Project: **882**

Project title: **CESM1 (Community Earth System Model) as a new MESSy basemodel: Evaluation and further development**

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Final report

Summary

The aim of the project was to continue the development and evaluation of the model system CESM1/MESSy. This model system uses the Community Earth System Model (CESM1), maintained by the United States National Centre for Atmospheric Research (NCAR), as a basemodel for the Modular Earth Submodel System (MESSy). The option to use the Community Atmosphere Model (CAM) atmospheric dynamical cores, especially the state-of-the-art spectral element (SE) core, as an alternative to the ECHAM5 spectral transform dynamical core provides scientific and computational advances for atmospheric chemistry and climate modelling with MESSy. For CESM1/MESSy setups, the MESSy process and diagnostic submodels for atmospheric physics and chemistry are used together with one of the CESM1(CAM) dynamical cores; the generic (infrastructure) submodels support the atmospheric model component.

Several evaluation simulations have been performed and show good agreement to ECHAM5/MESSy simulations. See Baumgaertner et al. (2016) for the documentation as well as brief evaluations.

Analysis of a simulation for the period 1950 – 2010 that was performed in a follow-up project at DKRZ is ongoing.

Introduction

The Community Earth System Model (CESM1; Hurrell et al., 2013) is a fully coupled global climate model, which has integrated individual Earth system component models, using a coupler and a generic IO library. CESM1 has shown to be a very useful tool for many types of studies; see, for example, the special issue on CCSM (Community Climate System Model) and CESM in the Journal of Climate[1]. The Modular Earth Submodel System (MESSy) uses a different approach. The code is organized in four layers: a base model of any level of complexity is complemented by a base model interface layer. A further interface layer to the submodels makes it possible to keep process submodels as distinct as possible in the submodel core layer. For the ECHAM5/MESSy atmospheric chemistry (EMAC) model, the base model ECHAM5 provides only the dynamical core, including advection; all physics parametrizations have been recoded or replaced by submodels, and infrastructure code has been recoded or replaced by generic infrastructure submodels. For a list of available submodels, see Table 1 in Jöckel et al. (2010) or the MESSy website.[2]

In this project, we have implemented CESM1 (version 1.2.1) as an additional base model for MESSy (implemented into MESSy version 2.50), similar to the implementation of ECHAM5. Note, however, that CESM1 provides a much larger number of process descriptions of all components of the Earth than ECHAM5. This means that much larger portions of the CESM1 code are still used in a CESM1/MESSy simulation.

The SE dynamical core in CESM1 originates from the High-Order Method Modeling Environment (HOMME; Dennis et al., 2005). More specifically, SE uses a continuous Galerkin spectral finite element method (Taylor and Fournier, 2010). It is currently implemented for a cubed–sphere grid, although the core can in principle be employed for fully unstructured quadrilateral meshes. The main advantages compared to traditional approaches are its scalability up to 10^5 compute cores, which is useful for current and future computing architectures, and local energy conservation on top of mass and potential vorticity conservation. Also, no polar filters are required since the grid is quasi-uniform.

1 http://journals.ametsoc.org/page/CCSM4/CESM1

Technical implementation of CESM1/MESSy

The development of CESM1/MESSy was driven by two goals: first, to provide the state-of-the art SE dynamical core to the MESSy user community, and second to provide further components (land, ice, etc.) to MESSy simulations, making it a comprehensive Earth system model. The strategy chosen to achieve both goals was to implement the entire CESM1 code as a base model into MESSy, analagous to the implementation of the base model ECHAM5. A diagram of the CESM1/MESSy structure is shown in the Figure below. It indicates the MESSy layer structure as described above, the basics of the call structure between CESM1 and MESSy submodels, and basics of the data exchange.

The entire CESM1 repository is taken over as part of MESSy, which makes updates to newer versions of CESM1 straight forward. All changes to the CESM1 Fortran code are encapsulated using preprocessor commands:

```
#ifdef MESSy
...
#endif
```

