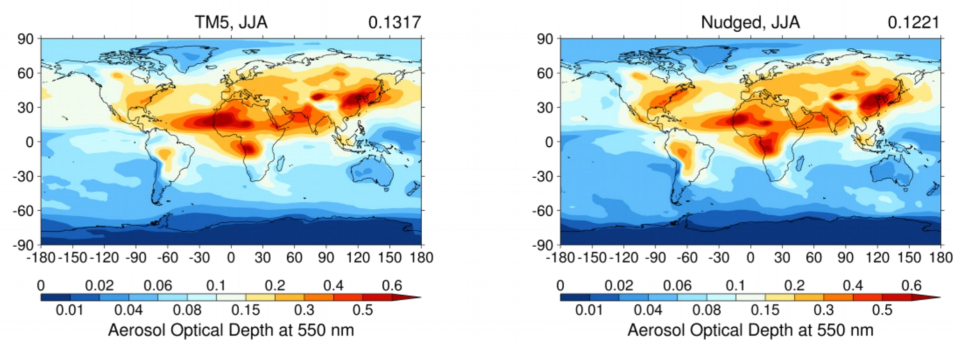

Figure 2. Aerosol optical depth for summer 2006, simulated by the standalone TM5 model driven by ERA-Interim (left) and by the same TM5 configuration as part of EC-Earth with IFS nudged to ERA-Interim (right).

We also tested the effect of reducing the coupling period for the exchange between IFS and TM5 in EC-Earth from six to three hours. The results from these tests indicate that reducing the coupling period below 6 hours does not substantially change the simulation of atmospheric composition variables.

Tuning of the dust emission source in free climate simulations

Additional simulations with EC-Earth 3.2-beta in free climate mode with one-way coupling to TM5 have been carried out. The resulting aerosol concentration and optical depth have been compared against the results obtained with the standalone version of TM5 driven by ERA-Interim. The wind-driven dust source calculated in TM5 turned out to be much higher in EC-Earth. This is a well-known feature of the dust source parameterization in the model, in which dust is assumed to be mobilized only above a certain threshold surface wind speed. To minimize resolution dependencies, a parameter was introduced in the parameterization which acts as a scaling factor for this threshold. A number of sensitivity simulations have been performed, in which the value of this parameter was changed between the default value of 0.6 and 1.0. For the untuned version of EC-Earth 3.2-beta, reasonable emission amounts are obtained using a value around 0.7. Increasing the tuning parameter from 0.6 to 0.7 reduces the global dust source from about 2660 to 1250 Tg/yr, compared to 990 Tg/yr in the standalone simulation. Additional fine tuning of this parameter will be undertaken once a finally tuned CMIP6 version of EC-Earth GCM will be released.

Albedo Parameterizations as Calibration Tool for a coupled Greenland Ice Sheet model and EC-Earth

The albedo of the surface of ice sheets changes through the year, as a function of deposition of fresh snow, ageing of dry snow, and melt and runoff. Currently, the albedo of ice sheets is highly simplified within the Earth System Model EC-Earth, by taking a constant value for areas with thick perennial snow cover. To improve on this, several adjusted snow albedo schemes are tested here on their performance on the Greenland ice sheet.

The different snow albedo schemes used in the different model groups in Stockholm, Copenhagen and Utrecht groups are compared. Different choices are made for time-decaying or constant albedo for either wet or dry conditions, and different values for maximum and minimum snow albedo are used.

As albedo influences the surface energy balance, and thereby the surface mass balance (SMB), the effect of different albedo schemes on Greenland ice sheet SMB is assessed. As a following step, SMB is downscaled to the Greenland topography on a higher resolution, and the influence of these different climatologies on the long-term evolution of the Greenland ice sheet is tested. This results in an optimal albedo parameterization that can be used in future EC-Earth simulations with interactive ice sheet component.

Testing, tuning and debugging the low resolution version of EC-Earth

Low resolution versions of EC-Earth are the configurations T159L62ORCA1L46 and T159L62ORCA1L75.
Stockholm university performed tuning and testing for EC-Earth 3.2 at lower resolution to resolve issues about numerical instabilities. The goal was to identify and correct any bugs in the code, configuration, or initial files that cause instabilities and make sure that the model can be run for at least 50 model years without regular crashes.

