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Implementation of the Community Earth System Model (CESM1, version 1.2.1) as a new basemodel into version 2.50 of the MESSy framework

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Abstract

The Community Earth System Model (CESM1), maintained by the United States National Centre for Atmospheric Research (NCAR) is connected with the Modular Earth Submodel System (MESSy). For the MESSy user community, this offers many new possibilities. The option to use the CESM1(CAM) atmospheric dynamical cores, especially the spectral element (SE) core, as an alternative to the ECHAM5 spectral transform dynamical core will provide scientific and computational advances for atmospheric chemistry and climate modelling with MESSy. The SE dynamical core does not require polar filters since the grid is quasi-uniform. By advecting the surface pressure rather then the logarithm of surface pressure the SE core locally conserves energy and mass. Furthermore, it has the possibility to scale to up to 10^5 compute cores, which is useful for current and future computing architectures. The well-established finite volume core from CESM1(CAM) is also made available. This offers the possibility to compare three different atmospheric dynamical cores within MESSy. Additionally, the CESM1 land, river, sea ice, glaciers and ocean component models can be used in CESM1/MESSy simulations, allowing to use MESSy as a comprehensive Earth System Model. 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. The other CESM1 component models as well as the coupling between them use the original CESM1 infrastructure code and libraries, although in future developments these can also be replaced by the MESSy framework. Here, we describe the structure and capabilities of CESM1/MESSy, document the code changes in CESM1 and MESSy, and introduce several simulations as example applications of the system. The Supplements provide further comparisons with the ECHAM5/MESSy atmospheric chemistry (EMAC) model and document the technical aspects of the connection in detail.

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1 Introduction

Increasing scientific and societal interest in understanding and forecasting the state of the atmosphere, oceans, land and ice has led to the development of so-called Earth System Models. The Community Earth Sytem 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, but otherwise modifying the component models as little as possible. CESM1 has shown to be a very useful tool for many types of studies, see e.g. the special issue on CCSM and CESM in the Journal of Climate.[1] The Modular Earth Submodel System (MESSy) uses a different approach. The code is organized in 4 layers, with the aim of keeping process submodels as distinct as possible in the submodel core layer, providing interfaces (submodel interface layer) to a basemodel interface layer, which finally connects to a basemodel that can have any level of complexity. For the ECHAM5/MESSy atmospheric chemistry (EMAC) model, the basemodel ECHAM5 provides only the dynamical core, including advection, all physics parametrisations have been recoded or replaced by submodels, and infrastructure code 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]

Here, we have implemented CESM1 (version 1.2.1) as an additional basemodel for MESSy (implemented into MESSy version 2.50), similar to the implementation of ECHAM5. Note however that CESM1 provides a much larger amount 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. Here, we present test simulations using MESSy atmospheric physics and chemistry submodels for the atmosphere, with execution and data handling by MESSy generic interface submodels, using one of the CESM1(CAM5) atmospheric dynamical cores, and CESM1 component models for ocean, land, ice and rivers.

[1]http://journals.ametsoc.org/page/CCSM4/CESM1
[2]http://www.messy-interface.org/

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The code integration can be seen from a MESSy or CESM user point of view. For MESSy users, CESM1/MESSy offers additional state-of-the art atmospheric dynamical cores, as well as the coupling to other component models.

As the development was aimed at MESSy users, the code structure, setup-design, configuration and script environment are analogous to ECHAM5/MESSy. For CESM users, CESM1/MESSy offers the opportunity to use an independent physics and chemistry suite, replacing the CAM physics and chemistry.

2 Model description

2.1 The Modular Earth Submodel System (MESSy)

The Modular Earth Submodel System (MESSy, Jöckel et al., 2005, 2010), maintained by the MESSy consortium, defines a strategy for building comprehensive Earth System Models (ESMs) from process based modules, the socalled submodels. Technically, MESSy comprises standard interfaces to couple the different components, a simple coding standard and a set of submodels coded accordingly. The code is organised into four different layers:

- The basemodel layer (BML) can be a model of arbitrary complexity starting from a GCM (as CESM1 or ECHAM5), to Regional Climate Models (RCMs, such as COSMO) to models spanning the basic entity of the process (i.e., a box model for atmospheric chemistry or a column model for a convection model).

