

SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	EC-EARTH: developing a European Earth System model based on ECMWF modelling systems
Computer Project Account:	SPNLTUNE
Start Year - End Year :	2012 - 2014
Principal Investigator(s)	W. Hazeleger (KNMI), R. Döscher (SMHI)
Affiliation/Address:	KNMI, Utrechtseweg 297, De Bilt, Netherlands.
Other Researchers (Name/Affiliation):	R. Bintanja (KNMI) J. von Hardenberg (ISAC) + many others, see www.ec-earth.org & eearth.knmi.nl .

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The overarching goal of this project is to develop a global Earth System model (EC-Earth) consisting of a state-of-the-art atmospheric general circulation model, a state-of-the-art ocean general circulation model, a sea-ice model, a land model, and an atmospheric chemistry model (see <http://ecearth.knmi.nl>), to be used for climate research and climate/decadal prediction studies. This is part of a seamless prediction strategy, linking NWP modelling at ECMWF to earth system modelling at Member States involved in EC-Earth.

Within this special project, the aim was to develop/tune new versions of the EC-EARTH earth system model. First, EC-Earth V2.3 (which was successfully developed and tuned using this special project) has been extensively used to perform climate runs for the CMIP5 (Climate Model Intercomparison Project, stage 5) initiative, and has been very successful as such (see below). Currently, development, testing and tuning is required for the next version: V3, which consist of a totally new layout, namely the IFS (CY36R4) atmosphere model, the NEMO V3 ocean model (which includes LIM2 and LIM3) coupled using OASIS-MCT (and later TM5 and other ESM components).

Summary of problems encountered

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

No specific problems, although in the near-future we will likely need additional storage to accommodate storage of more output of the various tuning/test runs. This is because V3 will be used at a higher resolution (T255) than V2 (T159), so an increased volume of output is expected.

Experience with the Special Project framework

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

No comments.

Summary of results

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

Brief summary

In the period 2012-2014, the consortium has been using Version 2.3 of EC-EARTH as its backbone version for national projects, EU-FP7 projects and for the CMIP5 (World Climate Research Program) projects. From 2014 onwards, however, we will use Version 3 which is based on IFS cycle 36r4, NEMO V3 and LIM2 or LIM3 in higher resolution (T255) than before. Moreover, the chemistry-transport model TM5 has been coupled to EC-Earth, and an interactive land scheme (LPJ) will probably be coupled as part of the ESM model. Aside from further development/testing of EC-Earth, new components will henceforth be added to Version 3 (e.g. ice sheets), which will obviously involve further development, testing and tuning. In fact, the tuning and development of Version 3 is already ongoing and has been a major activity during the latter part of 2013 and 2014. Generally, it is expected that ECMWF can take over modules developed within the EC-EARTH project. In fact, this has already happened as the snow scheme of Dutra et al. (2010) has been implemented in IFS cycle 36.

For a full description of results see the attached report: *Accomplishments, Current Status and Future Plans of EC-EARTH: a European Earth System Model*. The EC-Earth steering group, W. Hazeleger and R. Bintanja (Editors), 2014.

List of publications/reports from the project with complete references

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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.)

A continuation of the special project SPNLTUNE for the period 2015-2018 has been submitted and granted.

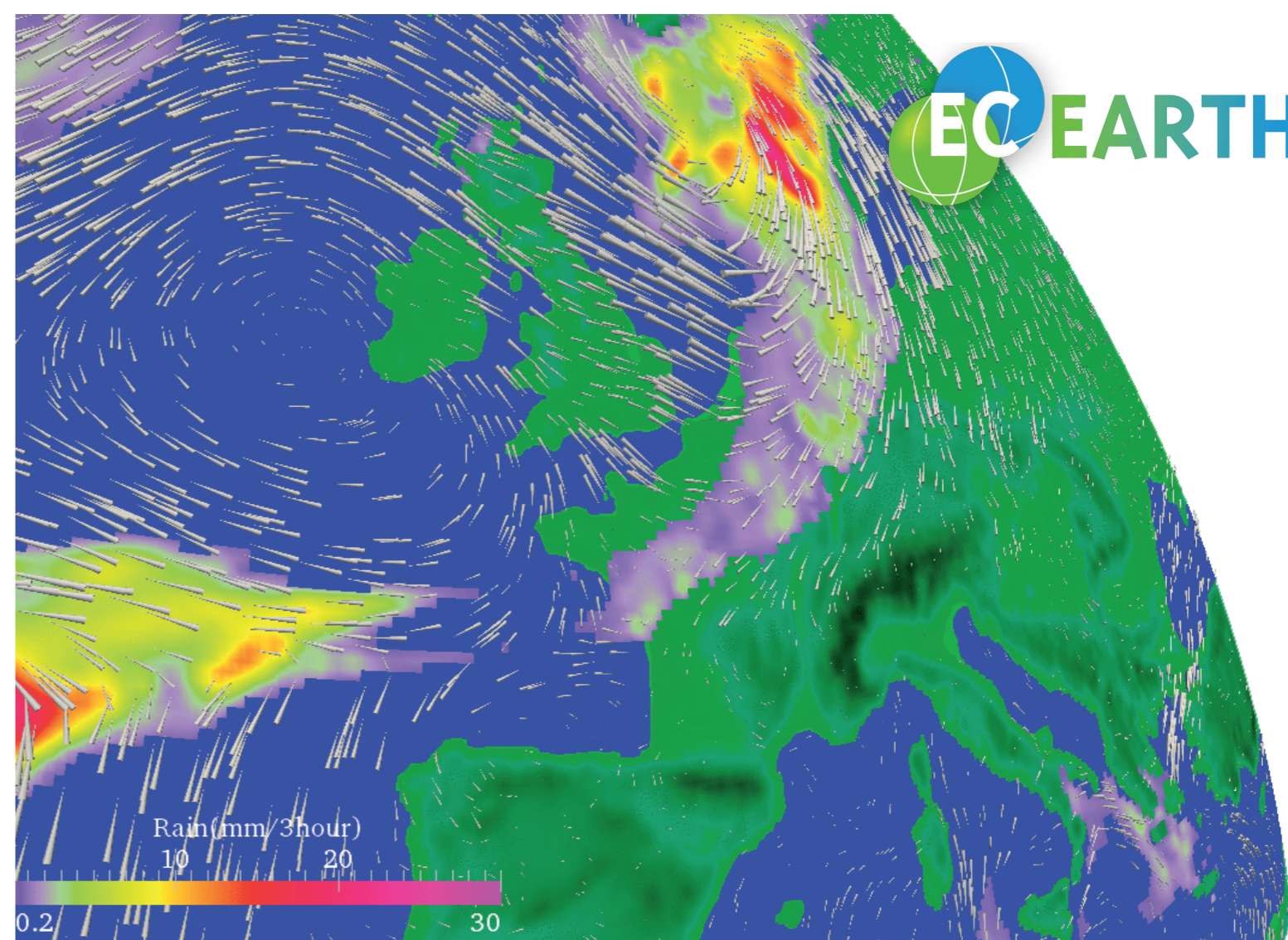


Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the
Environment

Accomplishments, Current Status and Future Plans of **EC-EARTH:** a European Earth System Model

