REQUEST FOR A SPECIAL PROJECT 2015–2017

MEMBER STATE: Sweden

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Project Title: EC-EARTH: developing a European Earth System model based on ECMWF modelling systems

If this is a continuation of an existing project, please state the computer project account assigned previously.	**SP** NLTUNE	
Starting year: (Each project will have a well defined duration, up to a maximum of 3 years, agreed at the beginning of the project.)	2015	
Would you accept support for 1 year only, if necessary?	YES ☒	NO ☐

Computer resources required for 2015-2017: (The maximum project duration is 3 years, therefore a continuation project cannot request resources for 2017.)		**2015**	**2016**	**2017**
High Performance Computing Facility	(units)	25,000,000	25,000,000	25,000,000
Data storage capacity (total archive volume)	(gigabytes)	70,000	70,000	70,000

An electronic copy of this form ***must be sent*** *via e-mail to:* *special_projects@ecmwf.int*

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1 The Principal Investigator will act as contact person for this Special Project and, in particular, will be asked to register the project, provide an annual progress report of the project's activities, etc.

Principal Investigator: Dr. Ralf Doescher

Project Title: EC-EARTH (SPNLTUNE)

Extended abstract

EC-EARTH: developing a European Earth System model based on ECMWF modelling systems

Introduction

Around 2006, the need for an Earth System Model (ESM) was recognized by various ECMWF Member States (MS). This effectively initiated the development of EC-Earth (see http://www.ec-earth.org). EC-Earth is both a model and a consortium that develops and applies the model. The model is almost completely based on ECMWFs seasonal forecasting system (system 4). EC-Earth offers the opportunity to use computational infrastructure efficiently, share expertise between MS and ECMWF, and limit the number of different model frameworks currently in use for forecasting and climate applications by MS. Collaboration with ECMWF has been quite fruitful, for instance in developing ECMWFs land and snow scheme, in providing boundary conditions for ERACLIM and in ocean-sea ice coupling to the atmosphere.

EC-Earth has been developed to a state-of-the-art model system and as such contributed significantly to CMIP5, the model intercomparison project that fed into the 5th IPCC report. It also provided MS data to downscale global climate change to regional levels. Scientifically, studies on the feedbacks in the climate system and on predictability of the climate system have been conducted with EC-Earth, which already led to dozens of scientific publications. Also, EC-Earth has become a prominent model within the European 'ecosystem' of Earth system models, as shown by the involvement in many European projects, including projects on high performance computing.

In 2012 EC-Earth v3 was released. This version is based on the ECMWF seasonal cycle version 4. More precisely, it is based on a newer cycle of ECMWFs IFS model (c36r4), the NEMO ocean model (v3.3.1), the LIM3 sea ice model, as well as H-TESSEL for land. Coupling is provided by OASIS3 and an OASIS3-MCT has been implemented and is currently being tested. This model is currently being optimized for a standard horizontal resolution of T255 and 91 vertical layers for the atmosphere, and for 1 degree and 46 layers for the ocean. In addition, high-resolution versions of this version are currently being tested (0.25 degrees in the ocean and T511 and T799 in the atmosphere). The latest version of the model (v 3.1) was released in May 2014 and contains several bugfixes and the results of the tuning efforts up to that moment.

Model configuration and future developments

For studying Earth system feedbacks and interactions with socio-economic systems, including exploring policy options on emissions of greenhouse gases and precursors of aerosols, atmospheric chemistry and a representation of ecosystems is needed. This implies an extension of the physical modules in EC-Earth towards chemical and biogeochemical components. In early 2013 a development ESM version of EC-Earth (v2.4) was released. This includes a coupling to the atmospheric chemistry model TM5, including the M7 aerosol module, and to the LPJ-GUESS dynamical vegetation module. This model version will merge at the end of the current year with v3, and in 2015 the PISCES ocean biogeochemistry module will be integrated, so as to progress in the development of EC-Earth v3 into a full Earth System Model (ESM). Moreover, as a way forward, new components are currently being developed and tested, such as interactive ice sheets and even coupling to integrated assessment models.