- The basemodel interface layer (BMIL) comprises the basemodel specific implementation of the MESSy infrastructure.

- The submodel interface layer (SMIL) represents the connector of a specific process to the infrastructure (BMIL).

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- The submodel core layer (SMCL) comprises the basemodel independent implementation of a specific process in the Earth System, or of a diagnostic tool of the model system. It uses data provided via its SMIL and returns data back via its SMIL to other submodels and/or the basemodel.

Coupled to the basemodel ECHAM5, MESSy has proven as a useful framework for atmospheric chemistry and physics studies. An up-to-date list of publications using the model is available at http://messy-interface.org. The layer structure described above makes comparisons of physics parametrisations a straightforward task, see e.g. Tost et al. (2006b).

For the second MESSy development cycle, which is comprehensively documented by Jöckel et al. (2010), complete independence of ECHAM5 was achieved by several new generic submodels. This has been exploited for example by the COSMO/MESSy development (Kerkweg and Jöckel, 2012a, b), for CMAT/MESSy (Baumgaertner et al., 2013a), and is also used here to connect to the CESM1 Earth system model. The CESM1 code was implemented into MESSy version 2.50, yielding an intermediate version 2.50+. The modifications will be made available in upcoming versions.

2.2 The Community Earth System Model (CESM)

The Earth system model CESM1 (version 1.2.1) is a fully coupled global climate model. The physics-based models that serve for the different earth system components are the "Community Atmosphere Model" (CAM), the "Community Land Model" (CLM), the sea ice model "Community Ice CodE" (CICE), the ocean model "Parallel Ocean Program" (POP), the land-ice model "Community Ice Sheet Model" (Glimmer-CISM), and the "River Transport Model" (RTM). As an alternative to the physics-based models, climatological data models are provided for each component. The models are coupled through the CESM1 coupler (CPL7), which uses the Model Coupling Toolkit (MCT). For a specific simulation, the user can choose a so-called component set, which describes the used model, model version as well as specific settings for each component.

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The atmosphere component, CAM5, provides a set of physics parametrisations, and several dynamical cores, which also include advection. While CAM5 provides four different cores, we describe only the cores implemented in CESM1/MESSy, the CAM5 default finite volume (FV) core and the new spectral element (SE) core. The FV dynamics were initially developed by the NASA Data Assimilation Office (DAO). The discretisation is local and entirely in physical space. In the horizontal, it uses a "flux-form semi-Lagrangian" scheme (Lin and Rood, 1996, 1997), whereas the vertical discretisation is quasi-Lagrangian. For more details see the CAM5 description,[3] Sect. 3.1.

The SE dynamical core 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 et al., 2009; Fournier et al., 2004; Thomas and Loft, 2005; Wang et al., 2007; 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, local energy conservation on top of mass and potential vorticity conservation. Also, no polar filters are required. A detailed description and further references are given in the CAM5 description, Sect. 3.2. A recent publication by Bacmeister et al. (2014) discusses some improvements, but also some problems at very high resolution (0.23° latitude $\times$ 0.31° longitude) simulations.

CESM1 timestepping (so-called run alarms) can be chosen through the driver namelist, but most component sets use 30 min for all components except for the ice sheet model. For CAM, the 30 min timestep applies to the physics parametrisation, whereas the dynamical cores can have shorter timesteps, depending on the horizontal resolution. This is achieved through substepping within the coupling to the core. The coupling is performed in a time-split manner for both, FV and SE. For details see Sect. 2 in the CAM5 description.

[3]http://www.cesm.ucar.edu/models/cesm1.0/cam/docs/description/cam5_desc.pdf

3 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 basemodel into MESSy, analagous to the implementation of the basemodel ECHAM5. A diagram of the CESM1/MESSy structure is shown in Fig. 1. 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 parametrisations 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 timestepping 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”.

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For MESSy, the submodel core layer remains unchanged, but the generic basemodel interface layer (BMIL) as well as the submodel interface layers (SMIL) are modified. For submodels with a generic SMIL the modifications are encapsulated using preprocessor statements (`#ifdef CESM1`). For most SMIL modules no changes or very minor adjustments were necessary. For the remaining submodels[4] that are more basemodel-specific new SMIL modules were created based on the respective ECHAM5 SMIL.