EC-Earth Steering Group

W. Hazeleger, R. Bintanja (editors)



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Introduction

Numerical modelling of the Earth System is an important research and development topic with practical applications in meteorological, ocean, hydrological and environmental forecasting, basic science and climate change. Moreover, it is recognized that the vulnerability on the scales of individuals to nations to climate variability and change will only increase. This drives the need for climate information in emerging Climate Services (cf. Global Framework for Climate Services, an initiative of the World Meteorological Organization; FP7 and H2020 programs of the European Committee, including pre-operational Copernicus Climate Services). Data from Earth system models form the backbone of emerging Climate Services. In these services climate information is provided that guides adaptation and mitigation policies from the level of individuals to nations. In addition, Earth system models are tools that integrate all our knowledge on the Earth system and can be used to address scientific hypothesis on climate and environmental change. As such, these models allow scientists to study the complex interactions within the Earth system.

Over the past few decades, global general circulation models have been actively developed. Early efforts contained separate atmosphere and ocean models. Later, coupled models became indispensable tools in climate and climate change research. The necessity of coupling different 'spheres' becomes immediately clear when large-scale climate changes are considered. Arctic change is a telling example of this. These coupled models have been quite successful in simulating present-day climate and are currently being used for seasonal to interannual predictions and projections of climate change. In the last decade, more subsystems have been coupled to these Earth System Models (ESMs). Models of atmospheric chemistry, marine and terrestrial ecosystems have now become an integral part of ESMs. Integrated Assessment Models (IAMs) provide boundary conditions related to socio-economic developments, and currently the direction of development is towards stronger coupling of ESMs and IAMs. Regional models have also been developed for more detailed studies of regional climate change and process-studies on a higher resolution than what is presently practically attainable with global models. Driven by growing computer power, the scales that are resolved are becoming smaller. Nowadays, global ESMs resolve horizontally about 100 km scales, but long-term eddy-permitting and synoptic resolving global simulations are being tested. At these resolutions weather regimes related to extremes to which society is vulnerability are much better simulated than in models that do not resolve synoptic scales (e.g. atmospheric blocking associated with hot and cold spells, storm tracks).

Climate and forecasting applications share a common ancestry and also build on the same physical principles. Nevertheless, climate research and weather forecasting used to be seen as separate fields. Recently developed applications such as seasonal forecasting, reanalyses and decadal predictability studies fall in between 'climate' and 'weather'. As a result, the concept of "seamless prediction" (cf. WCRP) has emerged to forge forecasting and climate change into a joint topic. Initialized decadal prediction aims at forecasting natural patterns of climate variability and the impact of anthropogenic climate change. This concept also extends the focus of the physical climate system toward a comprehensive view of the Earth System in which feedbacks with the biosphere are included.

Around 2006, the need for an Earth System Model (ESM) was recognized by various ECMWF

Member States (MS). This effectively initiated the development of EC-Earth. EC-Earth is both a model and a consortium that develops and applies the model. The model is almost completely based on ECMWFs seasonal forecasting system. For technical and scientific reasons it was deemed attractive to collaborate on modelling efforts with partners within Europe and with ECMWF. EC-Earth thus offers the opportunity to use computational infrastructure efficiently, share expertise between MS and ECMWF, and limit the number of different model frameworks currently in use for forecasting and climate applications by MS. Collaboration with ECMWF has been quite fruitful, for instance in developing ECMWFs land and snow scheme, in providing boundary conditions for ERA-CLIM and in ocean-sea ice coupling to the atmosphere.

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

EC-Earth has matured and Earth system science including its organization is in transition. CMIP5 is finalizing, the new H2020 program is starting in Europe, and globally, climate services develop. Scientifically, the integration of subsystems towards fully coupled physical, chemical, biophysical and even societal models is currently taking place. This implies that the objectives and implementation of EC-Earth need to be updated and revised. The main objective of EC-Earth is:

To develop and apply an Earth System Model based on ECMWFs seasonal forecasting system for providing trustworthy climate information to climate services and to advance scientific knowledge on the Earth system, its variability, predictability and long-term changes resulting from external forcing.

Past achievements (organizational and scientific)

1. Organizational achievements

Since a consortium of around 10 partners started in 2006 to develop a fully global coupled Earth system model, the consortium grew to 28 partners in 2014, of which currently 7 core partners provide financial contributions for technical support (see project structure and governance). The consortium is healthy with an extension of the Memorandum of Understanding that defines the collaboration up to 2016 (see Figure 1).

EC-Earth is based on ECMWF's seasonal forecasting system. Version 1 (V1) was developed from the Seasonal Forecasting

System 3. The model was used for atmosphere-only studies and for studying long-term behaviour and for closure of the climatic energy balance. It was the fully coupled atmosphere-ocean-sea-ice-land EC-Earth Version 2 that provided the backbone for CMIP5 and many other scientific studies carried out with EC-Earth. The standard resolution of EC-Earth V2 is T159 (~125 km, using ECMWF's convention to include aliasing) in the atmosphere, with 62 vertical layers, and 1 degree in the ocean with 42 vertical layers. EC-Earth was introduced in a BAMS paper (Hazeleger et al., 2010) in which it was shown