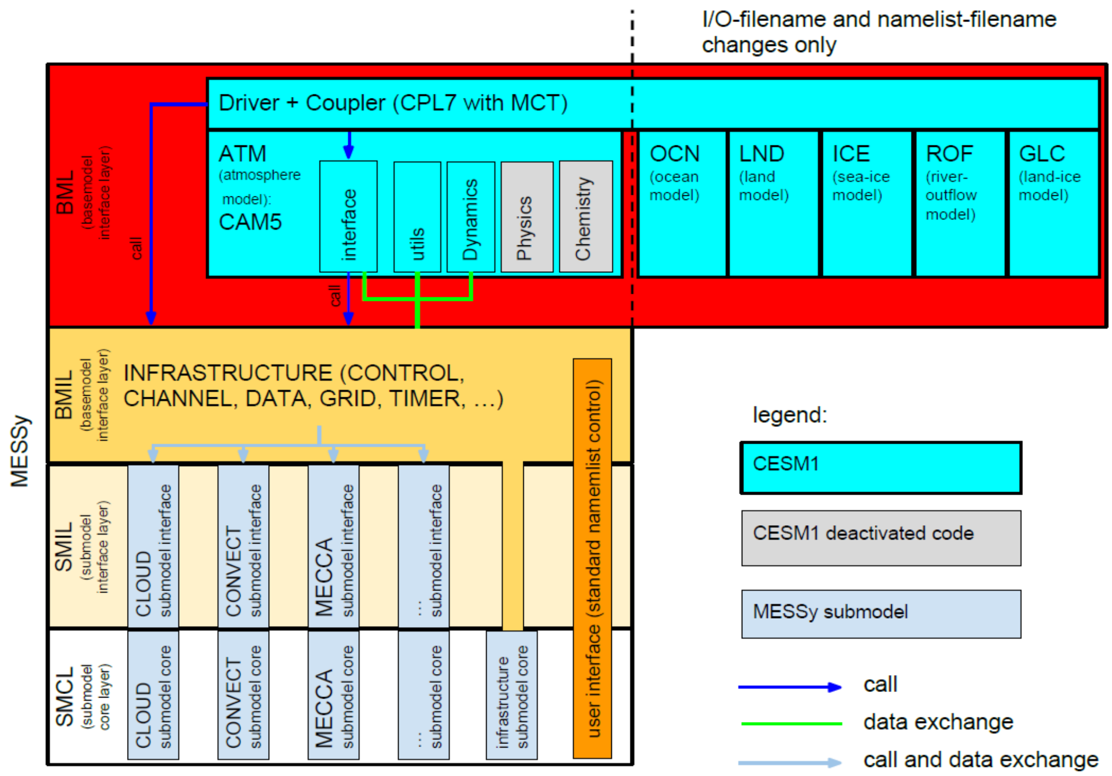
The CESM1 model components including the coupler can still be used in the CESM1/MESSy configuration; only the CAM5 process parametrizations are disabled and replaced by the MESSy atmospheric physics and chemistry.

The MESSy main control interface is called from the CCSM driver module `ccsm_comp_mod`, the CAM module `atm_comp_mct` and for the row loop in `physpkg`. The module `atm_comp_mct` is the outermost module in CAM, and also takes care of the coupling to the other component models. Most calls could also be moved to the `ccsm_comp` module, which controls the CESM1 time stepping and call the different component models, but since MESSy currently only replaces the CAM5 atmospheric physics and chemistry, `atm_comp_mct` is the most straightforward place in the code. For an overview of the call structure, see Fig. 1 in the Supplement “Implementation Documentation”.

CESM1/MESSy employs an explicit Euler time integration for the atmosphere with long time steps for the physics and chemistry, and higher-order types of integration (e.g. Runge–Kutta for SE) in the dynamical cores. The dynamical cores use sub-cycling for shorter integration times. Note that this is different to ECHAM5/MESSy, which uses leapfrog integration and a time filter. Sub-time stepping in MESSy is used for chemistry submodels such as MECCA and SCAV, whereas longer time steps are used for radiation; i.e. the radiation submodel is called less frequently.

For CESM1/MESSy, the CAM time-integration scheme was adopted. Note however that while CAM performs a time integration after every individual physics process, allowing to use the state x for each process, MESSy performs a time integration at the end of every time step, but explicitly integrates required variables in every submodel, $x + \mathrm{d}x/\mathrm{d}t \cdot \mathrm{delta}\, t$. When using the SE core, the CESM1/MESSy integration is applied to temperature, winds, specific humidity, cloud water (liquid and ice), and trace gas mixing ratios. The coupling between the physics and dynamics is a time-split coupling, where physical and dynamical core time-integration components are calculated sequentially. This is equivalent to the coupling of the FV and SE cores with the CAM physics, which is described in more detail in Sect. 2 of the CAM5 description.