The integration, testing and tuning of these components in EC-Earth v3 will represent the major effort in the development of the model in the framework of this project.

It is found that coupling atmospheric chemistry and aerosols dramatically increases the number of state variables. This is partially relieved by reducing the resolution at which the atmospheric chemistry component of EC-Earth (TM5) should run, which is thus considerable lower than that of the atmosphere model.

All physical modules should be run on sufficiently high resolution to be able to realistically simulate the large-scale circulation and internal variability in the atmosphere and ocean. Moreover, the model should be able to produce stable 'climates' without flux corrections. The model should also be computationally efficient so as to make seasonal, multi-annual and even multi-decadal runs 'routinely', particularly in high resolution. These may contribute to climate services by addressing the (regional) predictability and associated uncertainties on these time scales. A full interactive coupling between the components is required to realistically represent the physics of the climate system.

In order to simulate extremes, weather regimes should be well simulated. Experimentation has shown that for this purpose at least a horizontal resolution of T511 is required in the atmosphere. Moreover, the dynamical scales of relevance in the ocean are related to the Rossby radius of deformation, which is about 20 km in the midlatitudes, but reduces to km scale in high latitudes.

Finally, flexibility in the input fields such as emissions, concentrations, topography, land surface conditions, as well as in the output fields, is essential. The increase in resolution and the number of output variables puts a large burden on the storage capacity.

The standard resolution for v3 is T255 in the atmosphere and 1 degree in the ocean. This version is the first target for model tuning and optimization, performed by a dedicated tuning working group, with contributions from participants from all consortium members and using resources from this project. A high-resolution version at T511 with 91 vertical levels, coupled with NEMO using a ORCA025 grid is also being developed and tested. The ocean model version in the model will be upgraded to NEMO v3.6 for the beginning of 2015 and will allow using also a new version of LIM3 with multi-category ice and a smoother integration of PISCES.

EC-Earth V3 uses the Louvain-la-Neuve sea ice model version 3 (LIM3) as part of the NEMO system. LIM3 allows - in contrast to LIM2 - several ice thickness categories. While EC-Earth v3 is currently using only a single ice thickness category in its standard development, it is planned to implement multicategory ice in the framework of this special project and in time for CMIP6.

The Tracer Model 5 (TM5) has been integrated in EC-Earth for interactive simulation of atmospheric chemistry and transport. Currently, TM5 is used to simulate aerosol particles and reactive gases, including the greenhouse gases ozone and methane; in the near future, TM5 will also be used to simulate the transport of CO_2 through the atmosphere. The TM5 version currently included in EC-Earth simulates tropospheric photochemistry and aerosols (Van Noije et al., 2014). The gas-phase chemistry scheme is an updated version of the carbon bond mechanism 4. Sulphate, black carbon, organic carbon, sea salt and mineral dust are described by a modal aerosol microphysics scheme, and ammonium and nitrate by a thermodynamic equilibrium model. Aerosol optical properties are calculated based on Mie theory, using effective medium theory for internally mixed particles. A simplified, linearized chemistry scheme for stratospheric ozone will be included in a following version of EC-Earth v3. The data exchange between TM5 and other modules of EC-Earth takes place through OASIS3. TM5 receives both meteorological data and surface property fields from IFS. The concentrations of ozone and methane as well as the various aerosol concentration and optical property fields can be sent back to IFS. These fields will be used to evaluate the direct radiative effects and aerosol-cloud interactions in EC-Earth V3. Couplings between TM5 and LPJ-Guess are also under development.

LPJ-Guess allows for vegetation to dynamically evolve, depending on climate input, and in return provides the climate system with vegetation-dependent fields such as surface albedo and leaf area index. Major update from version 2.3 is the coupling with the state-of-the-art dynamic vegetation model LPJ-Guess (Smith et al., 2001; Sitch et al., 2003), replacing components of the previous parameterisation of vegetation. The interaction between the atmospheric land surface module of EC-Earth and the vegetation model LPJ-Guess is set up to cover many mutually exchanged variables. In the current version the dynamic vegetation model is driven by the daily atmospheric fields from EC-Earth (short-wave radiation, temperature, total precipitation, and snow) and it returns leaf area index separately for all high vegetation and all low vegetation per grid cell to the land-surface module (HTESSEL) of the atmospheric model. In this coupling approach we tolerate discrepancies in the soil hydrology, as soil water content were calculated individually by each model. The soil properties and horizontal resolution of LPJ-Guess are harmonized with HTESSEL.