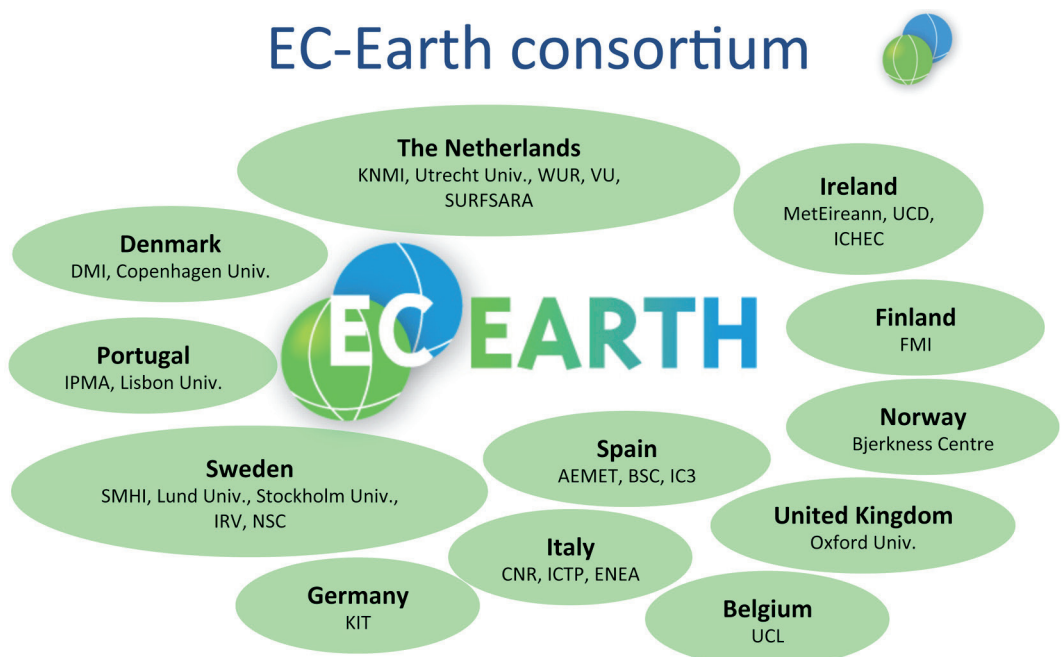


Figure 1. Schematic outline of the EC-Earth consortium and its members as of May 2014.

Steering group: W. Hazeleger (KNMI), R. Doescher (SMHI), J. Hesselbjerg Christensen (DMI), R. McGrath (Met Eireann), P. Viterbo (IPMA), E. C. Rodriguez (AEMET), J. von Hardenberg (CNR), observer E. Kallen (ECMWF), NEMO-representative.

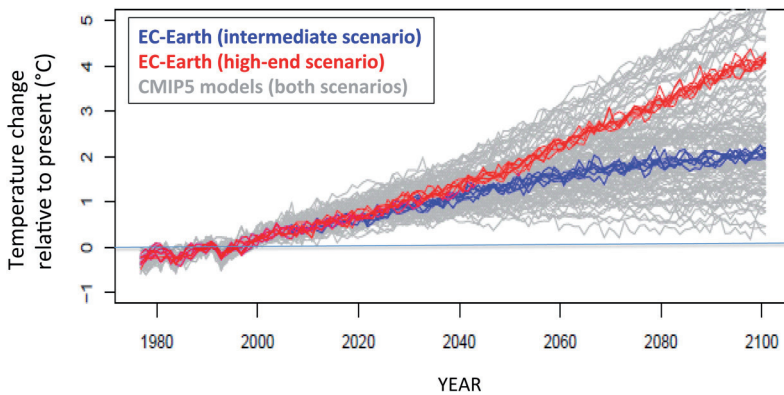


Figure 2. Global temperature response in EC-Earth to changing emissions according to the RCP4.5 and RCP8.5 emission scenarios. In grey all CMIP5 models and members are shown, in colour the various members of EC-Earth.

to perform at least as good, if not better in some aspects, than other state-of-the-art climate models. A collection of scientific papers on the general performance of the model and on different scientific questions appeared in a Special Issue on EC-Earth in *Climate Dynamics* (2012). Additionally, a multitude of scientific papers has been published on a wide array of climate (change) subjects (see scientific achievements below), and the scientific use of EC-Earth is ongoing and increasing with more modules being added to EC-Earth (V2.4 and V3, see below).

Much of the work done with EC-Earth was (and still is) subsidized through several national and international projects. A selection of European FP7 projects with EC-Earth partners participating: THOR (thermohaline circulation

predictions), IS-ENES (software development), COMBINE (feedbacks and predictability), SUMO (coupling), EMBRACE (model biases), ICE2SEA (Arctic Change), SPECS (seasonal to decadal predictions), IS-ENES2 (software development), PREFACE (tropical Atlantic), HiResClim (high performance computing).

As mentioned, the consortium put a great deal of effort to prepare the model to participate in CMIP5. Historical and future emissions (RCP scenario's) were implemented and in a coordinated effort a large ensemble of simulations was made following the CMIP5 protocol (Figure 2). Of particular interest are initialized decadal predictions, which build upon seasonal forecasts initialized from estimates of observed climate. EC-Earth contributed to CMIP5 with many simulations, some of which can currently be downloaded via ESG gateways. At a national level, these simulations are being used for dynamical, statistical and stochastic downscaling to provide local climate information (Figure 3). Part of this effort is being performed within the CORDEX project, which provides a framework for coordinated downscaling. For instance, EC-Earth V2 CMIP5 simulations have been used as boundary conditions to create high-resolution climate scenarios for the Karakorum-Himalaya and the Indian sub-continent regions in the Italian PAPRIKA project using the hydrostatic regional model RegCM3.

Aside for CMIP5, the consortium additionally contributed to a number of model intercomparisons initiatives such as CFMIP (cloud feedbacks), PMIP (paleo), GLACE (land surface),

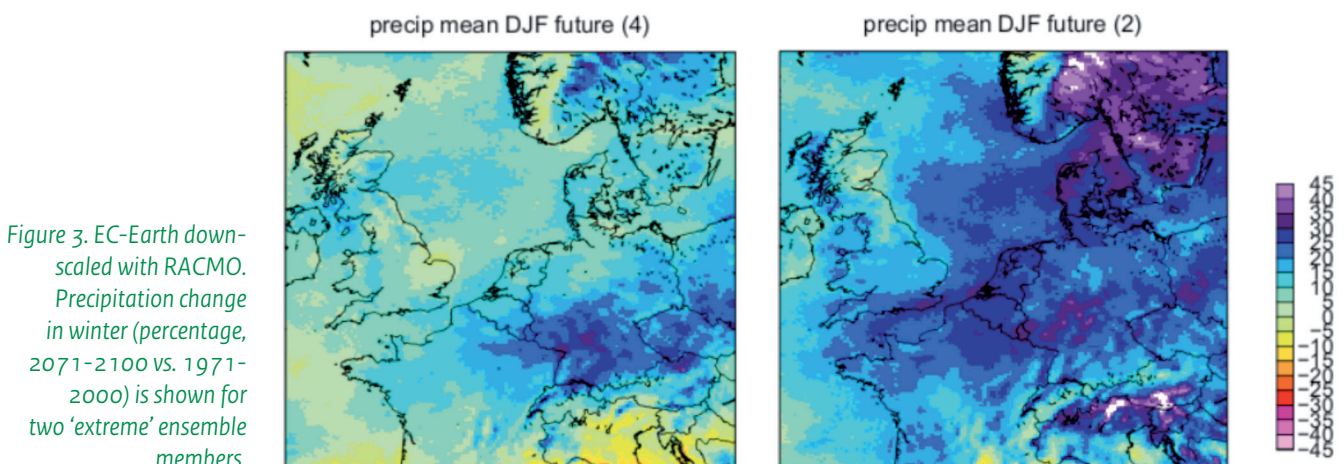


Figure 3. EC-Earth down-scaled with RACMO. Precipitation change in winter (percentage, 2071-2100 vs. 1971-2000) is shown for two 'extreme' ensemble members.