The following subsections provide an overview of these changes in MESSy and CESM1.

3.1 Time integration

CESM1/MESSy employs an explicit Euler time integration for the atmosphere with long timesteps 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 ($n \cdot \Delta t$) 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 performed 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, $x + \mathrm{d}x/\mathrm{d}t \cdot \Delta t$. 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.

[4] AEROPT, CLOUD, CLOUDOPT, CONVECT, NCREGRID, RAD

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3.2 Data representation, input/output

MESSy uses "representations" (see Jöckel et al., 2010, for an explanation of the terminology) that describe the geometric structure of data objects based on dimensions. For CESM1/MESSy, representations analagous to the ECHAM5/MESSy gridpoint (or Eulerian) representations are used for all atmosphere data for both the FV and SE cores. All data are stored in CHANNEL objects, which contain the data fields, the object's representation, and meta data. The CHANNEL infrastructure module (Jöckel et al., 2010) also controls the model output and writing of restart files. A namelist file gives the user full control over the output data.

For data import from files, MESSy provides the infrastructure submodel IMPORT. IMPORT is namelist controlled, and provides the data regridded to the required representation as channel objects, which every submodel can access through coupling with the respective channel objects. For CESM1/MESSy, this infrastructure is used for all data import. The TRACER submodel (Jöckel et al., 2008), which provides the handling of atmospheric trace gas variables, directly uses the NCREGRID Jöckel (2006) or GRID_TRAFO submodels for initialisation of the tracers. Note that currently for the SE core, which employs an unstructured grid, all imported data, including those for tracer initialisation, have to be provided on the grid used for the simulation.

In CESM1, explicit-shape arrays are used, such that the horizontal and vertical resolution as well as the number of tracers have to be selected before compilation. MESSy, in contrast, applies a dynamical memory management at run-time. However, the replacement of CESM1 explicit-shape arrays by pointers in the dynamical cores has so far only been implemented for the tracers. The horizontal and vertical resolution have to be specified when MESSy is configured, e.g. `CESM1HRES=1.9x2.5 CESM1VRES=26` have to be added to the call of `configure`.

For the gridpoint representation, each process (MPI-task) has its own set of rows and columns. The only difference is that for ECHAM the number of columns in the last row is in general different to the other rows, whereas in CAM the number of rows can

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be different for all rows. For the basemodel interfaces and submodel interfaces, this requires a distinction as detailed in the documentation Supplement.

3.3 Coupling to other component models through MCT

CESM1 uses the open-source Model Coupling Toolkit (MCT, Larson et al., 2005; Jacob et al., 2005), maintained by the Argonne National Laboratory. For CESM1/MESSy, this coupling is left in place, although in the future a coupling through the MESSy Multi-Model-Driver (MMD, Kerkweg and Jöckel, 2012b) is anticipated. The MESSy channel objects for the atmospheric component are coupled to the data of the other component model analagously to CAM coupling. For a list of variables and the technical documentation see the Supplement.

3.4 Parallelisation

CESM1 is structured to have all component models handle their parallelisation separately, giving each component model its own set of processors, which can be controlled via the namelist `drv_in`. The CAM physics and dynamical cores also have separate parallelisation, depending on the employed grid. Due to the similarity of the MESSy and CAM physics data representation, the parallelisation routines of the CAM physics are employed also for MESSy submodels. Technically, this means that the MPI infrastructure submodel uses the `spmd_utils` and `phys_grid` modules from CAM for the low level gather/scatter routines. Specifically, the parallel datatypes, gather (`gather_chunk_to_field`) and scatter (`scatter_field_to_chunk`) subroutines available from `spmd_utils`, which directly uses the MPI library, are employed. In comparison, for ECHAM5/MESSy simulations the MPI submodel uses ECHAM5's `mo_mpi` low level routines.

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3.5 Namelists and scripts

Similar to CESM1, CESM1/MESSy also offers a large variety of setup possibilities. In CESM1, there is a number of evaluated setups, so-called component sets (see Sect. 2.2). MESSy also offers several setups that the user can choose for a simulation, and that can be easily modified depending on the scientific requirements.