Planned updates of this interface are:

- Soil moisture nudging between HTESSEL and LPJ-Guess
- Exchange of fraction of vegetation cover (additional to the exchange of LAI)

- Flexible restart dates (LPJ-Guess currently can only be initialized on 1 Jan of each year)
- Refinement of determination of low and high vegetation LAI
- Effective vegetation cover through Lambert-Beer formulation of the vegetation densities

Model tuning and validation

The tuning activities in the past three years (2012-2014) have profited to a large extent from SPNLTUNE resources and have allowed to significantly improve EC-Earth 3, at standard resolution, leading to the recent release of version 3.1. Compared to the initial release from 2012 (EC-Earth 3.0.1) v3.1 presents the following main improvements obtained from development and tuning:

- The major improvement introduced during the tuning of the model is the reduction of the bias in the TOA-SFC radiation imbalance from -2.46 W/m^2 to -1.06 W/m^2, thanks to the introduction of a proportional advection mass fixer backported from IFS cycle 38r1. IFS transport is not conservative and extra water vapour is created, leading to a positive Precipitation-Evaporation imbalance. The latent heat released by condensation of this extra water vapour also was introducing an artificial source of heat, contributing to a negative net TOA-SFC radiative imbalance.
- The use of the advection mass fixer also leads to a partial improvement in the P-E bias, which is reduced from 0.03 mm/day to -0.016 mm/day.
- A considerable issue that was present in v3.01 was a cold surface temperature bias, of the order of 1°C (Table 1). In v3.1 this average bias is completely removed, although some inconsistencies with observations persist at regional scales. This warmer climate has been obtained removing the warm ocean flag, changing of the entrainment rate parameter for organized convection and reducing the diffusive albedo for the ocean.
- In agreement with these mean changes, Performance Indices (Reichler and Kim, 2008) report considerable improvements for surface temperature (PI=13.1 vs. 33.3) and for zonally averaged vertical profiles of temperature (PI=10.7 vs 25.5) and specific humidity (PI=16.5 vs. 23.8). Only slightly worse skills (larger PIs) are observed for the overall fluxes, total precipitation and SSTs. Good values are obtained for the zonal profiles of meridional and zonal wind and for MSLP (PI=1.8, 1.4 and 1.7 respectively).
- A small residual negative sea level height drift has been corrected in v3.1 with a flux correction operating on liquid precipitation over the oceans. Compared to the previous mass flux corrector which operated on runoff, this method has the advantage that extra water is added to the entire surface of the ocean, instead of concentrating it in coastal areas.
- Bug fixing of two different issues in NEMO/LIM3 that were causing a reduction of the sea level height.
- Various changes in the namelist of NEMO.
- The warm ocean flag (LEOCWA) has been disabled in coupled runs. Now it is true only for atmosphere-only runs.
- Heat flux correction between ocean and atmosphere has been removed.

Results from coordinated tuning experiments are stored and visualized at ISAC-CNR:
http://sansone.to.isac.cnr.it/ecearth/diag/
and at MISU:
http://misu228.misu.su.se/ecev3/amwg_diag5.2/
http://misu228.misu.su.se/ecev3/time_series/

A model development portal (https://dev.ec-earth.org/) based on redmine represents the main hub of model development activities and includes an issue tracker, a model documentation wiki, a discussion forum for model development and testing and a full svn server with all model development branches.

Tuning activities will continue in the next months of 2014, mainly aiming at fine-tuning the standard resolution model and at testing, also in long coupled runs, the model with the improved NEMO 3.6 ocean component.