LUCID (land use), GEOMIP (geoengineering), which strongly drive developments in EC-Earth. Some of these intercomparison studies now form part of the overall CMIP protocol. These model intercomparisons allow EC-Earth to be compared with other state-of-the-art models and provide a very useful quality check of EC-Earth's results.

In 2012 EC-Earth V3 was released. This version is based on the ECMWF seasonal cycle version 4. More precisely, it is based on a newer cycle of ECMWFs IFS model (c36r4) and a new NEMO ocean model (V3.5) and LIM3 sea ice model is used, as well as H-TESSEL for land. This model will be optimized for a standard resolution of T255 and 91 vertical layers for the atmosphere,

and for 1 degree and 46 layers for the ocean. In addition, high-resolution versions of this version are currently being tested (0.25 degrees in the ocean and T511 and T799 in the atmosphere).

In early 2013 EC-Earth V2.4 was released. This development version includes a coupling to the atmospheric chemistry model TM5, including the M7 aerosol module, and to the LPJ-GUESS dynamical vegetation module. This model version will ultimately merge with V3 so as to develop EC-Earth into an Earth System Model (ESM) with interactive biogeochemical cycles. Moreover, as a way forward, new components are currently being developed and tested, such as interactive ice sheets and even coupling to integrated assessment models.

2. Scientific achievements

CMIP5

The Coupled Model Intercomparison Project Phase 5 (<http://cmip-pcmdi.llnl.gov/cmip5>) is a coordinated effort of the climate modelling community to compare and evaluate climate models by following a specified experimental protocol. A novelty in CMIP5 concerns decadal predictions, short climate simulations that start from an initial state close to reality. The idea behind decadal predictions is that they should reduce the uncertainty of climate simulations that arises from the natural climate variability. The EC-Earth community has contributed with a number of different (climate and decadal) experiments to CMIP5. The Wiki (<http://eearth.knmi.nl/index.php?n=PmWiki.CMIP5>) provides an overview of the various CMIP5 experiments that were done by members of the EC-Earth consortium.

The long-term simulations started from initial states in 1850. Because not enough observations are available for that early period, a long simulation was done forced with pre-industrial concentrations of greenhouse gases and aerosols. The EC-Earth pre-industrial control run exceeded 700 years. Snapshots from this long control simulation then provide initial states for the historical climate simulations; a 14-member ensemble of historical simulations with the EC-Earth model was carried out this

way. During the historical and future simulations, the climate was forced by time-varying concentrations of greenhouse gases, ozone, and aerosols. The variability of the solar irradiation and changes in land-use was also accounted for. The EC-Earth community contributed with 14 members for the RCP4.5 and RCP8.5 experiments, and with 2 members to RCP2.6.

For the decadal prediction experiments, the EC-Earth community has chosen to follow two different strategies for the initialization and for each method a 10-member ensemble was done for 10 different start-dates from the 1960-2005 period. The forecast skills of the two initialisation methods were compared in a recent paper (Hazeleger et al., 2013). The start-dates are separated by 5 years as prescribed by the CMIP5 protocol, which has resulted in some spurious effects in the forecast quality. Therefore, the dataset was extended by starting a 10-member ensemble of decadal forecasts every year within the period 1960-2005, again with two different initialization methods.

In addition to these 'core' experiments, several members of the EC-Earth community have contributed to various additional experiments that aim at a better understanding of the model. Examples of such simulations are atmosphere-only time-slices (AMIP), the cloud

forcing model intercomparison (CFMIP), or climate sensitivity experiment with $4\times\text{CO}_2$.

The EC-Earth model output has been post-processed to CMOR-compliant format that is required for archiving at the ESG data-nodes. The results have been uploaded to the ESG data-node that is maintained by ICHEC and the data were published at the ESG data portal at BADC. The set of experiments and variables available from ESG is currently being completed and expanded. Despite this, the evaluation of the EC-Earth results has started, both by EC-Earth members and the international climate modelling community.

Antarctic sea ice increase

In contrast to the Arctic, where sea ice is declining rapidly, the sea ice cover surrounding Antarctica has been expanding over the past few decades at a rate of about 2% per decade. Some studies have attributed this increase to changes in the Southern Annular Mode (SAM), but apart from some regional correlations the link between Antarctic sea ice and SAM was not well established statistically. EC-Earth in fully coupled mode was used to explore a new

mechanism to explain this elusive increase in Antarctic sea ice, one which involves deep-ocean warming, basal ice shelf melt, and the formation of a low-density freshwater layer near the surface which can freeze over in winter more quickly. Sensitivity simulations with EC-Earth in which melt from Antarctica was artificially increased indeed show sea ice expansion through this mechanism, including cooling and freshening of the top ocean layers (Figure 4). The surface freshening and associated reduced mixing with the deep ocean are key features also seen in oceanic observations, and these aspects are not explained by alternative theories. The results, recently published in *Nature Geoscience* (Bintanja et al., 2013), clearly demonstrate the usefulness of a well-tuned global climate model like EC-Earth in finding and testing new climate mechanisms and feedbacks.

Predicting the warming hiatus

Despite a sustained production of anthropogenic greenhouse gases, the Earth's mean near-surface temperature paused its rise during the 2000–2010 period. To explain such a pause, an increase in ocean heat uptake below the

