SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	EC-Earth in CMIP6 (SPSEECCMIP)
Computer Project Account:	SPNLTUNE
Start Year - End Year :	2018 - 2020
Principal Investigator(s)	Dr. Ralf Döscher
Affiliation/Address:	Rossby Centre, SMHI Norrköping Sweden
Other Researchers (Name/Affiliation):	Dr. Twan van Noije Dr. Jost von Hardenberg

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The objective is to prepare the EC-Earth3-AerChem climate model for CMIP6 experiments. The model includes interactive aerosols and atmospheric chemistry, which affect the radiative properties of the atmosphere. Therefore it differs from the standard EC-Earth3 GCM model, where aerosols and greenhouse gases are prescribed, and it requires a dedicated tuning and spinup. The goal is to tune the IFS component to produce a global temperature for the pre-industrial period on par with observations. Long integration of more than 100 years are needed for robust tests of the various sets of tuning parameters.

Summary of problems encountered

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

The AerChem version of EC-Earth is slower and more expensive than its GCM counterpart. This is due to the coupling with TM5, a Chemistry and Transport Model (CTM). Substantial resources were spent on the tuning of this configuration, and the corresponding production simulations for CMIP6 and AerChemMIP. However, while running the CMIP6 historical simulation a coding error was found in the implementation of stratospheric aerosols, which affected specifically this configuration. As a consequence, after fixing the bug, the model needed to be retuned and production runs restarted.

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 procedure and reporting obligations are reasonable. We appreciate that there is some flexibility in the use of resources from closely related projects. For instance, we used resources from this project and the special project "EC-Earth climate simulation for AerChemMIP" project to complete our EC-Earth3-AerChem tuning and production simulations.

Summary of results

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

Here we chose to submit a combination of selected section from two peer-reviewed publications that document tuning of the global climate model EC-Earth3 and EC-Earth3-AerChem.

List of publications/reports from the project with complete references

Döscher, R., Acosta, M., Alessandri, A., Anthoni, P., Arneth, A., Arsouze, T., ... & Zhang, Q. (2021). The EC-Earth3 earth system model for the climate model intercomparison project 6. *Geoscientific Model Development Discussions*, 1-90.

van Noije, T., Bergman, T., Le Sager, P., O'Donnell, D., Makkonen, R., Gonçalves-Ageitos, M., ... & Yang, S. (2020). EC-Earth3-AerChem, a global climate model with interactive aerosols and atmospheric chemistry participating in CMIP6. *Geoscientific Model Development Discussions*, 1-46.

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.)

The special project ended. Contributions to the CMIP6 AerChemMIP have been provided. Next steps are the development of the next version of the EC-Earth model, EC-Earth4.

24 June 2021

Report on the tuning of EC-Earth3 and EC-Earth3-AerChem

By Ralf Döscher and Twan van Noije

1. Introduction

This report documents the tuning of EC-Earth3 and EC-Earth3-AerChem. The content is taken from selected sections of two publications (Döscher et al. 2021, and van Noije et al. 2021)

Döscher et al. (2021) describe the Earth System Model EC-Earth3 for contributions to CMIP6, with its flexible coupling framework, major model configurations, a methodology for ensuring the simulations are comparable across different HPC systems, and with the physical performance of base configurations over the historical period. The variety of possible configurations and sub-models reflects the broad interests in the EC-Earth community. EC-Earth3 key performance metrics demonstrate physical behaviour and biases well within the frame known from recent CMIP models. With improved physical and dynamic features, new ESM components, community tools, and largely improved physical performance compared to the CMIP5 version, EC-Earth3 represents a clear step forward for the only European community ESM.

Van Noije et al. (2021) documents the global climate model EC-Earth3-AerChem, one of the members of the EC-Earth3 family of models participating in the Coupled Model Intercomparison Project phase 6 (CMIP6). EC-Earth3-AerChem has interactive aerosols and atmospheric chemistry and contributes to the Aerosols and Chemistry Model Intercomparison Project (AerChemMIP). Van Noije et al. (2021) give an overview of the model and describe in detail how it differs from the other EC-Earth3 configurations, and what the new features are compared to the previously documented version of the model (EC-Earth 2.4). We explain how the model was tuned and spun up under pre-industrial conditions and characterize the model's general performance on the basis of a selection of coupled simulations conducted for CMIP6. The mean energy imbalance at the top of the atmosphere in the pre-industrial control simulation is -0.10 ± 0.25 W m -2 and shows no significant drift. The corresponding mean global surface air temperature is 14.05 ± 0.16 °C, with a small drift of -0.075 ± 0.009 °C per century. The model's effective equilibrium climate sensitivity is estimated at 3.9 °C and its transient climate response at 2.1 °C. The CMIP6 historical simulation displays spurious interdecadal variability in Northern Hemisphere temperatures, resulting in a large spread among ensemble members and a tendency to underestimate observed annual surface temperature anomalies from the early 20th century onwards. The observed warming of the Southern Hemisphere is well reproduced by the model. Compared to the ERA5 reanalysis of the European Centre for Medium-Range Weather Forecasts, the ensemble mean surface air temperature climatology for 1995–2014 has an average bias of -0.86 ± 0.35 °C in the Northern Hemisphere and 1.29 ± 0.05 °C in the Southern Hemisphere. The Southern Hemisphere warm bias is largely caused by errors in shortwave cloud radiative effects over the Southern Ocean, a deficiency of many climate models. Changes in the emissions of near-term climate forcers (NTCFs) have significant climate effects from the 20th century onwards. For the SSP3-7.0 shared socio-economic pathway, the model gives a global warming at the end of the 21st century (2091–2100) of 4.9 °C above the pre-industrial mean. A 0.5

°C stronger warming is obtained for the AerChemMIP scenario with reduced emissions of NTCFs. With concurrent reductions of future methane concentrations, the warming is projected to be reduced by 0.5 °C.

In this report we first describe the different model configurations based on the EC-Earth3 model, together with coupled tuning efforts, followed by a description of the component models including component tuning. Finally we decribe the tuning of EC-Earth3-AerChem in more detail.

2. Model configurations

2.1 The model architecture and coupling framework

EC-Earth is a modular Earth System Model (ESM) that is collaboratively developed by the European consortium with the same name. The current generation of the model, EC-Earth3, has been developed after CMIP5 and it is used in its version 3.3 for CMIP6 experiments.

EC-Earth3 comprises model components for various physical domains and system components describing atmosphere, ocean, sea ice, land surface, dynamic vegetation, atmospheric composition, ocean biogeochemistry and the Greenland ice sheet. The atmosphere and land domains are covered by ECMWF's IFS cycle 36r4, which is supplemented with a coupling interface to allow boundary data exchange with other components (ocean, dynamic vegetation, aerosols and atmospheric chemistry, etc). The NEMO3.6 and LIM3 models are the ocean and sea-ice components, respectively. Biogeochemical processes in the ocean are simulated by the PISCES model. Both LIM3 and PISCES are code-wise integrated in NEMO. Dynamical vegetation, land use and terrestrial biogeochemistry are provided by LPJ-GUESS (Smith et al., 2014, Lindeskog et al., 2013). Aerosols and chemical processes in the atmosphere are described by TM5 . The ice sheet model PISM is optionally utilized to model the Greenland ice sheet.

An overview of five ESM model configurations is given in this section. Descriptions are schematic and more detailed specifications will be given in forthcoming publications. Table 1 lists the configurations and their composition, while Table 2 shows the commonly used resolutions for CMIP6.

Most of the model components are coupled through the OASIS3-MCT coupling library (Craig et al., 2017) while some software components include more than one model component, e.g. the sea-ice model being a part of the ocean model. A new coupling interface has been developed and implemented to allow a flexible exchange between the model components. The OASIS3-MCT coupler provides a technical means of exchanging (sending and receiving) two- and three-dimensional coupling fields between different model components on their different grids. Of the above named model components, NEMO, LIM3 and PISCES exchange data directly via shared data structures. Thus, EC-Earth3 is implemented following a multi-executable

MPMD (multiple programs, multiple data) approach. The model components run concurrently and message-passing interface (MPI) is used for parallelisation within the components. A potential configuration of all components is illustrated in Figure 1, which also shows coupling links and frequencies. Note that a configuration including all possible components is not implemented in practice.

In order to manage different configurations, both at build and run time, EC-Earth3 includes tools to store and retrieve configuration parameters for different model configurations, computational platforms and experiment types. This allows consistent control of the build and run environments and improves reproducibility across platforms and use-cases.
Initial and forcing data, in the form of data files, are provided centrally for the EC-Earth community, and the data is versioned and checksummed for reproducibility.
For EC-Earth3 a tool was developed to convert the native model output to CF-compliant ("Climate and Forecast" standard) netCDF format (i.e., Climate Model Output Rewriter, CMOR), thus fulfilling the CMIP6 Data Requests for the MIPs that the community is contributing to (van den Oord et al. (2017), https://github.com/EC-Earth/ece2cmor3/).

2.2 Basic configurations EC-Earth3 and EC-Earth3-Veg

EC-Earth3 is the standard configuration consisting of the atmosphere model IFS including the land surface module HTESSEL and the ocean model NEMO3.6 including the sea ice module LIM3. Coupling variables are communicated between the different component models via the OASIS3-MCT coupler. The physical interfaces are defined specifying the variables exchanged and the algorithms used.

At the atmosphere-ocean interface, we follow the principle that the ocean provides state variables and the atmosphere sends fluxes. Flux formulations correspond to the documentation of IFS CY36R1, section 3, at https://www.ecmwf.int/en/publications/ifs-documentation. As the coupler ensures conservative remapping, momentum, energy, evaporation and precipitation fluxes are conserved.

The freshwater runoff from land to ocean is derived from a runoff mapper (Table. 4). It uses OASIS3-MCT to interpolate local runoff and ice-shelf calving (from Greenland and Antarctica) to the ocean. The runoff and calving received from the atmosphere and from the surface model HTESSEL are interpolated onto 66 hydrological drainage basins on a mapper grid by a nearest-neighbour distance-based Gauss-weighted interpolation method. Then, in a coupling post-processing step ("CONSERV GLBPOS step"), the residual (target minus source grid integrals) is distributed over the target grid, proportional to the original value. The resulting runoff to the ocean is evenly and instantaneously distributed along the ocean coastal points connected to each hydrological basin. This approach does not constitute a locally conservative method in a mathematical sense but it conserves mass.

In order to avoid a significant long-term sea-surface height reduction in coupled model runs due to a net precipitation - evaporation (P-E) imbalance in the EC-Earth3 atmosphere of about -0.016 mm/day in the historical period, the coupled model implements a runoff flux corrector, which amplifies river runoff by 7.95% in order to compensate for this effect.