A variety of scripts support the CESM1 model setup, which generate for instance the Makefiles and namelists. MESSy uses autoconf/configure/make utilities, and a single script for runcontrol (`xmessy_mmd`). Run-time options are set in well documented namelist files directly. The model comes with several namelist setups for different model configurations.

Instead of the automatic namelist generation in CESM1, the MESSy namelist setups contain some variables that are replaced by the runscript, e.g. for resolution-dependent filenames, or start/stop dates.

3.6 Trace constituents and mixing ratios

In general, atmospheric air masses can be treated to include ("wet") or exclude ("dry") water vapour. Both in CAM and MESSy, specific humidity is treated as wet mass mixing ratio, i.e. water mass with respect to total air mass [$\mathrm{kg\,kg^{-1}} = (\mathrm{kg\,H_2O})/(\mathrm{kg\,total\,air})$]. Also, in both CAM and MESSy cloud liquid and ice are treated as mass mixing ratios with respect to dry air [$\mathrm{kg\,kg^{-1}} = (\mathrm{kg\,H_2O})/(\mathrm{kg\,dry\,air})$]. In MESSy, other trace constituents are treated as "dry" volume mixing ratio, i.e. [$\mathrm{mol\,(mol\,of\,dry\,air)^{-1}}$]. The dynamical cores FV and SE both expect wet mass mixing ratios for advection. Therefore, advected trace constituents are converted before and back after the advection through the dynamical core.

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3.7 Vertical diffusion

The current suite of MESSy physical parametrisation submodels does not include a submodel for vertical diffusion. For ECHAM5/MESSy, vertical diffusion is treated by the ECHAM5 basemodel. For CESM1/MESSy, the vertical diffusion code of CAM5 was restructured as a MESSy submodel (VERTDIFF). However, both models use a similar approach. In both models, the free atmosphere diffusion coefficients are estimated using the gradient Richardson number. For the boundary layer, they both use a Monin Obukov similarity approach. The vertical diffusion equation is solved using an implicit method. For details of the implementation, see the VERTDIFF documentation in the Supplement.

4 Example applications and tests

The following simulations have been performed:

1. CMAC-FV: CESM1/MESSy with finite volume core at $1.9^{\circ} \times 2.5^{\circ}$ 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) 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, VERTDIFF. See table 1 for a brief description of the submodels.

2. CMAC-SE: CESM1/MESSy with SE dynamical core with "ne16" horizontal resolution (approx. $1.9^{\circ} \times 2.5^{\circ}$), 26 layers up to 2 hPa (approx. 40 km). MESSy submodels and CESM1 component models: same as CMAC-FV.

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3. 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, MSBM.
4. maEMAC: ECHAM5/MESSy with horizontal resolution T42 (approx. 2.8° × 2.8°), middle atmosphere setup 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.

The trace gas emissions and prescribed mixing ratios of long-lived trace gases (TNUDGE, see Kerkweg et al., 2006) are all for the year 2000. All simulations were performed for one model year, without spin-up using initialisations from existing simulations. Note that the maEMAC simulation contains a more complete set of trace gas emissions than the CESM1/MESSy simulations. The respective namelist setups are provided in the Supplement. Baumgaertner (2015) contains a comparison of these setups for all major output variables. The following subsections present several evaluation examples.

4.1 Using the Global Electric Circuit as a unique approach for a model evaluation

The Global Electric Circuit (GEC) is a system of currents spanning the globe. The currents are generated by thunderstorms and electrified clouds, whereas the spatial and temporal distribution of conductivity determines the potential and current distribution in the fair-weather atmosphere. For a recent review on the GEC see Williams and Mareev (2014).

The physical state of the atmosphere determines the current generation as well as conductivity. Therefore, for a model to simulate the state and variability of the GEC correctly depends on its ability to reproduce temperature, humidity, air density, cloud cover, trace gas transport and a correct representation of convection. Modelling studies on the GEC with CESM1 are presented by Lucas et al. (2015) and Baumgaertner et al. (2013b).

We use the GEC current generation as well as conductivity as a unique way to collectively evaluate the operation and coupling amongst the various submodels involved in CESM1/MESSy simulations. Since the derived variables combine several basic aspects such as temperature, pressure, and tracer transport, the GEC offers a way to evaluate several variables at the same time. Of course, this does not substitute a full evaluation, but rather presents an example application.