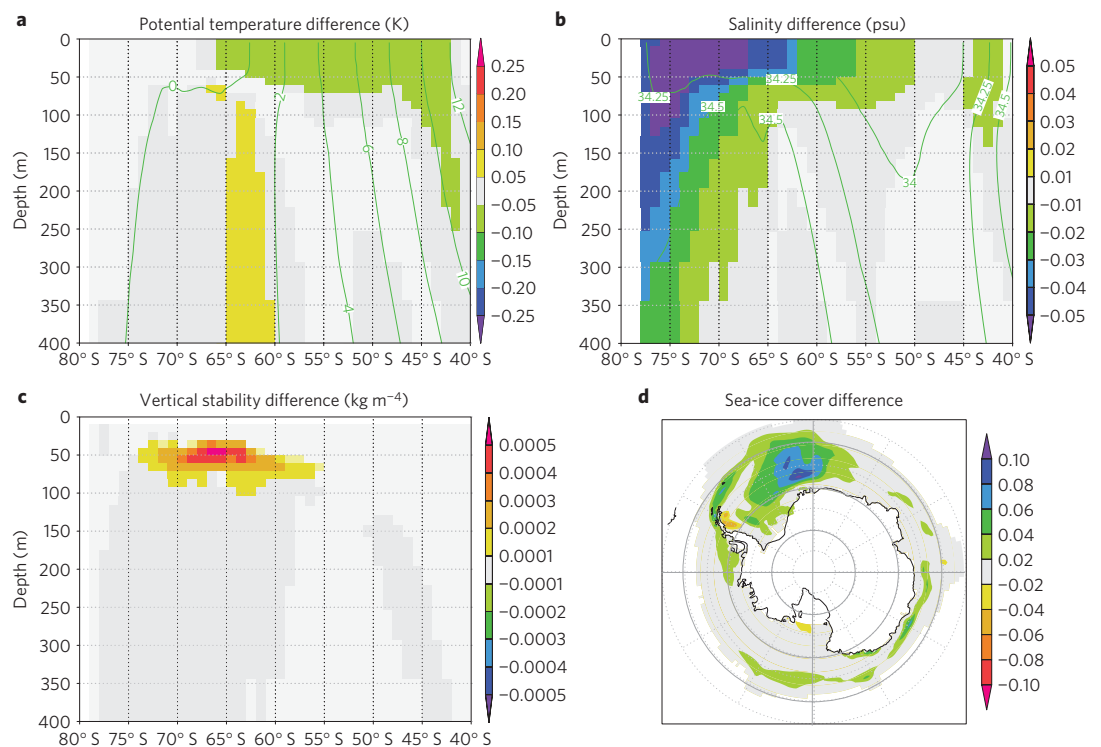


Figure 4. Simulated zonally-averaged distributions of potential temperature, salinity and vertically ocean stability, as well as sea ice cover (difference between increased and standard ice shelf melt rates).

superficial ocean layer has been proposed to overcompensate for the Earth's heat storage. Contributions have also been suggested from the deep prolonged solar minimum, the stratospheric water vapour, the stratospheric and tropospheric aerosols. In a paper published in *Nature Climate Change*, Guemas et al. (2012) show successful retrospective predictions of this warming slowdown up to 5 years ahead, the analysis of which allowed them to attribute the onset of this slowdown to an increase in ocean heat uptake. Sensitivity experiments accounting only for the external radiative forcings do not reproduce the slowdown.

The top-of-atmosphere net energy input remained in the $0.5 - 1.0 \text{ W m}^{-2}$ interval during the past decade, which is successfully captured by their predictions. Most of this excess energy was absorbed in the top 700 m of the ocean at the onset of the warming pause, 65% of it in the tropical Pacific and Atlantic oceans.

Their results thus point at the key role of the ocean heat uptake in the recent warming slowdown. The ability to predict retrospectively this slowdown not only strengthens our confidence in the robustness of our climate models, but also enhances the socio-economic relevance of operational decadal climate predictions.

More hurricanes to hit Western Europe?

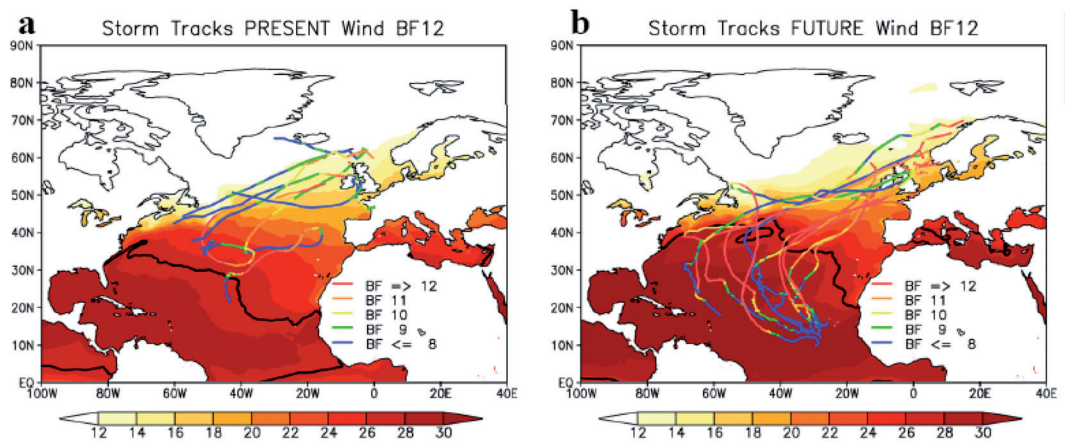
In a recent publication in *Geophysical Research Letters*, Haarsma et al. (2013) used EC-Earth in very high resolution mode (~25 km grid size) with prescribed sea surface temperatures to identify and quantify potential changes in

future weather extremes. They found that greenhouse warming is likely to enhance the occurrence of hurricane-force ($> 32.6 \text{ m s}^{-1}$) storms over Western Europe during early autumn (Aug-Oct), the majority of which originate as a tropical cyclone (Figure 5). The rise in Atlantic tropical SSTs extends eastwards the breeding ground of tropical cyclones, yielding more frequent and also more intense hurricanes following pathways directed towards Europe. En route they were found to transform into extra-tropical depressions and, importantly, they re-intensify after merging with the midlatitude baroclinic unstable flow. Their model simulations clearly show that future tropical cyclones are more prone to hit Western Europe, and they do so earlier in the season, thereby increasing the frequency and impact of hurricane force winds in Western Europe. This is a telling example of how climate change can impact weather extremes in Western Europe.

Future changes in regional precipitation

In another example of using EC-Earth to assess climate-change-related changes in weather extremes, Palazzi et al. (2013) study the properties of precipitation in the Hindu-Kush Karakoram Himalaya (HKKH) region using currently available data sets and the model EC-Earth. The observations were compared with simulation results from EC-Earth. All data sets, despite having different resolutions, coherently reproduce the mean annual cycle of precipitation in the western and eastern stretches of the HKKH. While for the Himalaya only a strong summer precipitation signal is present, associated with the monsoon, the data indicate that the Hindu-

Figure 5. Simulated tracks and frequency of hurricane-force storms (Aug-Oct) for present-day (left) and the end of the 21st century (right).



Kush Karakoram, which is exposed to midlatitude “western weather patterns”, receives water inputs in winter. Time series of seasonal precipitation confirm that the various data sets provide a consistent measurement of interannual variability for the HKKH. The longest observational data sets indicate a statistically significant decreasing trend in Himalaya during summer. Precipitation data from EC-Earth are in good agreement with the climatology of the observations (rainfall distribution and seasonality). The evolution of precipitation under two different future scenarios (RCP4.5 and RCP8.5) reveals an increasing trend over the Himalaya during summer, associated with an increase in wet extremes and daily intensity and a decrease in the number of rainy days. Unlike the observations, the model shows an increasing precipitation trend also in the period 1950–2009, possibly as a result of the poor representation of aerosols in this type of GCMs.