Orbital forcing in EC-Earth

Orbital forcing was implemented that can be controlled at runtime and testing in EC-Earth 3.2. The orbital forcing in IFS model was fixed at some present-day condition which is sufficient for most experiments. However, paleo runs and very long simulations e.g. last millennium runs, require a variation of the orbital forcing. Implementation and extensive testing has been carried out.

Variable land use in EC-Earth

Variable land-use and vegetation was implemented and tested in EC-Earth 3.1 and 3.2. IFS reads a seasonal cycle albedo based on MODIS observations and it is repeated after every year. For transient simulations we need to adjust this file to reflect the changes in land-use and vegetation over time. This is mainly targeted for ESM simulations and related to LPG-Guess. An albedo look-up table based on the 4 albedo values (UV, VIS, Diff, Direct) is derived based on the previous work.

AMIP tuning and coupled tuning

In particular owing to the need to keep to delayed CMIP6 deadlines, during 2017 it has been necessary to perform a large set of AMIP and coupled numerical simulations with the model using the project resources. The simulations which have been performed include long coupled model runs both at standard (T255L91/ORCA1), high (T511L91/ORCA025) and low (T159L62ORCA1L75) resolutions, over decades and hundreds of model years respectively. In particularly AMIP tuning of the standard and high-resolution versions of the model and long coupled runs at standard resolution (needed to investigate and fix energy conservation issues between the atmosphere and the ocean) had a consistent impact on the use of resources. Still, the use of the resources of this SP has allowed to reach solutions for all these issues.

The bulk of the tuning work was dedicated to testing of parameter combinations with central tuning targets in the radiative and heat flux balances at the TOA and between the ocean and the atmosphere. Also, global mean temperatures and precipitation and evaporation has been considered. As a result, we have well-balanced atmosphere standalone configurations, which currently serve as the base for further coupled tuning, which involves solving issues of ocean circulation, ocean temperature and sea ice cover.

Albedo of the Greenland ice sheet

The importance of albedo parameterization for the surface mass balance of the Greenland ice sheet in EC-Earth has been tested by Helsen et al. (2016). The albedo of the surface of ice sheets changes is a function of time, due to the effects of deposition of new snow, ageing of dry snow, bare ice exposure, melting and runoff. Currently, the calculation of the albedo of ice sheets is highly parameterized within the Earth System Model EC-Earth, by using a constant value for areas with thick perennial snow cover. This is an important reason why the surface mass balance (SMB) of the Greenland ice sheet (GrIS) is poorly resolved in the model. The purpose of this study was to improve the SMB forcing of the GrIS, by evaluating different parameter settings within a snow albedo scheme. The resulting SMB is downscaled from the lower resolution global climate model topography to the higher resolution ice sheet topography of the GrIS, such that the influence of these different SMB climatologies on the long-term evolution of the GrIS is tested by ice sheet model simulations (Fig. 3). This results in an optimised albedo parameterization that can be used in future EC-Earth simulations with an interactive ice sheet component.