Diagram of CESM1 integration into MESSy[2]:



Evaluation simulations

The following simulations have been performed:

- CMAC-FV: CESM1/MESSy with finite volume core at 1.9° × 2.5° horizontal resolution, 26 layers up to 2 hPa (approx. 40 km). The chemistry was calculated with the MECCA submodel (Sander et al., 2011). The selected mechanism (a description is provided in the Supplement to Baumgaertner et al. 2016) focuses on ozone-related chemistry, including tropospheric non-methane hydrocarbons (NMHCs) up to isoprene and stratospheric chlorine and bromine reactions. In addition, the following MESSy submodels were switched on: AEROPT, CLOUD, CLOUDOPT, CONVECT, CVTRANS, DRADRON, GEC, JVAL, LNOX, OFFEMIS, ONEMIS, ORBIT, RAD, SCAV, TNUDGE, TROPOP, and VERTDIFF. See table 1 for a brief description of the submodels.

- CMAC-SE: CESM1/MESSy with SE dynamical core with “ne16” horizontal resolution (approx. 1.9° × 2.5°), 26 layers up to 2 hPa (approx. 40 km). MESSy submodels and CESM1 component models: same as CMAC-FV.

- maCMAC-FV: CESM1/MESSy with finite volume core at 1.9° × 2.5° horizontal resolution, middle atmosphere configuration with 51 levels up to 0.01 hPa (approx. 80 km). MESSy submodels: same as CMAC-FV plus GWAVE and MSBM.

- maEMAC: ECHAM5/MESSy with horizontal resolution T42 (approx. 2.8° × 2.8), middle atmosphere set- up with 90 vertical levels up to 0.01 hPa (approx. 80 km). MESSy submodels: same as maCMAC-FV except for VERTDIFF, and plus H2O, DDEP and further diagnostic submodels.

- maCMAC-SE: CESM1/MESSy with SE dynamical core with “ne16” horizontal resolution (approx. 1.9° × 2.5°), 90 layers up to 0.01 hPa (approx. 80 km). MESSy submodels and CESM1 component models: same as CMAC-SE plus GWAVE and MSBM.

Baumgaertner et al. (2015) shows and compares the results of all simulations above.

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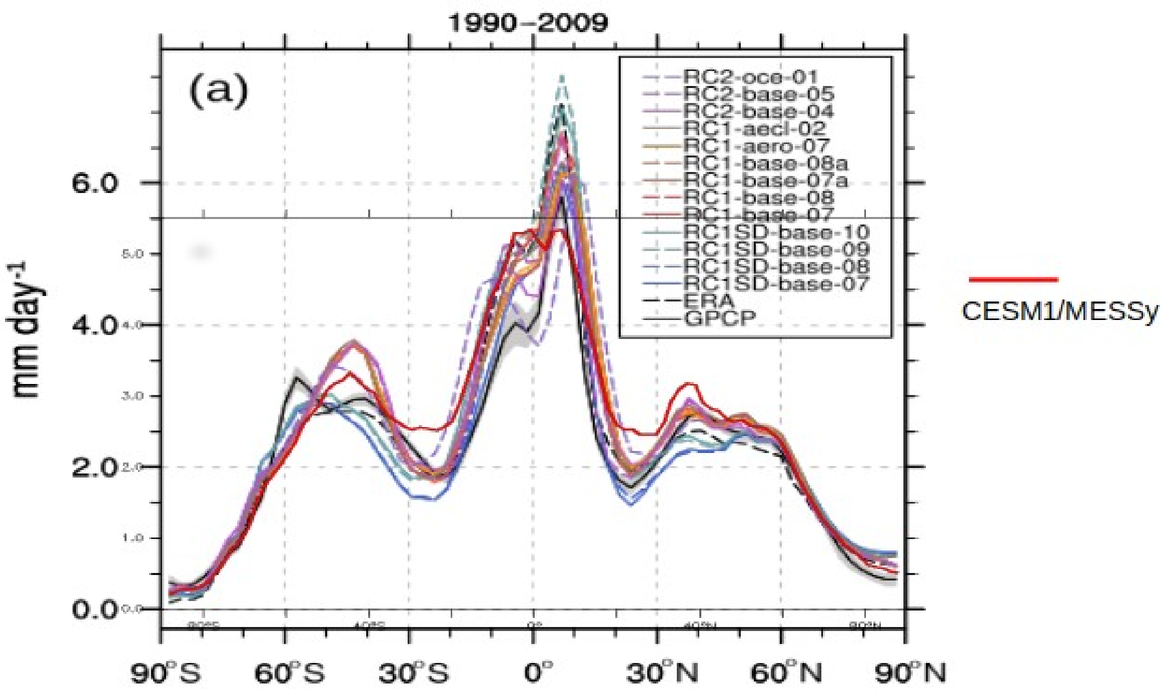
2 See also http://www.messy-interface.org/current/messy_interface.html for the generic MESSy interface structure.