EC-Earth3-Veg is a configuration extending EC-Earth3 by the interactively coupled 2nd generation dynamic global vegetation model LPJ-GUESS, which is described together with the coupling principles. Here we provide the variables exchanged through the coupler.
The coupling interface between the atmosphere and vegetation (Table 5) is characterized by the atmospheric model sending the driving variables, as well as selected biogeophysical soil parameters computed within HTESSEL. LPJ-GUESS returns vegetation parameters for both high and low vegetation categories needed for computing surface energy and water exchange in HTESSEL. This ensures that EC-Earth makes best use of both the advanced biophysics in the HTESSEL land-surface model and of the state-of-the-art vegetation dynamics, land use functionality and terrestrial biogeochemistry (carbon and nitrogen) in LPJ-GUESS. Since HTESSEL and LPJ-GUESS have very different soil water schemes (LPJ-GUESS updates soil moisture separately in each patch and stand-type for each gridcell whereas HTESSEL simulates soil moisture per gridcell), the water cycle is discontinuous and each model operates its own water cycle. The water cycle of LPJ-GUESS is thus loosely coupled to the rest of EC-Earth by means of the driving variables sent by HTESSEL/IFS.

Atmospheric tuning of EC-Earth3 and EC-Earth3-Veg

The atmospheric component of EC-Earth has been tuned with the goal of achieving a reasonably small radiative imbalance at the top of the atmosphere (TOA) at standard resolution (T255L91 – to which we refer in the following) in present-day atmosphere-standalone (AMIP) runs, using the CERES_EBAF_Ed4.0 dataset as a reference (Loeb et al. 2018). In particular the goal was to minimize the mean weighted absolute error in the global means of the net radiative flux at the surface, the TOA longwave flux, longwave cloud forcing and shortwave cloud forcing, with the first two fluxes considered most important. The net radiative flux at the surface included the latent heat contribution associated with snowfall which is not included in the latent heat flux stored by IFS. A series of convective and microphysical atmospheric tuning parameters was identified, listed in Table 6. Similar parameters have been commonly used also for the tuning of other climate models (e.g. Mauritsen et al. 2012). An additional critical radius for the autoconversion process of liquid cloud droplets, added in EC-Earth3, was considered for tuning (see Rotstayn (2000) for a discussion on the use of such parameters for model tuning). Changes in the tuning parameters have been adopted to avoid values too different to the original IFS CY36R4 values. In order to proceed with tuning, the sensitivity of the model radiative fluxes to changes in these parameters was determined through a series of short (6 years) AMIP runs for present-day conditions. The resulting linear sensitivities accelerate considerably the tuning process and reduce the number of simulations needed, allowing to construct a linear "tuning simulator" used to predict the impact of different combinations of tuning parameter changes on the target radiative fluxes and to determine combinations providing an optimal score. An iterative process was followed, alternating the construction of new sets of tuning parameters using the known sensitivities, AMIP tuning runs for present-day conditions (20 years, from 1990 to 2010) and the following construction of a new set of tuning parameters to correct the residual biases, allowing to converge rapidly to a desired radiative balance. During this process model biases in other fields were monitored using a Reichler and Kim (2008) metric. Following a suggestion by ECMWF, we reintroduced in the code a condensation limiter for clouds, which had been removed in CY36R4, but then reintroduced in later cycles starting from CY37R2. Apart from improving the upper tropospheric distribution of humidity in IFS, this change has an important impact on radiative fluxes (more than +1.6 W/m^2 in net flux at TOA), making it a useful tool for tuning the global radiative balance. The atmospheric tuning process showed that energy conservation in IFS is severely dependent on the timestep used. For example at standard resolution, reducing the timestep testwise from 2700s to 900s, changes net surface fluxes by -2 W/m^2 , mainly due to an increase in low clouds, possibly due to resolution dependent parameterizations. This issue has been improved in later operational versions at ECMWF.

A similar tuning procedure was used to find alternative tuning parameter sets also for other configurations (EC-Earth3-AerChem, EC-Earth3-LR, and EC-Earth3-Veg-LR). The atmospheric tuning for EC-Earth3 and EC-Earth3-Veg is the same, as is the case for EC-Earth3-LR and EC-Earth3-Veg-LR. This is because the vegetation fields used for EC-Earth3 were derived from dynamic vegetation model runs. Therefore there are only very small differences between the two configurations (with and without dynamic vegetation) for each resolution, in terms of impact of vegetation on the global energy balance.

Coupled tuning of EC-Earth3 and EC-Earth3-Veg

In parallel to forced ocean tuning experiments, the tuned atmosphere was used in coupled present-day experiments researching optimal ocean parameters that allow for a realistic ocean circulation.

Tuning the final coupled model was aimed primarily at obtaining a realistic global climate at equilibrium in CMIP6 pre-industrial experiments, focusing in particular on the sea-ice distribution and extent, the near-surface air temperature distribution, atmospheric variability, the Sea Surface Temperature (SST) distribution (in particular the Southern Ocean temperature bias) and ocean transport due to the Atlantic Meridional Overturning Circulation (AMOC), while at the same time reaching a realistic average global temperature at equilibrium (286.7 K to 286.9 K following IPCC 2018, Hawkins et al. 2017, Brohan et al. 2006). The goal was to where-possible modify only ocean and sea-ice parameters while maintaining the same atmospheric tuning (even if some changes have been explored). A common set of tuning parameters suitable for both EC-Earth3 and EC-Earth3-Veg experiments was searched. To this end we performed both a range of pre-industrial simulations and, for comparison, corresponding present-day simulations (using fixed 1990 forcing fields and compared to 2010 observations). Gregory plots (Gregory et al. 2004) were used to compare different coupled experiments, to anticipate their approximate equilibrium temperatures even when only partial results were available and to derive suggested corrections to the global net radiative forcing. The main change which was adopted during this stage was an improved pre-industrial aerosol climatology produced with a different calculation of the sea-spray source, characterized by a stronger dependence on surface wind speed (reverting from the formulation of Salisbury et al. (2013) to that of Monahan et al. (1986)) and by a dependence on sea-surface temperature, following Salter et al. (2015). These changes increased sea-spray production over the Southern Ocean and helped to reduce the Southern Ocean SST bias. Details about the revised parameterization are given by van Noije et al. (2020). Finally, a further minor change was a small reduction of thermal conductivity of snow in LIM3 (rn_cdsn=0.27).

An interesting observation for pre-industrial equilibrium simulations is that at equilibrium we expect radiative balance at TOA and at the surface on average, but we have to take into account two additional effects: 1) While NEMO takes into account the temperature of incoming and outgoing mass fluxes (rainfall, snowfall, evaporation and runoff fluxes) to represent dilution effects, IFS does not account for the heat content of the moisture field and of precipitation, leading to a missing closure of the global heat budget, corresponding to a heat sink in the ocean; 2) NEMO includes a representation of geothermal energy sources. Estimating the total heat imbalance in the ocean comparing ocean heating rate of increase with the net flux at surface in a pre-industrial experiment, leads to a total estimate of about -0.2 W/m^2 (as a global average). This energy sink compensates to a large extent an internal energy production observed in IFS (as difference between the net TOA and net surface radiative fluxes) of about 0.25 W/m^2, explaining the TOA net flux close to 0 of EC-Earth3 in pre-industrial experiments.

Low resolution configurations

EC-Earth3-Veg-LR is a configuration with interactive LPJ-GUESS feedback at low resolution (T159 for IFS and 1^o for ORCA/NEMO). This configuration is applied in the Paleoclimate Modelling Intercomparison Project (PMIP, Kageyama et al., 2018). The major aim of PMIP is to understand the response of the climate system to different climate forcings and feedbacks in the last millennium and in earlier periods. This requires substantial computational resources for multiple multi-centennial simulations. EC-Earth3-Veg-LR makes this possible by a reduced resolution. In addition to resolution differences, new physical parameterizations are also included and tuning parameters are further modified following the same strategy described in the previous paragraph.

Compared to the corresponding configuration with the standard resolution (EC-Earth3-Veg), additional parameter adjustments are introduced to allow for paleoclimate simulations. The adjustments mainly include two parts. Most importantly, orbital forcing parameters are made variable in time. In other configurations, used for centennial scale simulations, these parameters are treated as constants, representing present-day climate. That approximation does not hold for multi-centennial to millennial time scales. The new variable calculation for the orbital parameters are taken and modified from CAM3.0 (2004) using the method of Berger (1978). The annual and diurnal cycles of solar insolation are calculated with a repeatable solar year of 365 days and with a mean solar day of exactly 24 hours, respectively. This adjusted formulation facilitates paleoclimate simulations for any time within 10^6 years of 1950 AD.

Another adjustment is related to the description of glaciers and Greenland ice sheet. In the standard resolution configuration EC-Earth3-Veg, the physics of land ice is not accounted for. This is not appropriate for paleoclimate simulations. Therefore, a land ice physics package is implemented describing surface physics and time varying snow albedo over land ice (except for Antarctica) without including a dynamic ice sheet model.

Due to the revised parameterizations and reduced resolution (including the different timestep), key quantities and model biases are different from the standard configuration EC-Earth3-Veg. Therefore the EC-Earth3-Veg-LR configuration requires a separate tuning. The difference between net TOA and net surface radiative fluxes is almost independent of the tuning and only depends on the resolution. In the standard resolution, the difference is in the order of -0.25 W/m^2, while the difference increases to about 0.3 W/m^2 for the low resolution.

Rather than tuning towards the currently observed transient climate state with a global mean imbalance of the order of 0.5 W/m^2 at the top of TOA (Hansen et al., 2011), we aimed at a tuning of a climate in a radiative equilibrium, to prevent the global mean surface temperature from drifting too much under the conditions of a stable climate. This approach is necessary for millenium scale simulations. We aimed at a net surface energy balance close to 0 W/m^2 under pre-industrial level forcing (1850) after hundreds years of spin-up. Thereby we mainly focused on the net surface energy (SFC) balance rather than the TOA energy budget as we know that the atmospheric model is not fully conservative. The resulting parameter combination, together with historical simulations will be described in a forthcoming paper in conjunction with partners in the EU-Crescendo project.

In order to avoid a significant long-term sea-surface height reduction in coupled model runs due to a net precipitation - evaporation (P-E) imbalance in the EC-Earth3 atmosphere of about -0.0174 mm/day in the historical period, the coupled model implements a runoff flux corrector, which amplifies river runoff by 8.65% in order to compensate for this effect.

In addition to the EC-Earth3-Veg-LR configuration, there is also a configuration without interactive vegetation, EC-Earth3-LR. In this configuration, vegetation is prescribed by the Paleo MIP (PMIP). These two configurations produce very similar results when EC-Earth3-LR is forced by the vegetation from a corresponding EC-Earth3-Veg-LR simulation. The tuning parameters are identical in both configurations.

High resolution configurations

Earlier studies with EC-Earth at high resolution, using EC-Earth 3.1, have shown improvements with resolution, e.g. in North-Atlantic Blocking (Davini et al. 2017b) and in the representation of tropical rainfall extremes (Davini et al. 2017a). This motivated further development of EC-Earth3 configuration in high resolution, with increased atmospheric and oceanic resolution, derived from an earlier state of development. It features a T511 spectral resolution for IFS and 0.25 degree resolution for ORCA/NEMO. A preliminary tuned version EC-Earth3P-HR is used in current projects and in CMIP6 MIPs. Another high resolution configuration, EC-Earth3-HR, closer to the EC-Earth3 base configuration, is still under development. Here we focus on the so far better documented configuration EC-Earth3P-HR.