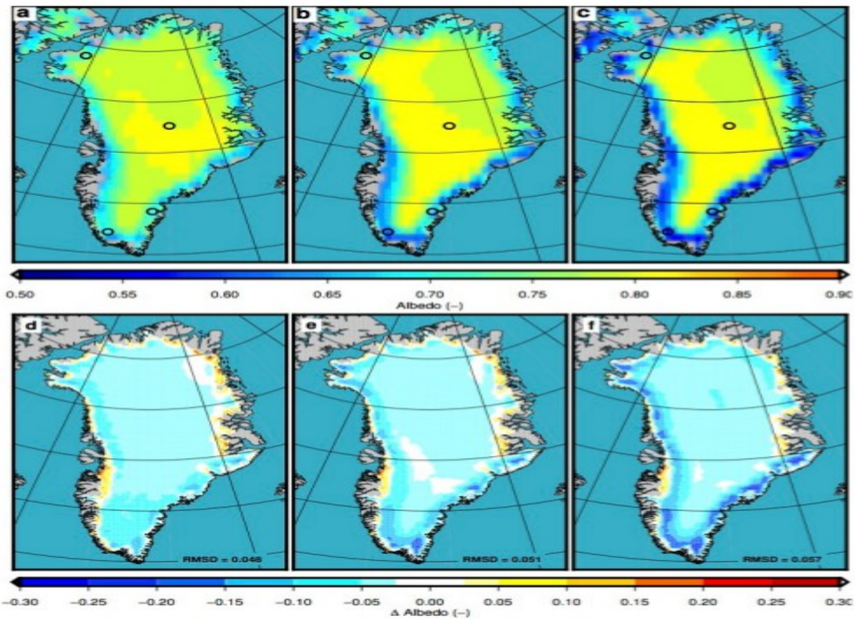

Figure 3. Average JJA albedo (1990-2012) from EC-Earth for the "Sto" scheme (a), "Cph" scheme (b) and the "Utr-8" scheme (c). Difference with JJA albedo from RACMO2 (Van Angelen et al., 2014) is shown in (d-f). Albedo is only shown for the ice sheet surface type, i.e. grey land area is outside the ice sheet domain in EC-Earth.

Implementing of primary biological aerosol particles (PBAP)

Treatments of emissions of primary biological aerosol particles (PBAP) were implemented in the global Earth System model EC-Earth. These emission schemes were improved to account for the strong peaks of PBAP concentrations in connection to precipitation events, which has been measured recently. The model is now able to treat the emission of bacteria, spores (Fig. 4) and pollen in dependency of precipitation, 10m wind speed, relative humidity, season, vegetation type, vegetation cover, and leaf area index. Sensitivity studies on the degree of detail of the PBAP emission parameterization were conducted. The resulting concentration fields of the three PBAP were compared between the different sensitivity setups and, more generally, to the rare available measurements. The model is applied for a set of sensitivity studies concerning the degree of detail of the enhanced PBAP emission parameterizations. The global simulations were conducted for one year (2006) with a 3°x2° horizontal resolution.

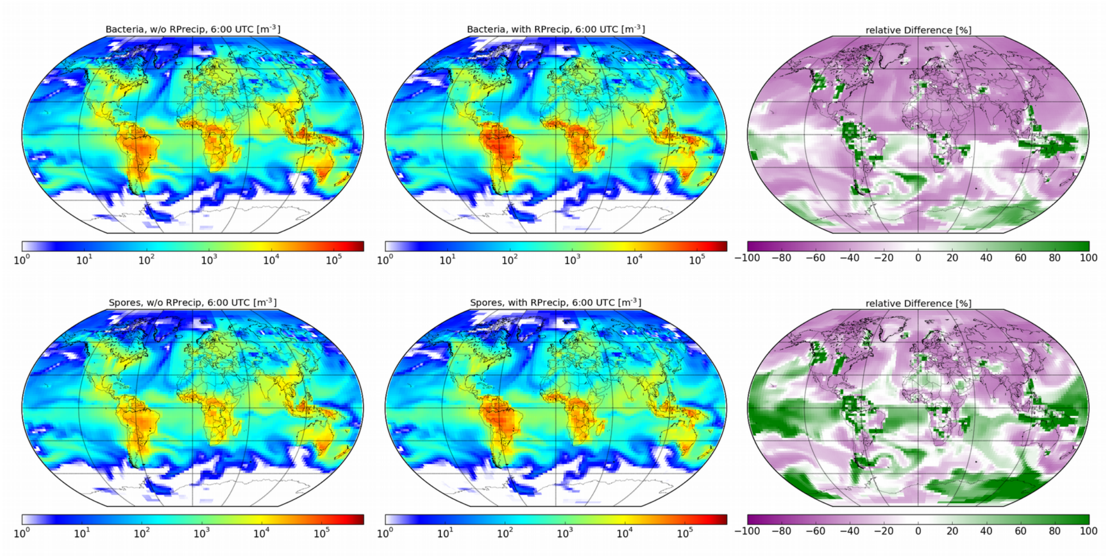

Figure 4. Modelled bacteria (upper) and spores (lower) number concentration without (left) and with emission additionally triggered by precipitation (middle), and relative difference between both.