Here, we only highlight a few examples.

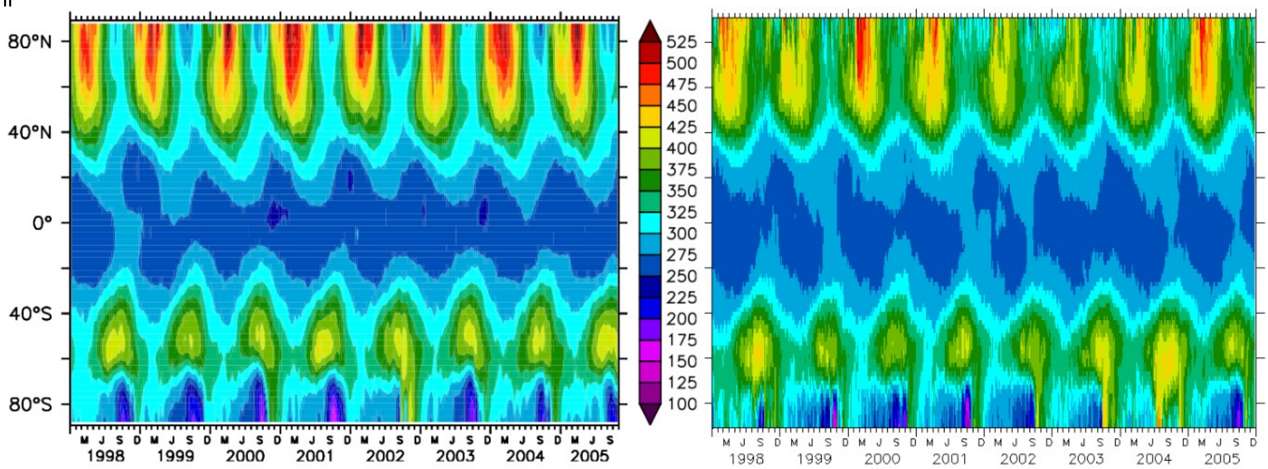
a. Scientific highlight: Precipitation

The figure below shows the zonal distribution of mean precipitation (mm day −1) for the time period 1990–2009 for the ESCiMo simulations and the CMAC-SE simulation plus GPCP and ERA-Interim. Figure adapted from Joeckel et al. (2016).