At an early stage of development, EC-Earth3P-HR has been branched off from the main line, in order to apply it for the EU project PRIMAVERA and the HighResMIP, endorsed by CMIP6. PRIMAVERA and HighResMIP are focusing on the impact of horizontal resolution on the simulation of climate and its variability. The HighResMIP protocol requires modifications of the standard configuration to allow for a clean assessment of the impact of horizontal resolution. Motivation and detailed description of those deviations from the base version, EC-Earth3, are described in Haarsma et al. (2020). Below we give a short summary of the most important deviations of EC-Earth3P-HR:

- The stratospheric aerosol forcing is handled in a simplified way that neglects the details of the vertical distribution and only takes into account the total aerosol optical depth in the stratosphere which is then evenly distributed across the stratosphere. No indirect aerosol effect has been implemented.
- A SST and sea-ice forcing data set specially developed for HighResMIP is used for AMIP experiments (Kennedy et al., 2017). The major differences compared to the standard SST forcing data sets for CMIP6 are the higher spatial (0.25 deg vs. 1 deg) and temporal (daily vs. monthly) resolution.
- The vegetation and its albedo are prescribed as present-day climatologies that are constant in time.

Under HighResMIP, simulations are performed with EC-Earth3P-HR in high resolution and in the standard resolution EC-Earth3P (T255 for IFS and 1.0 degree for ORCA/NEMO). A full description of EC-Earth3P-HR including a technical implementation and post-processing can be found in Haarsma et al. (2020). EC-Earth3P-HR has not been tuned differently compared to the standard resolution at the time, due to very high computational demands. This approach is consistent with most other models in Europe, as represented in the H2020 PRIMAVERA project (Roberts et al., 2018).

Based on results of Haarsma et al. (2020), increasing horizontal resolution does not result in a general reduction of biases and overall improvement of the climate variability. Deteriorating impacts can be detected for specific regions and phenomena such as some Euro-Atlantic weather regimes, whereas others such as El Niño-Southern Oscillation show a clear improvement in their spatial structure. Analysis of the kinetic energy spectrum indicates that the sub-synoptic scales are better resolved at higher resolution (Klaver et al., 2020) in EC-Earth.

Despite a lack of clear improvement with respect to biases and synoptic scale variability for the high resolution version of EC-Earth, the better representation of sub-synoptic scales results in better representation of phenomena and processes on these scales such as tropical cyclones (Roberts et al., 2020) and ocean-atmosphere interaction along western boundary currents (Belluci et al. 2020). The impact of resolution for EC-Earth and other climate models participating in HighResMIP will be analyzed more in depth in upcoming publications.

2.3 EC-Earth3-AerChem

EC-Earth3-AerChem (van Noije et al., 2020) is the configuration with interactive aerosols and atmospheric chemistry, used in the Aerosol and Chemistry Model Intercomparison Project (AerChemMIP; Collins et al., 2017). In this configuration, TM5 is used to simulate tropospheric aerosols and chemistry based on the CMIP6 emission pathways for aerosols and chemically reactive gases. The resolution of TM5 is 3×2 degrees (longitude × latitude) with 34 vertical levels and a top at 0.1 hPa. IFS and NEMO have the same resolutions as in the standard configuration. TM5 and IFS exchange fields with a 6 hour frequency. TM5 receives a large set of 2-D and 3-D meteorological fields from IFS, and provides 3-D distributions of aerosols, ozone (O_3) and methane (CH_4) in return. Table 7 lists the fields exchanged between IFS and TM5 through the coupler.

2.4 EC-Earth3-CC

EC-Earth3-CC is the configuration that includes a description of the carbon cycle, which is used for the Coupled Climate–Carbon Cycle Model Intercomparison Project (C4MIP; Jones et al., 2016). EC-Earth3-CC allows simulations with emissions forcing rather than with prescribed concentrations only as in the ScenarioMIP. This configuration uses a single carbon tracer in the atmosphere, advected by a version of TM5 with a reduced number of vertical levels (10 instead of 34), to simulate the transport of CO_2 through the atmosphere. The resolution and coupling frequency for the exchange between IFS and TM5 are the same as for the interactive aerosols and chemistry version of TM5 (EC-Earth3-AerChem). In effect the data transfer in both directions is much reduced (see Appendix). The CO_2 exchange with the ocean and terrestrial biosphere is calculated in PISCES and LPJ-GUESS, respectively, based on surface mixing ratios from the previous day, received from TM5.

PISCES calculates the air-sea CO_2 flux at every time-step after solving for carbon chemistry in sea-water. This flux is proportional to the difference in pCO2 between the atmosphere and the surface of the ocean. The exchange of CO_2 between the ocean and TM5 is realized once a day after accumulating the flux over each grid-cell over 24 hours. Furthermore, physical transport of passive tracers in the ocean presents a slight artificial mass imbalance. To prevent it from becoming significant for carbon during the spin-up we applied a uniform correction to dissolved inorganic carbon at the end of each year, after taking into account all sources and sinks.

A variant of EC-Earth-CC can also be run concentration driven by excluding TM5. PISCES and LPJ-GUESS then read a uniform global atmospheric CO_2 concentration.

Table 8 and 9 lists the fields exchanged between the CTM on the one hand side and the vegetation and ocean biogeochemistry models on the other hand side, through the coupler.

2.5 EC-Earth3-GrIS

EC-Earth3-GrIS is a configuration that couples the EC-Earth3-Veg to the Parallel Ice Sheet Model v1.1 (PISM). It is used to model the Greenland ice sheet (GrIS) evolution and its feedback with the climate system in the Ice Sheet Model Intercomparison project (ISMIP6, Nowicki et al, 2016).

In the configurations EC-Earth3 and EC-Earth3-Veg, ice sheets are represented by a perennial snow layer of 9 meter water equivalent. Snowfall on these areas is immediately redistributed into the ocean as ice to prevent excessive snow accumulation. Perennial snow albedo and snow density are fixed at 0.8 and 300 kg m^{-3} respectively and the snowpack is in thermal contact with the underlying soil. In EC-Earth3-GrIS, the surface parameterization in EC-Earth3 is adjusted in order to better account for the presence of the ice sheet. The modifications include introduction of an explicit ice sheet mask obtained from PISM into HTESSEL, and application of values representative of an ice sheet to calculate the surface energy balance and subsurface heat and energy transfer for glacierized grid points. In addition, if a grid cell is with ice sheet but no snow cover (i.e., bare ice), the ice can melt and contribute to surface run-off, if the energy flux at the surface is positive. Furthermore, a time-varying snow albedo parameterization is introduced for snow on ice sheets (Helsen et al, 2017) in the EC-Earth3-GrIS. The parameterization allows the dependence of snow albedo on snow aging, melt and refreezing. For fresh snow a maximum value of 0.85 is used. Under dry non-melting conditions, ageing may reduce the snow albedo to 0.75 and during snow melt the albedo decreases to a lower limit of 0.6. The albedo of refrozen meltwater is set to 0.65.

The new land ice physics described above is used for EC-Earth3 low resolution configurations, in particular for PMIP experiments. In this case, there is no coupling to the ice sheet model. Instead, the ice sheet mask can be either read in as boundary conditions or defined by snow depth exceeding a certain threshold (9 meters).

The fields exchanged between EC-Earth and PISM are listed in Table 10. Information is exchanged once a year with monthly variations. IFS provides forcing fields of surface mass balance (SMB) and subsurface temperature to PISM. The SMB is calculated from precipitation, evaporation and run-off. PISM returns the ice topography and ice mask to IFS and the calving (mass and energy) and basal melt (mass) fluxes to NEMO.

3. The component models

3.1 Atmosphere

The atmosphere component of the EC-Earth model is based on the Integrated Forecast System (IFS) CY36R4 of the European Centre for Medium Range Weather Forecasts (ECMWF). This specific cycle of the IFS has been part of ECMWF's operational seasonal forecast system S4 (https://www.ecmwf.int/sites/default/files/elibrary/2011/11209-new-ecmwf-seasonal-forecast-system-system-4.pdf). IFS solves the hydrostatic primitive equations using a two-time-level, semi-implicit semi-Lagrangian discretization. Horizontal derivatives are computed in spectral space while the computation of advection, the physical parameterizations, and in particular the nonlinear terms are conducted on the linear reduced Gaussian grid. The IFS is documented extensively at https://www.ecmwf.int/en/publications/ifs-documentation, for example https://www.ecmwf.int/sites/default/files/elibrary/2010/9232-part-iii-dynamics-and-numerical-procedures.pdf for the dynamics and https://www.ecmwf.int/sites/default/files/elibrary/2010/9233-part-iv-physical-processes.pdf for the physical processes. Here we only document the updates to the original IFS that were necessary for making long climate simulations.

The physical aspects of the atmosphere model in EC-Earth needed some adjustments and updates compared to the original IFS CY36R4. Most of these modifications are not necessary for Numerical Weather Forecast (NWP) or even seasonal forecasts but are crucial when running long climate simulations, decadal, centennial and longer, or simulations under different climate conditions (e.g. future scenarios or paleo simulations).

The semi-Lagrangian advection scheme of IFS does not conserve mass nor energy in the NWP version. A dry air mass conservation fixer has been available in IFS since CY25R1 and is active in EC-Earth to correct global pressure for the gain or loss of atmospheric mass. Similarly, to conserve humidity during transport we backported a simple proportional fixer from IFS cycle CY38R1 (Rasch and Williamson 1990, Diamantakis and Flemming 2014). This significantly reduced the bias of the average global precipitation-evaporation balance in the model from about +0.030 mm/day to -0.017 mm/day and, consistently (due to the associated latent heat of condensation), in the radiative balance in the atmosphere from about -1.65 W/m^2 (a source of energy) to about -0.25 W/m^2 .

The IFS CY36R4 version adopted for EC-Earth3 produces a reasonable Quasi-Biennial Oscillation (QBO) in the tropical stratosphere when running at the standard resolution (T255L91), but not for any other available horizontal or vertical resolutions. Therefore we substituted the original version-dependent latitudinal profile of the momentum flux in the non-orographic gravity wave scheme (which was originally developed ad-hoc for the ECMWF System 4 seasonal forecast system), with a resolution-dependent parameterisation of non-orographic gravity wave drag, backporting changes later introduced in IFS CY40R1 (see Davini et al. 2017a for more details). This change allowed EC-Earth to recover a realistic QBO at all resolutions considered, without deteriorating the jet streams.

Convection in the NWP version of IFS CY36R4 reaches its maximum around local noon in contrast to observations that peak later in the afternoon. A closure described by Bechtold et al. (2014) improves the diurnal cycle of convection in EC-Earth3. For EC-Earth3, Rayleigh friction was activated in EC-Earth IFS for all resolutions.

In atmosphere-only simulations, the sea-ice albedo is taken from a look-up table with climatological monthly values for sea-ice albedo (Ebert and Curry, 1993) that takes into account the annual cycle of highly reflective snow cover during winter and spring and the darker surface of melting sea ice during summer. In the coupled model, the sea-ice albedo is computed in the sea-ice model LIM3 and the updated values are used by the atmospheric component. The broadband sea-ice albedo from LIM3 is then mapped on 6 shortwave bands with a mapping function.