Other testing and tuning activities

Further simulations under the SPNLTUNE account have been carried out to

- implementing and testing CMIP6 stratospheric ozone and aerosols: the EC-Earth code has been modified to read the CMIP6 data sets and remap them to the IFS grid. Testing these implementation required running the model for few years with the old and new forcings and to compare the results. Additional small runs tested the robustness of the code with different setup (random start date, various run length, etc).

- prepare ERA-20C 1950 initial conditions: data sets were retrieved through MARS requests, modified to account for EC-Earth land characteristics (e.g. orography). Spin up runs of 20 years were needed to stabilize the soil moisture. This was done at standard and high resolutions.

- configure the AMIP-reader for fixed year application

- test and merge atmospheric nudging functionality

- test and merge aerosol forcing for GCM configurations (MACv2-SP)

- testing and syncronizing trunk and tuning branches

- implementing and testing a new description of Secondary Organic Aerosol (SOA) formation from monoterpenes and isoprene.

- A new particle formation was improved by a scheme taking into account both monoterpenes and sulfuric acid.

- tuning of the Atlantic meridional overturning circulation (AMOC)

- testing and tuning of the low-resolution of the new EC-EARTH versions, i.e. v3.2.1/3.2.2 in the T159L62ORCA1L75 configuration. Tuning was started based on parameters obtained from previous AMIP tunings at standard resolution T255L91ORCAL75, and continued by coupled simulation tuning at low resolution. Central tuning targets were the radiative balances at TOA and at the interface between ocean and atmosphere for recent climate. Tuning details of the experiments and the corresponding namelists are summarised on the EC-Earth portal.

List of publications/reports from the project with complete references

We are listing selected publications based on earlier phases of the SPNLTUNE project and predecessors.

Davini P.,von Hardenberg J., Filippi, L., Provenzale A. (2014). Impact of Greenland orography on the Atlantic Meridional Overturning Circulation. *Geophysical Research Letters.* Article in Press.

Palazzi, E., von Hardenberg, J., Terzago, S., Provenzale, A. (2014). Precipitation in the Karakoram-Himalaya: a CMIP5 view. *Climate Dynamics*, 25 p. Article in Press. doi: 10.1007/s00382-014-2341-z

Van Noije, T.P.C., Le Sager, P., Segers, A.J., van Velthoven, P.F.J., Krol, M.C., Hazeleger, W., Williams, A.G., and Chambers, C.D., 2014. Simulation of tropospheric chemistry and aerosols with the climate model EC-Earth, Geosci. Model Dev., 7, 2435-2475, doi:10.5194/gmd-7-2435-2014.

Weiss, M., Miller, P., van den Hurk, B., van Noije, T., Stefanescu, S., Haarsma, R., van Ulft, L.H., Hazeleger, W., Le Sager, P., Smith B., and Schurgers, G., 2014. Contribution of dynamic vegetation phenology to decadal climate predictability, J. Climate, doi:10.1175/JCLI-D-13-00684.1.

Pausata, Francesco SR, Gabriele Messori, and Qiong Zhang. "Impacts of dust reduction on the northward expansion of the African monsoon during the Green Sahara period." Earth and Planetary Science Letters 434 (2016): 298-307. doi:10.1016/j.epsl.2015.11.049

Muschitiello, F., Q. Zhang, H. S. Sundqvist, F. J. Davies, and H. Renssen, 2015: Arctic climate response to the termination of the African Humid Period. Quaternary Science Reviews, 125, 91-97, doi:10.1016/j.quascirev.2015.08.012.

Davini P.,von Hardenberg J., Filippi, L., Provenzale A. (2014). Impact of Greenland orography on the Atlantic Meridional Overturning Circulation. *Geophysical Research Letters.* Article in Press.

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.)

We did apply successfully for another SP starting 2018 and ending 2020.