b. Scientific highlight: Total ozone

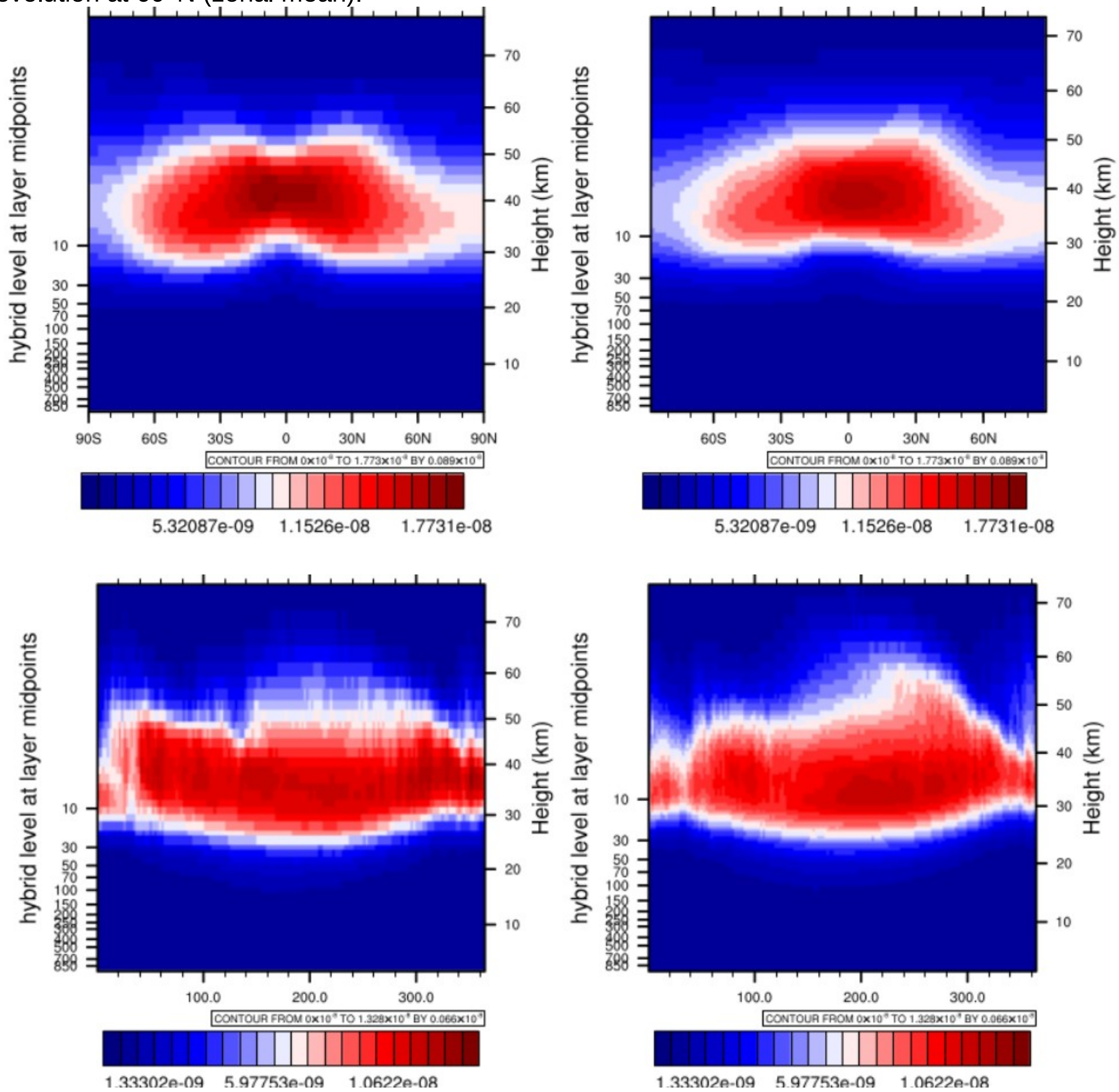
Total column ozone (DU) for maEMAC (left) and maCMAC-SE (right) for the years 1998 to 2005.



c. Scientific highlight: NOx

Mixing ratio for NOx (mol/mol). Left: maCMAC-SE, right: maEMAC

Top panel: zonal and height distribution averaged for the year 1998; bottom panel: Temporal evolution at 60°N (zonal mean).



d. Scientific highlight: Tropospheric methane lifetime

Tropospheric OH concentrations are important for the tropospheric methane lifetime (τ_{CH4}). With τ_{CH4}=7.61 years CMAC-FV is more reactive than maEMAC (τ_{CH4}=8.24 years), whereas CMAC-SE is less reactive (τ_{CH4}=10.46 years). This finding highlights the large influence τ_{CH4} of the dynamical core.

Further evaluation and developments

The more detailled evaluation is ongoing in DKRZ project 1054 (CESM1 (Community Earth System Model) as a new MESSy basemodel: Evaluation based on ESCiMo simulations with ECHAM5/MESSy).

Further development upgrading CESM to version 2 in MESSy is also ongoing.

Code availability

As planned in the proposal, all developments have been checked into the main trunk of the MESSy code and are available with version 2.52. The Modular Earth Submodel System (MESSy) is continuously further developed and applied by a consortium of institutions. The usage of MESSy and access to the source code is licensed to all affiliates of institutions, which are members of the MESSy Consortium. Institutions can be a member of the

MESSy Consortium by signing the MESSy Memorandum of Understanding. More information can be found on the MESSy Consortium Website (http://www.messy-interface.org).

Publications:

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Sander, R., Baumgaertner, A., Gromov, S., Harder, H., Jöckel, P., Kerkweg, A., Kubistin, D., Regelin, E., Riede, H., Sandu, A., Taraborrelli, D., Tost, H., and Xie, Z.-Q.: The atmospheric chemistry box model CAABA/MECCA-3.0, Geosci. Model Dev., 4, 373–380, doi:10.5194/gmd-4-373-2011, 2011.

Taylor, M. A. and Fournier, A.: A compatible and conservative spectral element method on unstructured grids, J. Comput. Phys., 229, 5879–5895, doi:10.1016/j.jcp.2010.04.008, 2010.