The time stepping scheme needed technical adjustments to avoid an overflow of integer timestep counters, in order to allow making simulations beyond 32768 timesteps. The IFS output is saved in the GRIB1 data format which also has a limit in the number of timesteps that can be saved. This limit was overcome in EC-Earth3 by setting the timestep to 0 and updating the GRIB encoded reference time instead, each time that output is written.

CMIP6 requires transient climate forcings to account for the change in atmospheric composition and other external drivers of the climate (e.g. insolation). The necessary interfaces to read the prescribed greenhouse gas concentrations, aerosol optical properties, stratospheric aerosols, stratospheric ozone, and insolation have been implemented in the IFS code in EC-Earth. Table 13 lists the sources and versions of the CMIP6 forcing datasets.

Well-mixed greenhouse gases (WMGHGs) explicitly included in EC-Earth's radiation scheme are CO_2, CH_4, nitrous oxide (N_2O), CFC-12, and CFC-11. Together these are responsible for about 98% of the total radiative forcing by WMGHGs in 2014 compared to 1850 (Meinshausen et al., 2017). The radiative effects of the remaining WMGHGs (HCFC-22, CFC-113, CCl4, etc.) are accounted for in terms of CFC-11 equivalents (Meinshausen et al., 2017). The mixing ratios of each of the WMGHGs that are explicitly included and not provided by TM5 are prescribed by scaling their monthly zonal mean climatologies as used in IFS by a single time-dependent global factor. In this way, the global mean surface mixing ratios are forced to their CMIP6 pathways (Meinshausen et al., 2017). To reduce discontinuities, the scale factors are calculated on a monthly basis by interpolation of the time series of annual values provided by CMIP6. Any delays due to transport from the surface to the upper parts of the atmosphere are ignored in this approach.

Tropospheric aerosols are either simulated interactively in TM5 (in the EC-Earth3-AerChem configuration) or prescribed as a pre-industrial climatology plus an anthropogenic contribution (all other configurations). The pre-industrial aerosol background is specified using a monthly climatology based on TM5. This climatology was obtained from an offline TM5 simulation driven by ERA-Interim meteorology for the years 1981-1985, using CMIP6 anthropogenic emissions for the year 1850. The radiative and cloud effects of the pre-industrial aerosols are calculated based on the ERA interim reanalysis and the same set of variables as when aerosols are interactively simulated by TM5. The anthropogenic contribution is specified following the simple plume approach of MACv2-SP (Stevens et al., 2017), which provides a simplified, parametric representation of the optical properties (extinction, single-scattering albedo and asymmetry factor) of the anthropogenic contribution to the tropospheric aerosol burden (relative to 1850 levels), consistent with the CMIP6 time series of historical (Stevens et al., 2017) and future (Fiedler et al., 2019) anthropogenic emissions. In EC-Earth, MACv2-SP is coupled with the IFS radiation scheme to compute the optical properties for the 14 wavelength bands of the SW radiation. More precisely, the optical properties are calculated at the band mean wavelengths weighted by the incoming solar radiation. In addition, MACv2-SP provides a simple way to account for the effect of anthropogenic aerosols on clouds. Specifically, it provides a scale factor for the cloud droplet number concentration (CDNC) in each column, based on the vertically integrated optical depth at 550 nm.

In the EC-Earth3-AerChem, aerosol impacts on clouds are included by calculating CDNC depending on the modal number and mass concentrations from TM5, following Abdul-Razzak and Ghan (2000). For all other model configurations the CDNC corresponds to pre-industrial aerosol conditions, and an additional scaling factor from MACv2-SP that is included to account for the cloud forcing by anthropogenic aerosols. The resulting forcing includes contributions due to both cloud reflectivity and cloud lifetime effects, as the lifetime of clouds explicitly depends on CDNC. Currently only the activation and autoconversion of liquid cloud droplets is linked explicitly to ambient aerosol concentrations. For ice clouds the EC-Earth3 model still retains the parameterization from original IFS CY36R4.

Stratospheric aerosols are prescribed using the CMIP6 data set of aerosol radiative properties, which covers the period 1850 to 2014 and for the more recent period is based on satellite data assembled by Thomason et al. (2018). The data set consists of monthly resolved zonal mean fields, which are provided at the 14 shortwave (SW) and 16 longwave (LW) bands of the IFS's radiation schemes. For the SW scheme, the extinction, single-scattering albedo and asymmetry factor are specified, whereas only the absorption is taken into account for the LW scheme, since aerosol scattering in the LW is neglected in the atmospheric component of EC-Earth. Forcing data are vertically interpolated beforehand for the 62 and 91 level configurations, taking into account the seasonality of model level heights, whereas horizontal and monthly to daily interpolation is done online. When interpolating or averaging the radiative property fields, they are first made extensive by including the appropriate weighting factors (e.g. extinction is converted to optical depth, single-scattering albedo to absorption optical depth, and likewise for the asymmetry factor). The forcing located below the online diagnosed thermal tropopause level is excluded.This implementation is used in all current EC-Earth3 configurations with the exception of the EC-Earth3P-HR configuration, which uses a simplified implementation based on a monthly vertically integrated, latitude-dependent AOD forcing at 550 nm which is then vertically distributed across the stratosphere. In both implementations, it is possible to set the forcing fields to a constant background distribution, computed as the time average over 1850 to 2014. This background forcing is applied in preindustrial control and future simulations, as recommended in the CMIP6 protocol.

The land use forcing dataset (LUH2) from CMIP6 (Hurtt et al. 2020) cannot be used directly as input to IFS because it does not provide the same vegetation cover or type categories as those used by the land surface scheme in IFS (HTESSEL, van den Hurk et al., 2000; Balsamo et al., 2009; Dutra et al. 2010; Boussetta et al., 2013) but instead provides agricultural management information and land-use transitions that are annually updated. The vegetation cover, leaf area index (LAI) and vegetation type that are needed for the land surface scheme and albedo parameterisation in IFS can be simulated by the dynamic vegetation model LPJ-GUESS (Smith et al., 2014). This happens automatically in the EC-Earth3-Veg configuration where the dynamic vegetation model, which uses the LUH2 dataset as an input, is active, but for all other configurations the required vegetation cover and type need to be precomputed. This is done by first making all CMIP6 experiments with the EC-Earth3-Veg configuration and saving the vegetation variables that can then be reused when making the same experiment with other model configurations

The orbital parameters of the original IFS CY36R4 are fixed for present-day conditions, following the recommendations of the International Astronomical Union (ARPEGE-Climate Version 5.1, 2008), which is sufficient for simulations of the recent past or near future. However for paleo simulations in PMIP the orbital parameters need to be variable or set fixed for a different time period. Orbital parameters and insolation are computed using the method of Berger (1978). Using this formulation, the insolation can be determined for any year within 10^6 years of 1950 AD. The formulation determines earth-sun distance factor and solar zenith angle. The annual and diurnal cycle of solar insolation are represented with a repeatable solar year of exactly 365 days and with a mean solar day of exactly 24 hours, respectively. The repeatable solar year does not allow for leap years. The orbital state may be specified in one of two ways. The first method is to specify a year, which is held constant during the integration for an equilibrium simulation, or varies yearly for a transient simulation. The second method is to specify the orbital parameters: eccentricity, longitude of perihelion, and obliquity. This set of values is sufficient to specify the complete orbital state. For example, settings for PiControl integrations under 1850 AD conditions are obliquity = 23.549, eccentricity = 0.016764, and longitude of perihelion = 100.33.

3.2 Land surface and vegetation

The Hydrology Tiled ECMWF Scheme of Surface Exchanges over Land (HTESSEL; van den Hurk et al., 2000; Balsamo et al., 2009; Dutra et al. 2010; Boussetta et al., 2013) is the land surface model interfacing with the atmospheric boundary layer and solving the energy and water balance at the land surface in EC-Earth. HTESSEL discretization, for each grid point, solves for up to six different land surface tiles that may be present over land (bare ground, low and high vegetation, intercepted water by vegetation, and vegetation-shaded and exposed snow). Surface radiative, latent heat and sensible heat fluxes are calculated as a weighted average of the values over each tile.

The discretization in HTESSEL is such that coexistence in each grid point of more than one type of low and high vegetation, respectively, is not allowed. Therefore, for each grid-point and for both low and high vegetation covers, a dominant type (dominant meaning type with the higher relative area fraction for either high or low vegetation) is identified, T_l and T_h , and a vegetation coverage for high and low vegetation types, C_h and C_l, is specified.

Vegetation types and vegetation coverage can be

1. prescribed from a static land-use map from the Global Land Cover Characteristics (GLCC, standard HTESSEL configuration; van den Hurk et al., 2000; Balsamo et al., 2009; Dutra et al. 2010; Boussetta et al., 2013); or
2. interactively provided when coupled with LPJ-GUESS; or
3. prescribed from a previous simulation with LPJ-GUESS.

When the tile fractions are prescribed from GLCC, vegetation density is parameterized according to the Lambert Beer law of extinction of light under a vegetation canopy and is therefore allowed to change as a function of Leaf Area Index (LAI) for both low and high vegetation as described in Alessandri et al (2017). Otherwise, LPJ-GUESS provides its own consistently-simulated background tile fractions and vegetation densities.

The coupling of biophysical parameters in HTESSEL has been enhanced since CMIP5 (Weiss et al., 2013), where only the surface resistance to evapotranspiration and water intercepted and directly evaporated from vegetation canopies were made to depend on LPJ-GUESS vegetation dynamics. In the version for CMIP6, as used in EC-Earth3-veg, the surface albedo (including the shading effect of high vegetation), surface roughness length and soil water exploitable by roots for evapotranspiration also vary following the variability of the effective vegetation cover. The improved representation of the effective vegetation cover variability brought a significant enhancement of the EC-Earth performance over regions where the land-atmosphere coupling is strong, in particular over boreal winter middle-to-high latitudes (Alessandri et al., 2017).
To represent time-dependent albedo for each grid-point, a new scheme has been adopted that computes the total surface albedo (A_{tot}) as a weighted combination of contributions from the albedo of the low and high vegetation types present in each grid point ($a_v(type)$, a function of the low or high vegetation type) plus a time-constant background soil albedo (a_s, function of space):

$$A_{\mathrm{tot}} = a_v(T_l)C^{\mathrm{eff}}_{\mathrm{low}} + a_v(T_h)C^{\mathrm{eff}}_{\mathrm{high}} + a_s\left[1 - C^{\mathrm{eff}}_{\mathrm{low}} - C^{\mathrm{eff}}_{\mathrm{high}}\right]$$

where C^{eff}_{low} and C^{eff}_{high} are the effective fractional coverages for low/high vegetation and T_l and T_h are the low and high vegetation types respectively at each gridpoint. The background soil albedo was adopted from the map from Rechid et al.

(2009) and a look-up table of the albedo values a_v for each vegetation type was estimated using least square minimization of errors against available monthly climatology of snow-free monthly MODIS albedo (Morcrette et al., 2008).