Both current generation parametrisation and the conductivity have been implemented as a diagnostic MESSy submodel named GEC.

We parametrise current generation analogously to Kalb et al. (2015), who found that convection updraft mass flux averaged between 200 and 800 hPa is correlated with measured electrified cloud and thunderstorm occurrence. The MESSy submodel CONVECT offers eight different convection schemes, all providing updraft mass flux. Here, we show results from several additional CESM1/MESSy and EMAC sensitivity simulations that use the Tiedtke scheme (Tiedtke, 1989) with Nordeng closure (Nordeng, 1994), and the Bechtold scheme (Bechtold et al., 2001), respectively. The most critical aspect of GEC source current is the diurnal cycle, referred to as the Carnegie curve from electric field measurements in fair-weather regions. Figure 2 shows the total current composite mean, averaged over 45° S to 45° N as a function of universal time, using hourly stored data for one simulation year, as well as the Carnegie E-field measurements, provided by Harrison (2013). In general, the simulations reproduce a diurnal cycle similar to the Carnegie data. However, the current peaks too early in the day for all simulations, which is a common problem with convection parametrisations (see e.g. Lucas et al., 2015). Only the simulation using the Bechtold convection scheme (blue) has its maximum at 18:00 UT, close to the peak in the Carnegie data.

Conductivity is calculated similar to the approach described by Baumgaertner et al. (2013b), B13 hereafter, who used CESM1(WACCM) to study spatial and temporal conductivity variability. Conductivity is proportional to ion pair concentrations, *n*, and posi-

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tive/negative ion mobilities, $\mu^{+/-}$, and is defined as

$$\sigma = ne(\mu^{+} + \mu^{-}), \tag{1}$$

where e is the elementary charge, and positive and negative ion concentrations are assumed to be equal. Ion concentration is given by

$$n = \frac{\sqrt{4\alpha q + (\sum_{\mathrm{i,\,r}} \beta(r_i) S(\mathrm{i,\,r}))^2} - \sum_{\mathrm{i,\,r}} \beta(r_i) S(\mathrm{i,\,r})}{2\alpha}, \tag{2}$$

with ion production rate q, the ion–ion recombination rate α and the effective loss of ions by aerosol particles with rate $\sum_{\mathrm{i,\,r}} \beta(r_i) S(\mathrm{i,\,r})$.

Here, we use the same parametrisations for Galactic Cosmic Ray (GCR) ion production, mobility, and ion–ion recombination as described by B13. Lower atmosphere ionisation sources include ^{222}Rn (Radon), obtained from the DRADON submodel, and further radioactive decay sources, also parametrised in the same way as presented by B13. While the aerosol attachment rate could be calculated using MESSy aerosol submodels, for consistency with B13 we use the same input datasets from CESM1(WACCM) simulations with CARMA (Community Aerosol and Radiation Model for Atmospheres). Note that clouds are not introduced as additional resistors in the present study. Column resistance is defined as the vertical integral of the reciprocal of conductivity (see e.g. B13 and references therein):

$$R_c = \int_{\mathrm{surface}}^{\mathrm{top}} \frac{1}{\sigma(z)} \mathrm{d}z, \tag{3}$$

where dz is the model layer thickness, which depends on height and geographic location.

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Figure 3 presents January column resistance from the maCMAC-FV (left) and maEMAC (right) simulations. Higher resistance at low latitudes, specifically at low geomagnetic latitudes, is due to the smaller GCR ionisation. Mountains lead to a decrease in column resistance because there is less atmosphere between the mountain and the upper boundary. Terrestrial emissions of Radon decrease column resistance over land compared to ocean. Radon has a half-life of approximately four days, therefore advection of Radon from land to ocean can lead to elevated ionisation rates near the coasts, so the transition is usually smooth.

4.2 Trace constituents and atmospheric chemistry

As a further example, we compare surface/tropospheric hydroxyl (OH), an important atmospheric cleaning agent, as well as stratospheric ozone concentrations. Note that the chosen variables and types of comparisons have no scientific justification for a full model evaluation, but are only example applications.