Different consortium participant have plans to focus on specific aspects of model development and tuning in the near future. Topics include understanding the causes for the residual radiative imbalance and the residual P-E imbalance in the model, improving mainly surface temperature and the vertical distribution of temperature and humidity, studying the sensitivity of the radiation scheme to model resolution and parameter changes, also in a single-column version of the model, improving the warm bias in boreal winter over the northern hemispheric subarctic continents and exploring the Southern ocean and ocean mixing. Recent discussions with M. Diamantakis, H. Hersbach and P. Bechtold at ECMWF have suggested different recent improvements in the IFS model, which could be explored also for EC-Earth 3.1.

In order to reach the goal to develop EC-Earth into a complete and state-of-the-art ESM, ready for participating in CMIP6, a strengthened development and tuning effort will be needed in the next years, requiring testing the model and performing long experiments under several forcing conditions, different physical parameterizations, model configurations and resolutions. Several long experiments and spin-up runs of several hundreds of years each will be needed during the development and tuning phase. We expect this project to provide the computational resources to aid in this effort, shared by all consortium members.

Joint technical model development and model tuning, with resources provided by SPNLTUNE, have been crucial in order to allow the inclusion of EC-Earth in CMIP5 and will be required for the inclusion of a full ESM version of EC-Earth in the CMIP6 comparison. Several novel papers, including some very high impact papers, have been published including EC-Earth results (see also the bibliography at the end of this document).

Workplan

The activities in the period 2015-2017, using computing resources from this Special Project, will aim mainly at:

- 2015: Completing tuning of the standard resolution version (T255L91 ORCA1L46) of EC-Earth 3.1 to reduce biases in the simulated climate
- 2015-2016: Tuning experiments also for a high-resolution version of the model (T511L91 ORCA025L75).
- 2015-2016: Completing the coupling of additional ESM components with EC-Earth v3 and performing control experiments.
- 2016: Tuning the full ESM version of the model
- 2016-2017: Testing all versions of the model (standard, high-resolution and ESM) in long simulations under both constant and transient forcing and preparing initial conditions suitable for CMIP6 experiments.
- 2015-2017: Technical model development and bug fixing

The phasing on model development related to scientific needs is strongly driven also by model intercomparisons that are part of the World Climate Research Program, and by large research programmes such as H2020. CMIP6 is the 6th coupled model intercomparison project in which EC-Earth will participate. A novel aspect of CMIP6 is that the work will now be separated into two elements: 1) to run a small set of standardized experiments, and 2) to provide standardization, coordination, infrastructure as well as documentation functions that allow the simulations to be made available to the broader community (Meehl et al., 2014). EC-Earth participated in CMIP5 with EC-Earth V2.3 and will do so in CMIP6 with a model that includes biogeochemical cycles and atmospheric chemistry.

Currently, EC-Earth V3 does not yet include chemical and biogeochemical components. The roles of aerosols and different nutrient cycles are essential for the development of the Earth System. In EC-Earth V2.4 couplings between terrestrial ecosystems, atmospheric chemistry and physical modules are explored. A full coupling in EC-Earth v3 is foreseen before 2016, such that EC-Earth will include biogeochemical cycles and atmospheric chemistry modules, and can as such be used as a full ESM within CMIP6 and in H2020 projects.

A timeline for further model development has been defined, as summarized in figure 1.

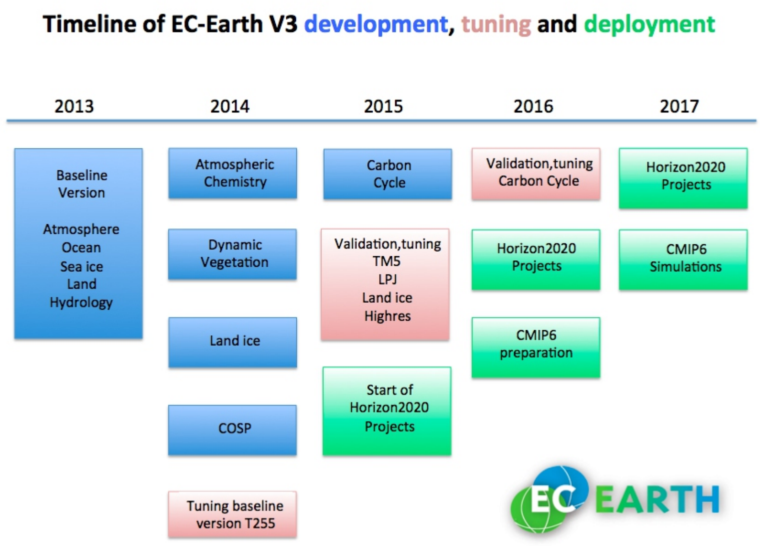

Figure 1. Timeline of EC-Earth V3 in terms of development, tuning and use within CMIP6 and H2020 projects. A key development goal will be the inclusion of modules representing the carbon cycle.