3.3 Dynamic vegetation and terrestrial biogeochemistry

LPJ-GUESS (Smith et al. 2001, 2014; Lindeskog et al. 2013; Olin et al. 2015a, b), a process-based 2nd generation dynamic vegetation and biogeochemistry model, is the terrestrial biosphere component of EC-Earth, globally simulating vegetation dynamics, land use and land management following the LUH2 dataset (Hurtt et al., 2020), and both carbon (C) and nitrogen (N) cycling in terrestrial ecosystems. LPJ-GUESS has been evaluated in numerous studies (Smith et al. 2014; Wårlind et al. 2014), and reproduces vegetation patterns, dynamics and productivity, C and N fluxes and pools, and hydrological cycling from global to regional scales, in line with independent datasets and comparable models (e.g. Piao et al. 2013; Zaehle et al. 2014; Sitch et al. 2015, Peters et al. 2018).

LPJ-GUESS is a new component in EC-Earth3 (Miller et al., in prep), though it has previously been coupled to EC-Earth v2.3 (Weiss et al. 2012; Alessandri et al. 2017) using a simplified coupling scheme in which updates to leaf area index (LAI) alone were transferred between the submodels.

LPJ-GUESS is one of the first vegetation submodels coupled interactively to an atmospheric model, in which the size, age structure, temporal dynamics and spatial heterogeneity of the vegetated landscape are represented and simulated dynamically. Such functionality has been argued to be essential for correctly capturing biogeochemical and biophysical land-atmosphere interactions on longer timescales (Purves and Pacala 2008; Fisher et al. 2018), and has been shown to improve realism compared with more common area-based vegetation schemes (Wolf et al. 2011; Pugh et al. 2018). Different plant functional types (PFTs) co-occur in natural and managed stands governed by climate, atmospheric CO_2 (Meinshausen et al., 2017; Riahi et al., 2017), and N deposition (Hegglin et al. GMD, in prep) forcings. Evolving stand structure impacts growth, survivorship and the outcome of competition by affecting the availability of the key resources: light, space, water and nitrogen. Disturbances due to management actions such as forest clearing, prognostic wildfires and a stochastic generic disturbance regime affect patches at random, inducing biomass loss and resetting vegetation succession (Hickler et al. 2004). N cycle-induced limitations on natural vegetation and crop growth, C-N dynamics in soil biogeochemistry and N trace gas emissions are included (e.g. Smith et al. 2014; Olin et al. 2015a, b) as well as biogenic VOC emissions (Hantson et al. 2017).

Meteorological inputs imposed on LPJ-GUESS are daily fields of surface air temperature and 25 cm soil temperatures, precipitation, net shortwave and net longwave radiation from IFS/HTESSEL (Table 5). LPJ-GUESS calculates its own soil moisture for potential plant uptake in all patches in each of the six simulated stands, independently of the single grid cell-averaged hydrology scheme used in HTESSEL.

Vegetation dynamics are simulated on six stand types in the land portion of the gridcell (excluding large water bodies based on the static LUH2 ice and water fraction information), five stands having dynamic gridcell fractions consistent with the LUH2 dataset, namely Natural, Pasture, Urban, Crop, and Irrigated Crop, and one, Peatland, having a fixed gridcell fraction derived from the GLCC global map used in the standard HTESSEL configuration - see Sec. 3.2. The LUH2 dataset, including land cover fractions, management options (N fertilization in this case) and land cover transitions, are read in yearly, after aggregation to the atmospheric and land surface model resolution in a preprocessing step. Ten woody and two herbaceous PFTs compete in the Natural stand (Smith et al. 2014), whereas two herbaceous species, one each conforming to the C3 and C4 photosynthetic pathways, are simulated on Pasture, Urban and Peatland fractions. The Crop stands each have five crop functional types (CFTs) representing the properties of global crop types and encompassing the classes found in the LUH2 database, namely both annual and perennial C3 and C4 crops, and C3 N fixers (Lindeskog et al. 2013).
At the end of each day, LPJ-GUESS calculates the effective cover for low (high) vegetation, C_l (C_h), and LAI for low (high) vegetation, LAI_{low} (LAI_{high}), taking into account phenology and stand fractions in the gridcell. Dominant high and low vegetation types corresponding to the standard HTESSEL types are calculated and sent by LPJ-GUESS to IFS/HTESSEL on Dec 31st each year. These six fields link the vegetation dynamics and land use in LPJ-GUESS to the biophysical processes simulated at the land surface in HTESSEL, namely albedo, latent and sensible heat exchange, runoff and momentum exchange.

In the EC-Earth-CC configuration, LPJ-GUESS is coupled to TM5 in addition to IFS, and exchanges additional fields to enable prognostic global C cycle calculations. Spatiotemporally variable surface CO_2 concentrations are sent by TM5 to LPJ-GUESS (and PISCES) to replace the annual and global mean CO_2 concentrations used in the EC-Earth-Veg configuration. LPJ-GUESS sends daily averaged fields of net ecosystem C exchange (i.e. uptake or release) to TM5 to complement the surface C exchange with the ocean calculated in PISCES (see below), thereby completing the carbon cycle in EC-Earth-CC. This daily flux includes contributions from net primary production (NPP), heterotrophic respiration (Rh), wildfires, land use (including crop and pasture harvest) and natural disturbances on non-managed land. Since some processes in LPJ-GUESS are simulated with a yearly timestep (e.g. wildfires, disturbance, establishment of new individuals and mortality, land use change), these annual fluxes are distributed evenly throughout the year and added to the daily NPP and Rh fluxes the following year to conserve carbon mass. Negative NPP fluxes account for CO2-uptake by vegetation.

3.4 Atmospheric chemistry

The Tracer Model version 5 (TM5) is the atmospheric composition model of EC-Earth (Van Noije et al., 2014) used in the EC-Earth3-AerChem and EC-Earth3-CC configuration. It can be used for the interactive simulation of carbon dioxide (CO_2), methane (CH_4), ozone (O_3), tropospheric aerosols, and other trace gases. These components are prescribed in IFS from forcing datasets (see Sec 3.1) if not provided interactively by TM5. Other well-mixed greenhouse gases and stratospheric aerosols are prescribed in all configurations. This section briefly describes how the various components are configured.

As an alternative to the scaling approach for WMGHG presented in 3.1, the 3-D distributions of CO_2 and CH_4 can be calculated online by TM5. In the EC-Earth-CC configuration a single-tracer version of TM5 is used for simulating the transport of CO_2 through the atmosphere. Anthropogenic emissions of CO_2 are prescribed following the CMIP6 historical inventory (Hoesly et al., 2018) or future scenarios (Gidden et al., 2019). Exchange of CO_2 with the ocean and terrestrial biosphere is included by coupling TM5 to PISCES and LPJ-GUESS, respectively. An important feature of the model is that the transport in TM5 is mass conserving (Krol et al., 2005). For the simulation of CH_4, a version of TM5 that includes atmospheric chemistry and aerosols is used (Van Noije et al., 2020). A recent description of the chemistry scheme applied in EC-Earth has been presented by Williams et al. (2017). Emissions of aerosols and chemically reactive gases are taken from the CMIP6 historical data sets for anthropogenic sources (Hoesly et al., 2018) and biomass burning (van Marle et al., 2017) or the corresponding CMIP6 scenario data sets (Gidden et al., 2019). To force the CH_4 simulation to follow the pathway provided by CMIP6, its surface mixing ratios are nudged towards the monthly zonal means from CMIP6 interpolated to daily values. Moreover, because TM5 lacks a comprehensive stratospheric chemistry scheme, the CH_4 mixing ratios in the stratosphere are nudged towards a monthly zonal mean observational climatology representative for the 1990s (interpolated to daily values), scaled by a global factor based on the CMIP6 time series of global annual mean surface values. To calculate the scale factor, we assume a one-year delay between the mixing ratios at the surface and in the stratosphere (Meinshausen et al., 2017), and a reference value based on a 10-year average.

The chemical production of water vapour (H_2O) by oxidation of methane in the stratosphere is included in IFS in a similar way as in the standard version of IFS. The assumption made in the standard version of IFS is that

$$2 \times [CH4] + [H2O] = Co,$$

where square brackets denote local mixing ratios (in ppmv) and the constant is set to 6.8 ppmv based on observations for the present day. To account for long-term variations in CH_4, in EC-Earth it is assumed instead that

$$2[\mathrm{CH4}]+[\mathrm{H2O}]=\mathrm{C(t)},$$

where

$$\mathrm{C(t)=Co+2([CH4]S(t)-[CH4]0S)}.$$

Here [CH4]S(t) is the monthly-varying global mean surface mixing ratio obtained by linear interpolation from the CMIP6 time series of annual values, and [CH4]0S is a reference value for the present day, which is set to 1.78 ppmv.

Ozone is simulated by TM5. As for CH_4, TM5 applies a nudging scheme for O_3 in the stratosphere. In EC-Earth3, the mixing ratios are nudged towards daily zonal means obtained from the CMIP6 data set.

For aqueous-phase chemistry in the troposphere, the acidity of cloud droplets is calculated assuming a uniform CO_2 mixing ratio, following the CMIP6 time series of annual global mean surface values.

TM5 simulates tropospheric aerosols, namely sulphate, black carbon, primary and secondary organic aerosol, sea salt and mineral dust in four size ranges describing nucleation, Aitken, accumulation and coarse modes, using the M7 aerosol microphysical model (Vignati et al., 2004). In addition, it simulates the total mass of ammonium, nitrate and methane sulfonic acid (MSA). Optical properties of the aerosol mixture are calculated based on Mie theory in combination with the mixing assumptions described by Van Noije et al. (2014).

For calculation of the SW radiative effects of the aerosol mixture, TM5 provides the extinction, single-scattering albedo and asymmetry factor at the 14 wavelength bands of the SW radiation scheme (using the same wavelength values as in MACv2-SP). In addition, TM5 provides the particle number and component mass mixing ratios for each of the M7 modes, plus the total mass mixing ratios of nitrate and MSA. LW absorption is calculated based on the mass mixing ratios of the M7 components using absorption efficiencies from IFS. The contribution of the aerosol mixture described by MACv2-SP and/or TM5 to SW extinction and LW absorption is removed above the tropopause, where the stratospheric aerosol data set from CMIP6 is applied. The tropopause level is diagnosed online following the thermal tropopause definition of the World Meteorological Organization (WMO, 1957) as detailed by Reichler et al. (2003). Where the thermal tropopause does not exist according to this definition, tropospheric and stratospheric aerosols are merged at the 100 hPa level.

3.5 Ocean

The ocean component of the EC-Earth model is the Nucleus for European Modelling of the Ocean (NEMO; Madec 2008, Madec et al., 2015) that includes the ocean model OPA (Océan Parallélisé), the LIM3 sea ice model and the PISCES biogeochemistry model. The CMIP6 version of the EC-Earth model uses NEMO3.6 (revision r9466) in combination with the ORCA1 shared configuration.

OPA is a primitive equation model of ocean circulation. Prognostic variables are velocity, hydrostatic pressure, sea-surface height and thermohaline variables (potential temperature and salinity). The distribution of variables is given by a three-dimensional Arakawa-C-type grid (Arakawa and Lamb 1977). OPA uses a partial step implementation for the geopotential z*-coordinate (grid boxes do not continue below topography) and a diffusive bottom boundary layer scheme (similar to that of Beckmann and Döscher, 1997) with implicit bottom friction to mix dense water down a slope.