Zonal mean surface OH number concentrations are shown in Fig. 4 for the CMAC-FV (left), CMAC-SE (middle) and maEMAC (right) simulations for one year. As the CESM1/MESSy simulations are free-running, different synoptics lead to some differences on timescales of weeks, but overall the expected annual variations are present in all three simulations. The zonal mean ozone between 60 and 90° S is depicted in Fig. 5. Again, good agreement is found between the maCMAC-FV (left) and ma-EMAC (right) simulations.

5 Conclusions

CESM1 is connected to the the Modular Earth Submodel System (MESSy) as a new basemodel. This allows MESSy users the option to utilize either the state-of-the art spectral element dynamical core or the finite volume core of CESM1. Additionally, this makes several other component models available to MESSy users. As example ap-

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plications, an initial evaluation with respect to the Global Electric Circuit, which offers a unique opportunity for evaluating a range of atmospheric parameters under a single scientific aspect, was performed. Good agreement between the CESM1/MESSy simulations and ECHAM5/MESSy is found. Similarly, an exemplary comparison of surface OH and Antarctic ozone as examples for atmospheric chemistry functionality shows good agreement. A broader evaluation will be published elsewhere. The developments and experiences will be useful also for further MESSy extensions, for example with the new ICON (Icosahedral non-hydrostatic) GCM (Zängl et al., 2015).

Further technical work on CESM1/MESSy is likely to include the following:

- The coupling between the CESM1 component models with MCT can be replaced with the MESSy coupler.
- The CESM1 component models can be adapted to use the MESSy CHANNEL infrastructure submodel for memory management and data output.
- The CAM5 physical parametrisations can be implemented as MESSy submodels such that they can be used as alternative submodels for the current parametrisation suite.
- The new MESSy infrastructure submodel GRID (Kerkweg and Jöckel, 2015) for regridding can be adapted for handling the SE data.

Code availability

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 licenced 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).

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Table 1. List of process and diagnostic submodels used in the simulations presented here. For a full list of available submodels see Table 1 in Jöckel et al. (2010) or the MESSy website (http://www.messy-interface.org/).

submodel	description	reference
AEROPT	AERosol OPTical properties	Dietmüller et al. (2015)
CLOUD	ECHAM5 cloud scheme as MESSy submodel	Roeckner et al. (2006)
CLOUDOPT	cloud optical properties	Dietmüller et al. (2015)
CONVECT	convection parametrisations	Tost et al. (2006b)
CVTRANS	convective tracer transport	Tost (2006)
DRADRON	^{222}Rn as diagnostic tracer	Jöckel et al. (2010)
GEC	Global Electric Circuit	Sect. 4.1
GWAVE	ECHAM5 gravity wave parametrisations	Roeckner et al. (2006)
JVAL	photolysis rates	based on Landgraf and Crutzen (1998)
LNOX	lightning NO_x production	Tost et al. (2007)
MECCA	atmospheric chemistry	Sander et al. (2011)
MSBM	multi-phase stratospheric box model	Jöckel et al. (2010)
OFFEMIS	prescribed emissions of trace gases and aerosols	Kerkweg et al. (2006) (renamed from OFFLEM)
ONEMIS	on-line calculated emissions of trace gases and aerosols	Kerkweg et al. (2006) (renamed from ONLEM)
ORBIT	Earth orbit calculations	Dietmüller et al. (2015)
RAD	ECHAM5 radiation scheme as MESSy submodel	Dietmüller et al. (2015)
SCAV	scavenging and wet deposition of trace gases and aerosol	Tost et al. (2006a)
TNUDGE	Newtonian relaxation of species as pseudo-emissions	Kerkweg et al. (2006)
TROPOP	tropopause and other diagnostics	Jöckel et al. (2006b)
VERTDIFF	vertical diffusion	see Supplement