Climate model response within GEOMIP

Solar geoengineering – deliberate reduction in the amount of solar radiation retained by the Earth – has been proposed as a means of counteracting some of the climatic effects of anthropogenic greenhouse gas emissions. In a recent paper, Kravits et al. (2013) present results from Experiment G1 of the Geoengineering Model Intercomparison Project (GEOMIP), in which 12 climate models (including EC-Earth) have simulated the climate response to an abrupt quadrupling of CO₂ from preindustrial concentrations brought into radiative balance via a globally uniform reduction in insolation. Models show this reduction largely offsets global mean surface temperature increases due to quadrupled CO₂ concentrations and prevents 97% of the Arctic sea ice loss that would otherwise occur under high CO₂ levels but, compared to the preindustrial climate, leaves the tropics cooler (–0.3 K) and the poles warmer (+0.8 K). Annual mean precipitation minus evaporation anomalies for G1 are less than 0.2 mm day⁻¹ in magnitude over 92% of the globe, but some tropical regions receive less precipitation, in part due to increased moist static stability and suppression of convection. Global average net primary productivity increases by 120% in G1 over simulated preindustrial levels, primarily from CO₂ fertilization, but also in part due to reduced plant heat stress compared to a high

CO₂ world without geoengineering. All models show that uniform solar geoengineering in G1 cannot simultaneously return regional and global temperature and hydrologic cycle intensity to preindustrial levels. Evidently, ESMs such as EC-Earth are essential to provide detailed climate projections associated with geoengineering initiatives and plans.

Coupling an ice sheet to EC-Earth

Simulations using EC-Earth coupled to an interactive ice sheet module for Greenland have been carried out at DMI to investigate climate feedbacks related to the Greenland ice sheet (GrIS). For this purpose, EC-Earth was coupled with the Parallel Ice Sheet Model, PISM. The coupling of the PISM includes a modified surface physical parameterization adapted to the land ice surface over glaciated regions in Greenland, which conserves energy and mass. The surface mass balance (SMB) accounting for the precipitation, the surface evaporation, and the melting of snow and ice over land ice is computed inside the EC-Earth atmospheric module. The PISM ice sheet model, forced with the EC-Earth simulated SMB and surface temperatures, provides, in return, basal melt, ice discharge and ice cover (extent and thickness) as boundary conditions to the EC-Earth. The GrIS was initialized by running the stand-alone PISM with a paleo-climatological spin-up, followed by the EC-Earth preindustrial climatology in order to reach an ice sheet state that is in equilibrium with EC-Earth’s preindustrial climate. The fully coupled EC-Earth – PISM system is then integrated under the preindustrial condition until it has reached the quasi-stationary state for a considerably long period (pre-industrial spin-up). Several climate-change simulations were consequently carried out using the coupled EC-Earth – PISM system (e.g. 1%/yr increase of CO₂, abrupt 4xCO₂).

Current status

1. Model configuration

IFS

EC-Earth V3 uses IFS version 36R4. Changes over previous IFS versions include the resolution of the Global wave model resolution being increased from 0.36 to 0.25 degrees in the deterministic model, a correction of short-wave radiation interaction with clouds and an update in the snow density formulation in the presence of fresh snow. The latter reduces the snow density resulting also in the reduction of the increments of snow water equivalent. More specific changes are:

- Five-species prognostic microphysics scheme, introducing cloud rain water content, and cloud ice water content as new model variables
- Retuning and simplification of convective entrainment/detrainment and land/sea dependent threshold for precipitation
- Retuning of subgrid-scale orographic gravity wave drag
- Adjustment to diffusion in stable boundary layers near the surface
- New soil-moisture analysis scheme (SEKF, simplified ensemble Kalman filter)
- New snow analysis based on OI (Optimum Interpolation)

Objective verification shows statistically significant improvements in terms of 1000 and 500 hPa height for Europe and for both extra-tropical hemispheres. There is also a systematic improvement of temperature at 850 hPa. The location and intensity of synoptic features are improved in many cases, and the frequency of occurrence of intense rainfall events has increased resulting in better agreement with observations. The wind fields from the new cycle are better at representing features such

as tropical storms, fronts, land/sea transitions which translates into better wave forecasts. Tropical cyclone track and intensity forecasts are generally improved in the higher-resolution system, based on the relatively small sample available. Modifications to the stable boundary layer improve the diurnal cycle of 2m temperature, especially some reduction of the nighttime cold bias over Europe. The tropospheric humidity analysis has significantly improved.

NEMO

The EC-Earth V3 employs version 3.3.1 of the Nucleus for European Modelling of the Ocean (NEMO) developed by the Institut Pierre Simon Laplace (IPSL) as its ocean component. NEMO uses a tri-polar grid with poles over northern North America, Siberia and Antarctica. The standard configuration of EC-Earth V3 uses the so-called ORCA1-configuration with a horizontal resolution of about 1° including a refinement at the equator of up to 1/3° and 46 vertical levels (instead of 42 in EC-Earth V2); note that a high resolution EC-Earth V3 exists using ORCA025 at a horizontal resolution of about 0.25° and 75 vertical levels. The horizontal discretization is done on a curvilinear C-grid. In the vertical, a z-coordinate is used with a layer thickness of 6 m at the surface (compared to 10 m in EC-Earth V2), about 15 m at 100m depth and further increasing with depth. The deepest level is now at 5875 m instead of 5350 m in EC-Earth V2. NEMO is a primitive equation model with a free surface. It uses a Turbulent Kinetic Energy (TKE) scheme for vertical mixing, a partial step implementation for the z-coordinate, a bottom boundary scheme to mix dense water and total

variance dissipation for horizontal advection. Horizontal tracer diffusion follows the Gent-McWilliams parameterization of eddy-induced turbulence.

The TKE-scheme has undergone major improvements compared to the NEMO-version used in EC-Earth V2: it now includes a Langmuir cell parameterization, Mellor and Bumberg surface wave breaking parameterization and a time discretization that is consistent with the ocean model equations.