NEMO allows for various choices for the physical sub-gridscale parameterizations as well as the numerical algorithms. EC-Earth uses the Turbulent Kinetic Energy (TKE) scheme for vertical mixing. The vertical eddy viscosity and diffusivity coefficients are computed from a 1.5 turbulent closure model based on a prognostic equation for the turbulent kinetic energy, and a closure assumption for the turbulent length scales. This turbulence closure model has been developed by Bougeault and Lacarrère (1989) in atmospheric cases, adapted by Gaspar et al. (1990) for oceanic cases and embedded in OPA by Blanke and Delecluse (1993).

Since the CMIP5 version of EC-Earth, major changes in the TKE schemes have been implemented: it now includes a Langmuir cell parameterization (Axell 2002), the Mellor and Blumberg (2004) surface wave breaking parameterization, and has a time discretization which is energetically consistent with the ocean model equations (Burchard 2002, Marsaleix et al. 2008). A mixed layer eddy parameterization following Fox-Kemper et al. (2008) has been newly implemented in NEMO3.6. An enhanced vertical diffusion and a double diffusive mixing parameterization are part of the OPA code in EC-Earth. Since CMIP5, a tidal mixing parameterization has been added to OPA (de Lavergne et al. 2020).
Horizontal tracer diffusion is described by the Gent-McWilliams (Gent and McWilliams 1990) parametrization of mesoscale eddy-induced turbulence.

The ORCA family is a series of global ocean grid configurations. The ORCA grid is a tripolar grid and based on the semi-analytical method of Madec and Imbard (1996). ORCA1 with a resolution of about 1 degree is used for standard or low resolution simulations, and ORCA025 (resolution 0.25 deg) for high resolution simulations with EC-Earth3-HR. A meridional grid refinement of 1/3 deg in the tropics allows a partial representation of tropical instability waves. There are 75 vertical levels in the ocean with an upper level of about 1 m and 24 levels distributed over the uppermost 100m.

The main difference of the OPA-version used in EC-Earth compared to the reference OPA-version of NEMO3.6 is that the parameterization of the penetration of TKE below the mixed layer due to internal and inertial waves is switched off (nn_etau=0). This has been done because the penetration of TKE below the mixed layer caused a too deep surface layer of warm summer water masses in the North Atlantic convection areas which lead to a breakdown of the Labrador Sea convection within a few years and a strongly underestimated Atlantic Meridional Overturning Circulation (AMOC) in EC-Earth. A minor modification compared to the standard NEMO setup from the ORCA1-shared configuration for NEMO (ShacoNemo) is an increased tuning parameter rn_lc (=0.2) in the TKE turbulent closure scheme that directly relates to the vertical velocity profile of the Langmuir Cell circulation. Consequently, the Langmuir Cell circulation is strengthened.

3.6 Sea ice

The sea ice component is version 3.6 of the Louvain-la-Neuve Ice Model (LIM, Vancoppenolle et al., 2009; Rousset et al, 2015), which works directly on the NEMO environment, including the ORCA grid. LIM3.6 is based on the Arctic Ice Dynamics Joint EXperiment (AIDJEX) framework (Coon et al., 1974), combining the ice thickness distribution (ITD) framework, the conservation of horizontal momentum, an elastic-viscous plastic rheology, and energy-conserving halo-thermodynamics (Vancoppenolle et al., 2009). All of these components of the sea ice model have been introduced or revised since CMIP5.

The ice thickness distribution framework was introduced (Thorndike et al, 1975) to deal with meter-scale variations in ice thickness, which cannot be resolved explicitly, but should preferably be accounted for, as many sea ice processes, in particular growth and melt, depend non-linearly on thickness h. In practice, this is achieved by treating h as an independent variable, leading to the introduction in discrete form of $L=5$ thickness categories, each characterized by a specific set of state variables (namely ice concentration, ice volume per unit area, snow volume per unit area, ice enthalpy, snow enthalpy, sea ice salt content). Ice and snow enthalpy also depend on vertical depth in the ice (z). All sea ice state variables $Xijl$, $l=1,\ldots, L$ are updated due to transport and thermodynamic processes. The default choice of 5 categories, with the upper category above 4 meters, has been shown to provide reasonable results at an acceptable computing cost (Massonnet et al., 2019).

Vertical sea ice motions are irrelevantly small and hence neglected, and the sea ice velocity field reduces to its horizontal components. The 2D ice velocity vector is considered the same for all categories and stems from the horizontal momentum conservation equation. The internal stress term is formulated assuming that sea ice is a viscous-plastic material, i.e., assuming viscous ice flow at very small deformation and plastic flow (stress independent of deformation) above a plastic failure threshold. This threshold lies on an elliptical yield curve in the principal stress components space, whose size can be changed by tuning classical ice strength parameter $P^* = 20000$, following the classical formulation of Hibler (1979). The horizontal momentum equation is resolved using the Elastic-Viscous-Plastic (EVP) C-grid formulation of Bouillon et al (2009), using 120 sub-time steps. Once the velocity field is computed, the sea ice state variables are transported horizontally, using the second-order moment-conserving scheme of Prather (1986).

Ice thermodynamics are based on the Bitz and Lipscomb (1999) enthalpy formulation, and account for dynamic changes in ice salinity, through temperature and salinity-dependent thermal properties (Ono, 1968; Pringle et al., 2007). The salt entrapment and drainage parameterizations follow from Vancoppenolle et al. (2009): each category is characterised by a dynamic mean salinity, from which a profile shape is derived for the computation of the vertical diffusion of heat. The broadband surface albedo of each ice category empirically depends on ice thickness, snow depth, surface temperature and cloud fraction, based on a reformulation of the Shine and Henderson-Sellers (1985) parameterization, that solves a few inconsistencies associated with state transitions (e.g. snow / no snow) following Grenfell and Perovich (2004), and tuned to match observations of Brandt et al. (2005). The impact of melt ponds is implicitly accounted for through imposed changes on the albedo activated when the surface temperature is 0°C. Energy, salt and mass conservations have been carefully checked within the ice component and its interfaces with the atmosphere and ocean (Rousset et al 2015).

All surface fluxes are computed in the atmosphere, and the IFS atmospheric model has only one ice thickness category. The solar and non-solar heat fluxes are therefore distributed on the different sea ice categories in LIM3, taking into account the differences in albedo and temperature among the sea ice categories in each gridpoint.

During the tuning phase it was found that the Arctic sea ice volume grew to unrealistically high values, especially during phases with reduced AMOC. An analysis showed that the thermal conductivity of snow needed a slight reduction (rn_cdsn=0.27) to reduce basal growth and increase bottom melt.

3.7 Ocean biogeochemistry

PISCES-v2 (Pelagic Interactions Scheme for Carbon and Ecosystem Studies volume 2) is a biogeochemical model that simulates the nutrient cycle and the inorganic and organic carbon cycle and comprises lower trophic phytoplankton and zooplankton (Aumont et al. 2015). It has two functional groups for phytoplankton (nanophytoplankton, including calcite producers, and Diatoms that can produce siliceous shells) and two size classes for zooplankton (mesozooplankton and microzooplankton). Growth rate of phytoplankton depends on photosynthetic available radiation (PAR) intensity and temperature. A limitation for primary production is computed based on the availability of the main nutrients (P, N, Si, Fe). In case of low nitrate concentrations nitrogen fixation by diazetrophiccyanobacteria is parameterized in waters warmer than 20°C (Aumont et al., 2015). PISCES uses a constant P/N/C ratio of 1/16/122 for primary production. Organic particulate matter produced by food-web processes in the euphotic layer is represented by two size classes. These sink throughout the water column with different velocities while being decomposed into dissolved inorganic nutrients (DIN, DOP) and dissolved inorganic carbon (DIC). A further pool for dissolved organic matter (DOM) is fed by phytoplanktonic exudation and excretion by zooplankton. DOM in PISCES represents only the semi-labile fraction with turnover times ranging from months to years and it is further remineralized at a constant rate. PISCES includes two different chemistry models to describe iron pools interactions. In EC-Earth3 we use the complex model by Tagliabue and Arrigo (2006). The global river and atmospheric deposition input of nutrients are not balanced to match the fraction lost by sediment burial. For this reason, PISCES allows for a homogeneous correction towards global mean values for alkalinity, nitrate, phosphate and silicate. Furthermore, physical transport of passive tracers presented a slight artificial mass imbalance. To prevent it from becoming significant for carbon during the spin-up we applied a uniform correction to dissolved inorganic carbon at the end of each year, after taking into account all sources and sinks.

With respect to climate studies PISCES is capable of simulating the relevant processes of the marine carbon cycle, i.e. it comprises the soft-tissue carbon pump, and the carbonate counterpump to realistically simulate the feedback of the marine carbon cycle to the climate.

The air sea gas exchange for carbon dioxide and oxygen is parameterized according to Wanninkhof (1992). The interface to the seafloor is given by basic assumptions for the exchange between the active sediment layer and the water bottom layer where different assumptions are made for the burial efficiency for silicate, calcite, and particular organic matter (see Aumont et al. 2015 for further details).

PISCES is part of the community model NEMO and runs on the same model grid. In EC-Earth3 the horizontal resolution is about 1 degree (ORCA1) with 75 vertical levels. Advection/diffusion of the 24 biogeochemical tracers are done in the hydrodynamic ocean model. A detailed description of the PISCES reference version is given in Aumont et al. (2015). In EC-Earth3 PISCES can be run in passive mode or with feedback to the atmosphere by prognostically simulating air-sea carbon fluxes and contributing to determine atmospheric pCO2 when the global carbon cycle is fully closed in the case that the atmospheric chemistry model TM5 and the terrestrial biosphere model LPJ-GUESS are also enabled. A feedback to the ocean physics is not foreseen, i.e. the thermal effect of light absorption by chlorophyll on water temperature is not communicated to NEMO (although possible).

3.8 Greenland Ice Sheet

The Parallel Ice Sheet Model v1.1 (PISM, Bueler and Brown, 2009, and Winkelmann et al., 2011, The PISM Team, 2019) is used in the EC-Earth3-GrIS configuration to model the Greenland ice sheet (GrIS) evolution in the climate system. PISM is an open source model jointly developed by a group of universities, and available from www.pism-docs.org. While all surface processes over ice sheet (such as the snow layer) are modelled in EC-Earth3, PISM handles the ice sheet dynamical and thermodynamical processes, including ice flow, subglacial hydrology, bed deformation, as well as the basal ice melt.

The spatial domain of PISM is built on a three-dimensional, equidistant polar stereographic grid. The equations are solved with an adaptive time stepping procedure. Boundary conditions include subsurface temperature and mass balance on the ice surface (provided by EC-Earth3), bedrock elevation and bed geothermal heat flux (considered as invariant, geographic conditions).