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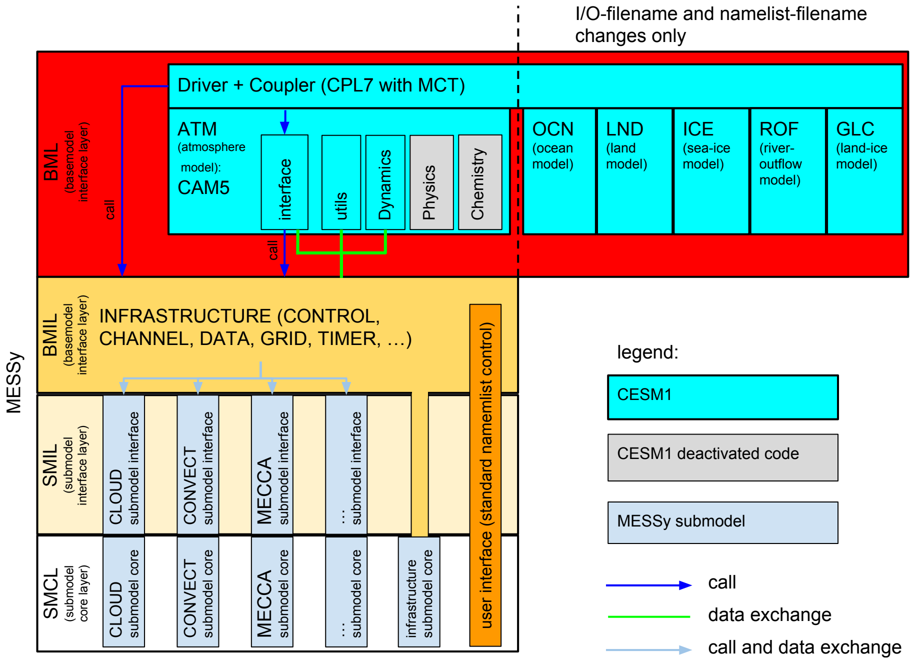

Figure 1. Diagram of CESM1 integration into MESSy. See also http://www.messy-interface.org/current/messy_interface.html for the generic MESSy interface structure.

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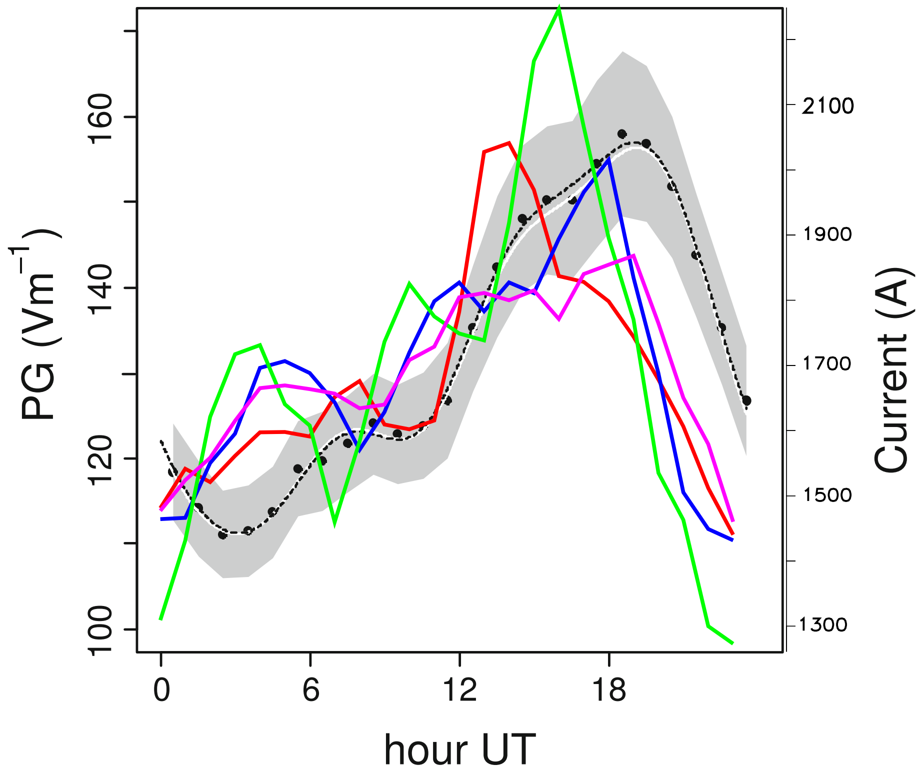

Figure 2. Black/grey: re-calculated Carnegie curve, showing the potential gradient (PG), taken from Harrison (2013). Coloured lines: composite day parametrised GEC source current averaged over 45° S to 45° N from additional CESM1/MESSy and EMAC sensitivity simulations. Red: CMAC-FV with Tiedtke/Nordeng convection scheme; blue: CMAC-FV with Bechtold convection scheme; purple: CMAC-SE with Bechtold convection scheme; green: EMAC with Tiedtke/Nordeng convection scheme.