Justification of resources

Running the model at standard resolution (IFS at T255L91 with NEMO ORCA1L46) on c2a currently consumes 8800 SBU per model year (using 4 full nodes). The model needs to be ported and tested on the new CRAY at ECMWF and this will be done using still available SPNLTUNE resources within 2014 (still 10M SBU at the time of writing). Based on experience on different HPC machines in Europe, the model consumes between 640 and 800 core-hours per model year at T255L91-ORCA1.

Storage requirements are around 26 GB/model-year, assuming 6-hourly output storage and storage of monthly means for NEMO (suitable for testing and tuning purposes). This figure would increase to about 50 GB/model year if 3-hourly output (CMIP5 specs.) are included.

Experience with tuning runs in 2013-2014 has shown that at least 500 years are needed to reach approximately statistically stationary conditions under constant forcing conditions, particularly for the equilibration of ocean temperatures. The addition of every new module added to the model (interactive aerosols, interactive vegetation) will require extensive tuning of the coupled system.

Including atmospheric chemistry makes the model even 3.5 times more expensive. For tuning purposes, EC-Earth including TM5 is expected to be tested only in time slice simulations. For 10 slices of 20 years, about 6 MSBU will be additionally needed. TM5 standard output at 3x2 degrees and ~31/34 levels is about 50Gb/year. Including 3-hourly output fields will typically increase this number to 100 Gb/year .

To summarize, for 2000 years of simulation with Version 3 at T255 (including spinup and test runs with different physical parameterizations), about 17.6 MSBU will be needed. Adding time slices with TM5 will add another 6 MSBU. An extra 1 MSBU will be needed for technical work such as porting and bugfixing. . Including also restarts we estimate a total requirement for storage of 70 TB.

A similar effort is expected also for tuning with other modules, such as dynamic vegetation and interactive ocean biogeochemistry.

For comparison, tuning activities in the framework of SPNLTUNE in recent years have required the following resources:

Year	Total budget (Mio SBU)	Percent used
2009	5	92
2010	5	94
2011	7	85
2012	10.4	94
2013	15	87
2014 (up to May)	15	32

We expect that in the period 2015-2017 a great number of additional computing resources, in excess to those provided by SPNLTUNE, will be needed in order to allow tuning and testing of the full ESM model, particularly at higher resolutions. These additional resources will be secured through applications, in part already submitted, to PRACE, DECI and INCITE programmes and through national resources.

References and recent papers involving EC-Earth:

Please see http://ecearth.knmi.nl/index.php?n=PmWiki.Papers for a full list of papers (50 papers) published with EC-Earth results from 2009 to-day.

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Partners of EC-Earth as of May 2014 (Core partners and Members of Steering Group)*:

AEMET* - Spain, CNR-ISAC*- Italy, DMI* - Denmark, IPMA* - Portugal, KNMI* - The Netherlands, Met Éireann* - Ireland, SMHI* - Sweden, Utrecht University -The Netherlands, WUR - The Netherlands, VU- The Netherlands, SurfSARA -The Netherlands, Bolin Centre (Stockholm University) - Sweden, Lund University - Sweden, IRV - Sweden, NSC -Sweden, IC3 - Spain, BSC -Spain, ENEA- Italy, ICTP- Italy, BSC - Spain, UCD Met & Climate Centre- Ireland, ICHEC - Ireland, UCL - Belgium, KIT - Germany, Bjerkness Centre (University of Bergen) - Norway, Copenhagen University - Denmark, FMI - Finland, Oxford University- United Kingdom.