PISM considers the ice sheets as a slow, nonlinearly viscous isotropic fluid, characterized by a creeping flow induced by gravitational forces and constrained by the conservation laws of momentum, mass and energy for ice. A combination of two shallow ice approximations, the non-sliding shallow ice (SIA) and the shallow shelf (SSA) approximations is applied, depending on the ice regime (Bueler and Brown, 2009). The former is applied to bed-frozen parts of the ice sheets, while the latter is applied to ice shelves, and also used as a sliding law in areas with low basal resistance. This hybrid formulation enables the modelling of fast-flowing ice streams and outlet glaciers, and is commonly used for simulations of whole ice sheets for which it is too expensive to solve the full set of stress balance equations.

The ice velocities are determined from geometry (i.e, ice thickness and ice surface elevation), ice temperature and basal strength using momentum/stress balance equations. The ice thermodynamics is formulated as the energy balance based on enthalpy that enables solutions for polythermal ice masses (Ashwanden et al 2012), and the Glen-Paterson-Budd-Lliboutry-Duval flow law (Lliboutry et al. 1985) that accounts for softening of the ice as the liquid water fraction increases. The ice flow law is a single-power law in which the exponent can be selected independently for the SIA and SSA. Furthermore, an enhancement factor is used to account for the anisotropic nature of the ice.

The subglacial processes are resolved by the sliding law that relates the basal sliding velocity to the basal shear stress. PISM uses a pseudo-plastic sliding law and the Mohr-Coulomb model for yield stress that depends on the till friction angle and the effective pressure of the saturated till. The latter is based on a subglacial routing scheme and the basal melt rate is calculated from energy conservation across the ice-bedrock layer. A geothermal heat flux map is applied at the basal boundary to account for the heat entering the ice sheet from below. Ice bed deformation is approximated by the viscoelastic deformable Earth model formulated in (Bueler et al 2007).

Calving of marine terminating glaciers at the ocean boundary is parameterized in PISM as the model does not have a good representation of the narrow fjord systems of the marine outlet at the considered resolution. Several calving schemes are implemented in PISM to cope with different conditions, including the Eigencalving, von Mises calving, thickness calving, and flow kill calving, etc. A commonly used calving scheme for GrIS is adapted from the von Mises yield criterion which is suited for ice flows confined in narrow valleys and fjords (Morlighem et al. 2016). The parameterization assesses the calving speed from the amount of ice fracturing.

4. Tuning and spin-up of EC-Earth3-AerChem

As a first step in the tuning process, a small number of parameters in TM5 were optimized in a standalone configuration driven by meteorological and surface fields from the ERA-Interim reanalysis (Dee et al., 2011) using the same horizontal resolution and number of vertical levels as in EC-Earth3-AerChem (see van Noije et al., 2014). Specifically, the correction factor for the threshold friction velocity applied in the calculation of the mineral dust source was set to 0.6, resulting in a global source of

1.12×10^3 Tg in the year 2010. This is well within the range obtained in other global models (e.g. Huneeus et al., 2011; Gliß et al., 2021), although for a proper comparison of emitted mass amounts from different models one should account for differences in the representation of the upper end of the size distribution. Moreover, the scale factor applied to the NO_x produced in lightning flashes was determined from the requirement that the total production in 2006 is 6.0 Tg N. The assumptions about the size distribution and solubility of carbonaceous aerosols emitted from biofuel and open biomass burning have also been revised as part of the tuning. Initially, 65 % of the organic matter from open biomass burning was assumed to be water soluble, consistent with observations (Mayol-Bracero et al., 2002; Reid et al., 2005). POA emissions from other sources, including solid biofuel burning, as well as freshly emitted BC were assumed to be 100 % insoluble and thus emitted in the Aitken mode. This resulted in too high particle number concentrations in residential regions with substantial biofuel burning. The carbonaceous emissions from solid biofuel burning have therefore been separated from the other emissions in the residential sector and are treated as emissions from open biomass burning. In an intermediate version of the model, 50 % of the BC mass emitted by biofuel and biomass burning was assumed to be emitted into the (soluble) accumulation mode (see e.g. Kodros et al., 2015). In line with measurements of the size distributions of emissions from open biomass burning (Janhäll et al., 2010) and biofuel burning (Li et al., 2009; Winijkul et al., 2015), this percentage has later been increased to 95 % for both POA and BC. This revision has led to modest reductions in the aerosol optical depth in parts of East Asia and, during boreal winter and spring, in Western Africa and the tropical Atlantic, improving the comparison with observations in these regions (not shown). An evaluation of aerosol optical properties for the year 2010 simulated with the final parameter settings in TM5 is presented by Gliß et al. (2020). This evaluation includes both the TM5 standalone configuration driven by meteorological and surface fields from the ERA-Interim reanalysis (Dee et al., 2011) and the EC-Earth3-AerChem model in atmosphere-only configuration with sea surface temperatures (SSTs) and sea ice concentrations prescribed as in the Atmospheric Model Intercomparison Project (AMIP) experiment (Döscher et al., in preparation) and atmospheric temperatures and surface pressures nudged to ERA-Interim fields.

The tuning of the model's climate started from the tuned configuration of EC-Earth3 (Döscher et al., in preparation). As explained in the introduction, the main differences between the two configurations are due to tropospheric aerosols and tropospheric and lower-stratospheric ozone. In EC-Earth3, tropospheric aerosols are described by the MACv2-SP simple plume representation of anthropogenic aerosol optical properties and cloud effects (Stevens et al., 2017) in combination with a pre-industrial climatology

produced by TM5.

EC-Earth3 produces an aerosol effective radiative forcing (ERF) of about -0.8 W m^{-2} over the CMIP6 historical period (1850–2014), as estimated from a set of 30-year atmosphere-only simulations performed as part of the Radiative Forcing Model Intercomparison Project (RFMIP; Pincus et al., 2016). For comparison, using the same IFS parameter settings as in EC-Earth3, the aerosol ERF in EC-Earth3-AerChem was estimated at -1.1 W m^{-2} . The final revision of the treatment of carbonaceous emissions from biofuel and biomass burning emissions resulted in a ~ 0.4 W m^{-2} weaker aerosol forcing, bringing the forcing in EC-Earth3-AerChem closer to that in EC-Earth3. This is mainly due to a reduction in the SW cloud forcings, as we have verified using the method proposed by Ghan (2013). (The aerosol ERF estimates for both configurations were obtained from 15-year simulations with AMIP SSTs and sea ice concentrations for the years 2000–2014, as the difference in the net energy imbalance at the top of the atmosphere (TOA) between simulations with emissions for 2000–2014 and 1850, respectively. To isolate the effects of tropospheric aerosols, the mixing ratios of methane and ozone in these simulations were prescribed in IFS as in EC-Earth3.)

In view of these results, our tuning efforts focused on the pre-industrial climate of EC-Earth3-AerChem; no attempt was made to make specific adjustments to improve the model's climate for the present day or the simulated warming over the historical period. When tuning the pre-industrial climate of EC-Earth3-AerChem, a small number of atmospheric tuning parameters in IFS has been re-adjusted, leaving ocean and sea ice parameters in NEMO untouched. The model was initialized from the IFS and NEMO states taken from the EC-Earth3 pre-industrial control simulation (member r1i1p1f1, after 500 years), and a TM5 state representative of pre-industrial conditions. (After 10 years, a small update of the pre-industrial vegetation climatology was introduced. This had only a minor impact on the simulated pre-industrial climate.) Without re-adjusting any tuning parameters in IFS the model started to drift to a new climate state, characterized by higher temperatures especially in the Northern Hemisphere. The increase in zonal mean surface air temperatures varied from less than a few tenths of a degree in the mid-latitudes of the Southern Hemisphere to a few degrees at high latitudes in the Northern Hemisphere, turning the cold biases of EC-Earth3 into warm biases in these regions.

Informed by a comparison with the ERA5 reanalysis for the 1980s (Hersbach et al., 2020), corrected for the observed warming since pre-industrial times, we tried to reduce these warm biases by re-adjusting a small set of tuning parameters in IFS. Based on experience gained during the tuning of EC-Earth3 (Döscher et al., in preparation), three parameters were selected affecting both warm and cold regions: ENTRORG, the fractional entrainment (m^{-1}) for positively buoyant deep convection divided by the gravitational constant; RSNOWLIN2, which governs the temperature dependence of the autoconversion of ice crystals to snow in large-scale precipitation (Lin et al., 1983); and RLCRIT_UPHYS, the critical cloud droplet radius for the autoconversion of droplets into rain in large-scale precipitation (see Sect. 2.2). Using parameter sensitivities derived from EC-Earth3 atmosphere-

only simulations, two combinations of settings were defined corresponding to a target global mean surface cooling of 0.5 and 0.75 °C (see Table A).

Table A. Parameter settings for the three IFS parameters that have been re-adjusted for tuning the model's pre-industrial climate. The column labelled 'EC-Earth3-AerChem' contains the values adopted in the CMIP6 configuration of the model, which correspond to a target reduction in the global mean surface temperature of 0.5 °C compared to the configuration with the standard EC-Earth3 settings. The settings indicated in the column labelled 'EC-Earth3-AerChem, cold variant' correspond to a target surface cooling of 0.75 °C.

Tuning parameter	IFS cycle 36r4	EC-Earth3	EC-Earth3-AerChem	EC-Earth3-AerChem, cold variant
ENTRORG ($s^2\ m^{-2}$)	1.8×10^{-4}	1.7×10^{-4}	1.75×10^{-4}	1.75×10^{-4}
RSNOWLIN2 (K^{-1})	0.025	0.035	0.030	0.029
RLCRIT_UPHYS (m)	Not applied	8.75×10^{-6}	8.75×10^{-6}	8.84×10^{-6}

Initially, the focus was on the cold variant of the model. A sensitivity simulation for this configuration was started by branching off from the reference simulation with standard EC-Earth3 settings (after about 20 years from the start). As expected, the configuration with adjusted settings produced a colder climate. The Northern Hemisphere was more strongly affected than the Southern Hemisphere: at northern high latitudes, the zonal mean surface air temperature was reduced by more than 2 °C. After another ~ 100 years, a third simulation was started with parameter settings as in the final EC-Earth3-AerChem configuration (see Table 8). This simulation branched off from the reference simulation. After having completed a few decades, the reference simulation was stopped and the two sensitivity simulations were continued for another ~ 90 years. At that point it was discovered that the correction factor for the dust source was set to 0.7, a value obtained for an intermediate version of EC-Earth3-AerChem, resulting in a reduction of the global source to about 550 Tg yr -1 in these simulations. After resetting the factor to the intended value of 0.6, a new set of simulations was launched for the three configurations indicated in Table 8. This increased the dust source to about 1.1 × 10 3 Tg yr -1 , as verified from the first few years of the simulations. The configuration with a cooling target of 0.5 °C produced satisfactory behavior for the same set of atmosphere and ocean variables considered in the tuning of EC-Earth3 (Döscher et al., in preparation), and was spun up for 300 years. Compared to EC-Earth3, this configuration produced higher, more realistic pre-industrial temperature levels in the Northern Hemisphere, resulting in reduced long-term variability in the global mean surface temperature. While running the CMIP6 historical simulation with the selected parameter settings, another bug was discovered in the code dealing with the stratospheric aerosols. This bug affected only EC-Earth3-AerChem, and led to spurious warming by absorption of SW radiation in the stratosphere. This resulted in a completely wrong response to large volcanic eruptions. After fixing this bug, the pre-industrial spin-up simulation was continued for another 150 years. The impact of the bug fix on pre-industrial surface climate turned out to be small. This completed the tuning and spin-up of the model, totalling to 770 continuous years for the final configuration (on top of the EC-Earth3 pre-industrial control simulation).