LIM

EC-Earth V3 uses the Louvain-la-Neuve sea ice model version 3 (LIM3) as part of the NEMO system. LIM3 is run on the same grid as the ocean model NEMO. It uses an elastic-viscous-plastic (EVP) rheology, which replaces the viscous-plastic rheology of LIM2, which was used in EC-Earth V2. LIM3 allows - in contrast to LIM2 - several ice thickness categories. However, EC-Earth V3 uses only one ice thickness category in the standard configuration. Sea ice is redistributed as a result of thermodynamical growth and melt processes as well as of dynamical opening, ridging and rafting processes. These dynamical redistribution processes are new in LIM3. Also new in LIM3 is the explicit calculation of salinity, which takes the impact of ice growth and decay and brine entrapment and drainage into account.

TM5

The Tracer Model 5 (TM5) has been integrated in EC-Earth V2.4 for interactive simulation of atmospheric chemistry and transport. Currently, TM5 is used to simulate aerosol particles and reactive gases, including the greenhouse gases ozone and methane; in the near future, TM5 will also be used to simulate the transport of CO₂ through the atmosphere. The TM5 version currently included in EC-Earth simulates tropospheric photochemistry and aerosols (Van Noije et al., 2014). The gas-phase chemistry scheme is an updated version of the carbon bond mechanism 4. Sulphate, black carbon, organic carbon, sea salt and mineral dust are described by a modal aerosol microphysics scheme, and ammonium and nitrate by a thermodynamic equilibrium model. Aerosol optical properties are calculated based on Mie theory, using effective

medium theory for internally mixed particles. A simplified, linearized chemistry scheme for stratospheric ozone will be included in EC-Earth V3.

Within EC-Earth, TM5 is discretized on a regular latitude/longitude grid of 3° x 2° or 6° x 4° (longitude x latitude). To avoid the use of very short time steps, a reduced grid can optionally be applied in the polar regions. Vertically, TM5 uses the hybrid sigma-pressure levels of IFS or a subset of these.

The data exchange between TM5 and other modules of EC-Earth takes place through OASIS3. TM5 receives both meteorological data and surface property fields from IFS. The concentrations of ozone and methane as well as the various aerosol concentration and optical property fields can be sent back to IFS. These fields will be used to evaluate the direct radiative effects and aerosol-cloud interactions in EC-Earth V3. Couplings between TM5 and LPJ-Guess are also under development.

LPJ-Guess

LPJ-Guess allows for vegetation to dynamically evolve, depending on climate input, and in return provides the climate system with vegetation-dependent fields such as surface albedo and leaf area index. Major update from version 2.3 is the coupling with the state-of-the-art dynamic vegetation model LPJ-Guess (Smith et al., 2001; Sitch et al., 2003), replacing components of the previous parameterisation of vegetation. LPJ-Guess uses 11 plant functional types (PFT), of which 2 are herbaceous and 9 are woody types, to simulate the phenological cycle of natural vegetation. Survival and establishment is based on energy and carbon balances. Individual bio-climatic limits determine windows of climatic conditions in which survival, regeneration and growth is possible for each PFT. The model includes a specific representation of age structure, species dynamics, competitions, soil bio-geochemistry and fire.

The interaction between the atmospheric land surface module of EC-Earth and the vegetation model LPJ-Guess is set up to cover many mutually exchanged variables. In the current version (2.4) the dynamic vegetation model is

driven by the climatological fields from EC-Earth (short-wave radiation, temperature, total precipitation, and snow) and it returns leaf area index separately for all high vegetation and all low vegetation per grid cell to the land-surface module (HTESSEL) of the atmospheric model. In this coupling approach we tolerate discrepancies in the soil hydrology, as soil water content were calculated individually by each model. The soil properties and horizontal resolution of LPJ-Guess are harmonized with HTESSEL.

2. EC-Earth consortium and governance

As mentioned earlier, EC-Earth is organized as a consortium of international partners.

A partner has to be from a member state (MS) of ECMWF. Only member states of ECMWF can get access to the code of ECMWF.

A Memorandum of Understanding describes the governance of the consortium. Partners that contribute financially to the consortium (currently 15 k€ per year) and that sign the Memorandum of Understanding can have a representative in the Steering Group. Executive decisions on EC-Earth are made exclusively by the Steering Group. Partners that contribute financially also receive technical support for EC-Earth on their hardware system. Currently 7 partners from 7 MS constitute the Steering Group (The Netherlands, Sweden, Denmark, Spain, Portugal, Ireland, Italy) supplemented by observers from ECMWF and the NEMO team).

Not all partners can (or want to) contribute financially. These partners can still get access to the code by signing a Letter of Intent by which partners promise to work actively on EC-Earth, but they do not commit financially. These partners also have to be from a MS of ECMWF. They are eligible to receive technical support out of central EC-Earth resources. There are currently 28 partners in EC-Earth (Table 1).

The Steering Group has set up working groups (WG's) responsible for developing the model and work actively on Earth system processes and projects. The working groups are directed by the Steering Group through an annually updated Terms of Reference. The (co)chair is

Planned updates of this interface are:

- Soil moisture nudging between HTESSEL and LPJ-Guess
- Exchange of fraction of vegetation cover (additional to the exchange of LAI)
- Flexible restart dates (LPJ-Guess currently can only be initialized on 1 Jan of each year)
- Refinement of determination of low and high vegetation LAI

appointed, but otherwise membership is open. The current working groups are:

- Technical Issues and Data Management working group (chair Camiel Severijns, KNMI)
- Tuning working group (chair Jost von Hardenberg, CNR)
- Ocean and sea ice working group (chair Torben Koenigk, SMHI)
- Atmospheric Chemistry and Land working group (co-chairs Twan van Noije KNMI and Paul Miller Lund University)

An atmospheric physics working group and a paleo-modelling working group will likely be set up in the near future.

Model development is a shared effort and done at the participating institutes. The institutes openly share their expertise. Institutes are free to work on new modules and test coupling to EC-Earth.

Every ~9 months a meeting is organized for developers and scientists of the various participating institutes (*see Table 1*) to exchange experiences and monitor progress. Every other meeting is held at ECMWF in Reading to facilitate exchange between EC-Earth scientists and developers and staff of ECMWF. This interaction could be further strengthened, for instance through working visits.

Table 1. Partners of EC-Earth as of May 2014 (* Core partners and Members of Steering Group).

Institute	Country	Institute	Country
KNMI*	The Netherlands	NSC	Sweden
DMI*	Denmark	IC ₃	Spain
Met Éireann*	Ireland	BSC	Spain
SMHI*	Sweden	ENEA	Italy
CNR-ISAC*	Italy	ICTP	Italy
AEMET*	Spain	BSC	Spain
IPMA*	Portugal	UCD Met & Climate Centre	Ireland
Utrecht University	The Netherlands	ICHEC	Ireland
WUR	The Netherlands	UCL	Belgium
VU	The Netherlands	KIT	Germany
SurfSARA	The Netherlands	Bjerkness Centre, University of Bergen	Norway
Bolin Centre, Stockholm University	Sweden	Copenhagen University	Denmark
Lund University	Sweden	FMI	Finland
IRV	Sweden	Oxford University	United Kingdom

3. Resources

Resources should be dedicated to make the development of EC-Earth a successful venture. These can be provided as computing time, full time equivalents (fte) for model development and fte's for model analysis/research.