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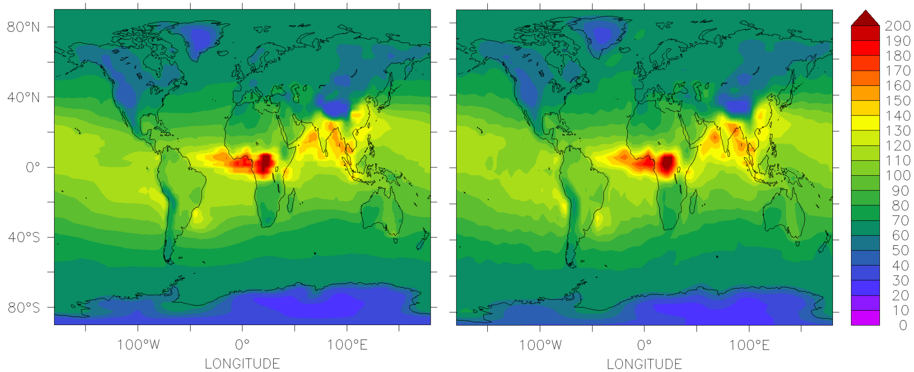

Figure 3. Column resistance ($P\Omega\,m^2$) for January for the maCMAC-FV (left) and maEMAC (right) simulation.

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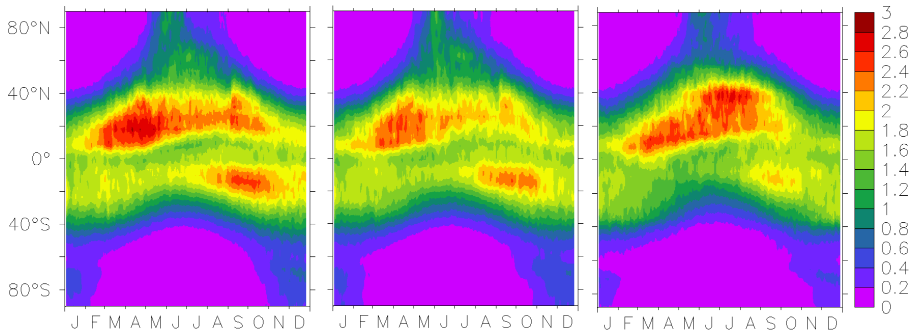

Figure 4. Zonal mean OH number concentration (10^6 molecules cm^{-3}) at the surface for the year 2000 from CMAC-FV (left), CMAC-SE (middle) and maEMAC (right) simulations.

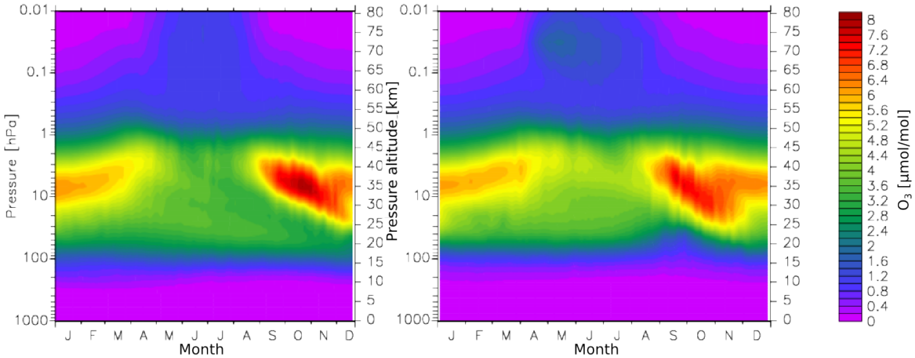

Figure 5. Zonal mean ozone ($\mu mol\,mol^{-1}$) averaged between 60 and 90° S for the year 2000 from maCMAC-FV (left) and maEMAC (right) simulations.

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