5. References

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Tables

Configuration	Atmosphere + land surface	Ocean + sea ice	Dynamic vegetation	Atmospheric composition	Greenland ice sheet
	IFS 36r4 + HTESSEL	NEMO3.6 + LIM3	LPJ-GUESS	TM5	PISM
EC-Earth3	x	x			
EC-Earth3-Veg	x	x	x		
EC-Earth3-AerChem	x	x		x	
EC-Earth3-CC	x	x	x	x (CO2 only)	
EC-Earth3-GrIS	x	x	x		x

Table 1: Configurations of the EC-Earth model for CMIP6, the name of the configuration is used as source_id in the CMIP6 context.

	Resolution atmosphere	Resolution ocean	Timestep
Standard resolution	T255L91 (~80 km)	ORCA1L75 (1 deg)	2700 s
Low resolution EC-	T159L62 (~125 km)	ORCA1L75 (1 deg)	3600 s

Earth3-LR and EC-Earth3-Veg-LR			
High resolution (EC-Earth3P-HR and EC-Earth3-HR))	T511L91 (~40 km)	ORCA025L75 (0.25deg)	900 s

Table 2: Commonly used resolutions for CMIP6. The suffixes LR and HR are added to the name of the model configuration where applicable (e.g. EC-Earth3-Veg-LR)

Atmosphere -> Ocean	Ocean -> Atmosphere
Momentum flux	Sea surface temperature
Heat flux solar + non solar	Sea ice concentration
Evaporation	Sea ice temperature
Precipitation liquid + solid	Sea ice albedo
Sensitivity of non solar heat flux over ice	Sea ice thickness (not used)
	Snow thickness on sea ice

Table 3: Variables and fluxes exchanged at the ocean-atmosphere interfaces.

Atmosphere -> Runoff mapper	Runoff mapper -> Ocean
Runoff	Runoff
Excess snow	Calving

Table 4: Variables and fluxes provided to the ocean via the runoff mapper

Atmosphere -> Vegetation	Vegetation -> Atmosphere
2m temperature	Dominant vegetation type low + high
Precipitation	Leaf area index low + high

Soil temperature (4 layers)	Vegetation cover low + high
Shortwave radiation	
Longwave radiation	

Table 5: Variables exchanged between the atmosphere and the vegetation model

IFS parameter name	Description	EC-Earth3	IFS CY36R4
RPRCON	Rate of conversion of cloud water to rain	1.34E-3	1.4E-3
ENTRORG	Entrainment in deep convection	1.7E-4	1.8E-4
RVICE	Fall speed of ice particles	0.137	0.15
RLCRITSNOW	Critical autoconversion threshold for snow in large-scale precipitation.	4.2e-5	5.0E-5
RSNOWLIN2	Constant governing the temperature dependence of the autoconversion of ice crystals to snow in large-scale precipitation.	0.035	0.025
ENTRDD	Average entrainment rate for downdrafts	3.0E-4	2.0E-4
RMFDEPS	Fractional mass flux for downdrafts	0.3	0.35

RCLDIFF	Mixing coefficient for turbulence, controls cloud cover	3.6E-6	3.0E-6
RLCRIT_UPHYS	Critical droplet radius for the autoconversion in large-scale precipitation	0.875E-5	0.93E-5

Table 6: Atmospheric tuning parameters changed in EC-Earth compared to IFS CY36R4. The table reports the new values adopted for T255L91 EC-Earth3 and EC-Earth3-Veg tuning.

Atmosphere -> CTM	CTM -> Atmosphere
Logarithm of surface pressure	Ozone mixing ratio
Vorticity (3D)	Methane mixing ratio
Divergence (3D)	Aerosol number and component mass mixing ratios (25 fields in total)
Surface orography	Aerosol extinction (14 wavelengths)
Surface pressure	Aerosol single scatter albedo (14 wavelengths)
Air temperature (3D)	Aerosol asymmetry factor (14 wavelengths)
Specific humidity (3D)	
Cloud liquid/ice water content (3D)	
Cloud area fraction (3D)	
Overhead/underfoot cloud area fraction (3D)	
Updraft/downdraft convective air mass flux (3D)	
Updraft/downdraft convective air mass detrainment rate (3D)	
Land sea mask	

Surface albedo	
Surface roughness length	
Sea ice fraction	
Sea surface temperature	
10m wind speed	
Skin reservoir water content	
2m temperature	
2m dew point temperature	
Surface latent heat flux	
Surface sensible heat flux	
Eastward/northward surface stress	
Large scale precipitation	
Convective precipitation	
Surface shortwave radiation	
Snow depth	
Soil wetness in top soil layer	
Vegetation type fraction (15 categories)	
High/low vegetation cover	

Table 7: Variables exchanged with a 6 h frequency between the atmosphere and the chemical transport model (CTM) TM5 in EC-Earth3-AerChem.

Vegetation -> CTM (CC only)	CTM -> Vegetation (CC only)	Atmosphere -> CTM (every 6h)	CTM -> Atmosphere
Net primary production	CO2 mixing ratio	Logarithm of surface pressure	CO2 mixing ratio
Heterotrophic respiration		Vorticity (3D)	
Establishment*		Divergence (3D)	
Reproduction*		Surface orography	
Burnt vegetation and litter*		Surface pressure	
Sowing*		Air temperature (3D)	
Fast and slow harvested products*		Specific humidity (3D)	
Landcover change*		Updraft/downdraft convective air mass flux (3D)	
Carbon leaching		Updraft/downdraft convective air mass detrainment rate (3D)	
		Land sea mask	
		Surface roughness length	
		10m wind speed	
		Surface latent heat flux	
		Surface sensible heat flux	
		Eastward/northward surface stress	

*Table 8: Variables exchanged with a 24 h frequency between the vegetation model LPJ-GUESS and the Chemical transport model TM5 in EC-Earth3-CC. *Fluxes that occur once a year and are distributed evenly over the following year.*

Ocean BGC -> CTM (CC only)	CTM -> Ocean BGC (CC only)
CO_2 flux	CO_2 mixing ratio

Table 9: Variables exchanged with a 24 h frequency between the chemical transport model TM5 and the ocean biogeochemistry model PISCES.

Atmosphere -> Ice sheet	Ice sheet -> Atmosphere
Subsurface temperature	Ice topography
Surface Mass Balance (P-E-R)	Ice extent

Ocean -> Ice sheet	Ice sheet -> Ocean
	Calving fluxes (mass and energy)
	Basal melt flux (mass)

Table 10: Variables exchanged between the atmosphere model IFS and the ice sheet model PISM, as well as between the ocean model NEMO and ice sheet model PISM.

Architecture	Configuration	Platform	SYPD	ASYPD	CHSY	Parallelization
LENOVO SD530	EC-Earth3	MN4	15.2	9.87	1119	768
BullX B500	EC-Earth3	RN	16.2	16.2	1276	864
CRAY XC40	EC-Earth3	CCA	6.03	4.84	1289	324
CRAY XC40	EC-Earth-Veg	BK	12.4	6.65	1676	864
CRAY XC40	EC-Earth-Veg	CCA	6.67	5.32	1332	342

Table 11. Basic CPMIP metrics of EC-Earth3 and EC-Earth3-Veg Standard resolution for four different architectures and platforms: Marenostrum4 (MN4, LENOVO SD530), Rhino (RN, BullX B500), ECMWF-CCA (CCA, CRAY XC40) and Beskow (BK, CRAY XC40). The basic metrics are SYPD (Simulated Years Per Day), ASYPD (Actual Simulated Years Per Day), CHSY (Core Hours per Simulated Year) and Parallelization (number of MPI processes used).

Configuration	Resolution [# gridpoints]	Cmpx	SYPD	ASYPD	CHSY	Paral.	JPSY (Joules)	Coup. C. (%)	Mem. B.	DO (%)	DI (GB)
EC-Earth3	1.60×10^{7}	0.31	15.2	9.87	1119	768	4.41×10^{7}	8	11	12	3

Table 12. CPMIP metrics analysis for EC-Earth3 on Marenostrum4. Complete CPMIP metrics are shown in this table. Resolution Complexity (Cmpx), SYPD (Simulated Years Per Day), ASYPD (Actual Simulated Years Per Day), CHSY (Core Hours per Simulated Year), Parallelization, JPSY (Joules per Year Simulated), Coup. C. (Coupling Cost), Mem. B. (Memory Bloat), DO (Data Output Cost) and DI (Data Intensity). From left to right we have resolution (Resol) as the total number of gridpoints for all the components used (ocean, atmosphere…). Cmpx includes all prognostic variables of a model. JPSY quantifies the energy cost of the execution. Coup.C. represents the cost associated with the coupling among components (including interpolation and communication calculations, 8% in this case with respect to the total execution time). Mem.B. is the division between the theoretical memory of a memory and the real one. DO is the cost of the output process (12% in this case with respect to the total execution time). DI is the output volume in GB per day of simulation.

Forcing dataset	Version	Further info	Comments
Greenhouse gas concentration	1.2.0	Meinshausen et al. (2017)	
Stratospheric aerosols	3.0.0	Thomason et al. (2018)	
Ozone volume mixing ratio	1.0	http://blogs.reading.ac.uk/ccmi/forcing-databases-in-support-of-cmip6/; Hegglin et al. (in prep)	
Solar	3.2	Matthes et al. 2017	
Aerosol Optical Properties and Relative Change in Cloud Droplet Number Concentration	MACv2-SP	Stevens et al. (2017)	
Land use	v2.1h	https://cmip.ucar.edu/lumip	Used only in combination with dynamic vegetation model
Nitrogen deposition	v2.0	http://blogs.reading.ac.uk/ccmi/forcing-databases-in-support-of-cmip6/ ; Hegglin et al., (in prep)	Used only in combination with dynamic vegetation model

Table 13: CMIP6 forcing datasets used by EC-Earth3 and EC-Earth3-Veg for DECK(Diagnostic, Evaluation and Characterization of Klima) and historical experiments. All datasets are available from https://esgf-node.llnl.gov/search/input4mips/. A more detailed description of the CMIP6 forcing datasets is available at http://goo.gl/r8up31.

Variable	Description	Spatial Mean differences (%)
t2m	2m air temperature	1.2
msl	Mean sea level pressure	0.7
qnet	Net thermal radiation	0.8
tp	Total precipitation	1.4
ewss	Zonal wind stresses	1.1
nsss	meridional wind stress	1.3
SST	sea surface temperature	0.7
SSS	sea surface salinity	0.8
SICE	sea ice concentration	1.1
T	3-D air temperature	1.3
U	3-D zonal wind	1.5
V	3-D meridional wind	1.2
Q	specific humidity	0.7

Table 14.: Difference in 20-year mean and ensemble mean near-surface for different variables between Rhino and CCA platform experiments.