The partners in EC-Earth that have signed the Memorandum of Understanding receive scientific support from technical support specialists at ECMWF.

Ideally, a dedicated amount of computing time should be available at both the computing facilities of the participating institutes and ECMWF. In addition, member states are encouraged to apply for computing time in Special Projects at ECMWF, such as SPNLTUNE, a special project designated for EC-Earth development and tuning.

An indicative amount of effort per participating institute would be at least 1 fte for

model development per module and 1 fte per science project. Every participating institute should make a concrete commitment to its participation in the EC-Earth system on both development efforts and science projects.

It has become clear that data management is of utmost importance to EC-Earth. The data management support during CMIP5 was clearly insufficient. A full-time data management support person is needed as part of EC-Earth. Moreover, large storage capabilities should be present. While during CMIP5 a central ESG server was used at ICHEC, a distributed system of peer-node ESG servers is foreseen during CMIP6. Nonetheless a central coordination for data management, taking care of data validation and checking completeness in the archives would be useful.

Future plans

1. Goals and overall objectives

The partners within EC-Earth consortium share two important common goals: 1) to provide reliable and trustworthy climate information to decision makers and 2) to advance understanding of the functioning of the Earth system. The latter obviously serves a scientific purpose, but will also lead to further improvements of the quality of knowledge on the Earth system, which in the somewhat longer term will lead to better information to decision makers. Within the consortium, we explicitly use a Numerical Weather Prediction modelling framework and extending it to longer time scales in order to obtain climate (change) information. Since its initiation, EC-Earth has undergone continuous development by the members of the consortium. The relevant developments can be roughly divided in three parts:

- Enabling to make available actionable climate information from global to local scales in support of climate services, based on ensembles of long-term and near-term climate simulations
- Further integration within EC-Earth of chemical, biophysical and societal climate components
- Increases in model resolution towards atmospheric synoptic resolving and oceanic eddy resolving resolutions

These developments, in relation to the

missions and tasks of the various partners within the EC-Earth consortium, can be summarized into the following overarching goal: To develop and use an Earth system model based on ECMWFs seasonal forecasting system for providing trustworthy climate information for providing services and for advancing scientific knowledge on the Earth system, its variability, predictability and changes due to external forcing. These ongoing developments are (mostly) driven by the following specific objectives:

- Study global change and their local implications in multi-decadal integrations
- Provide global climate forecasts and scenarios (boundary conditions) for partners regional climate and impact studies
- Explore seasonal to multi-decadal predictability and predictions of the climate system
- Study feedbacks in the Earth's climate system
- Study feedbacks between the (bio)physical Earth system and socio-economic systems
- Develop global climate predictions and climate change scenarios as new European contributions to international efforts (such as CMIP6)
- Provide an advanced modelling tool for the investigation of mitigation options, in particular the impact of emission controls on atmospheric composition change

2. Requirements and future development

EC-Earth has developed into a state-of-the-art physical climate model. The specific objectives outlined above imply that the requirements for the model system have

evolved into a more elaborate Earth System Model that can run at higher resolutions than used in current EC-Earth versions.

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

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

For studying Earth system feedbacks and interactions with socio-economic systems, including exploring policy options on emissions of greenhouse gases and precursors of aerosols, atmospheric chemistry and a representation of ecosystems is needed. This implies an extension of the physical modules in EC-Earth towards chemical and biogeochemical components. This is already partially accomplished by the release of EC-Earth V2.4, which includes atmospheric

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

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

To meet the objectives mentioned earlier, the current EC-Earth versions will be further developed. The following modules are needed (they should be able to run in stand-alone as well as in coupled configurations):

- Global state-of-the-art primitive equation model for the atmosphere, with flexibility in the choice of horizontal resolution from at least T₁₅₉ to T₇₉₉
- Global state-of-the-art primitive equation model for the ocean, with flexibility in the choice of horizontal resolution from at least 1 degree to 0.25 degrees
- Dynamic sea-ice model
- Atmospheric chemistry model
- Land-snow model
- Dynamic vegetation model
- Ocean biogeochemistry model
- Ice sheet model
- Coupler

A final setup may allow for a flexible coupling to Integrated Assessment Models, as well as incorporating flexible I/O in general.

3. EC-Earth and climate services

Reliable meteorological information has entered everyday’s life through the media and in many operations, but climate information is often scattered and not well tailored to user needs. Only recently ‘Climate Services’ are being set up coordinated by the World Meteorological Organization in the Global Framework for Climate Services and in Europe in the H2020 and Copernicus programs. The search is on for effective provision of climate

information in these services. The prime challenge is to utilize the output by third parties, either public or private. Climate Service centres play a major role in this process. By 2020 operational Climate Centres serving the general public, media, private parties and public institutions will have matured and will be fed by data from model simulations such as EC-Earth. EC-Earth simulations contribute to Climate

services through the provision of actionable and reliable model information. Global model simulations of future climate are used to assess changes in climate. In particular changes in extremes where vulnerability of society becomes apparent are relevant. The global model output is used as boundary conditions for regional climate models, which provide more detail (cf. CORDEX project). The RCM output, or directly the global climate model output, can be further downscaled through stochastic downscaling methods to obtain climate scenarios at spatial resolution down to ~1 km, to be used as input for impact and assessment studies. Also, seasonal to decadal

initialized climate predictions with EC-Earth provide information on natural variability and the impact of anthropogenic forcing. High-resolution global simulations provide unprecedented detail and physical realism of the simulations. Both in national and European projects EC-Earth already play a crucial role in preparing for climate services. Examples are the SPECS and Euporias projects where services around seasonal to decadal predictions are developed. In ECLISE and CLIMRUN stakeholders are actively involved. In IS-ENES2 and CLIPC software and data challenges are tackled in preparation for COPERNICUS climate services.

4. Tentative time schedule

In general the phasing of EC-Earth developments depend on science needs and requirements and on the development of the seasonal forecasting system at ECMWF. EC-Earth versions will remain as close as possible to the seasonal forecasting systems of ECMWF. The current EC-Earth V3 is based on System 4 of ECMWF. That is, the atmospheric and oceanic components are in principle the same, but requirements in climate science imply some different optimizations of the parameters. EC-Earth and ECMWF developments are intricately linked through improvements on either side that can be taken over by the other, so as to be mutually beneficial.

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

The phasing on model development related

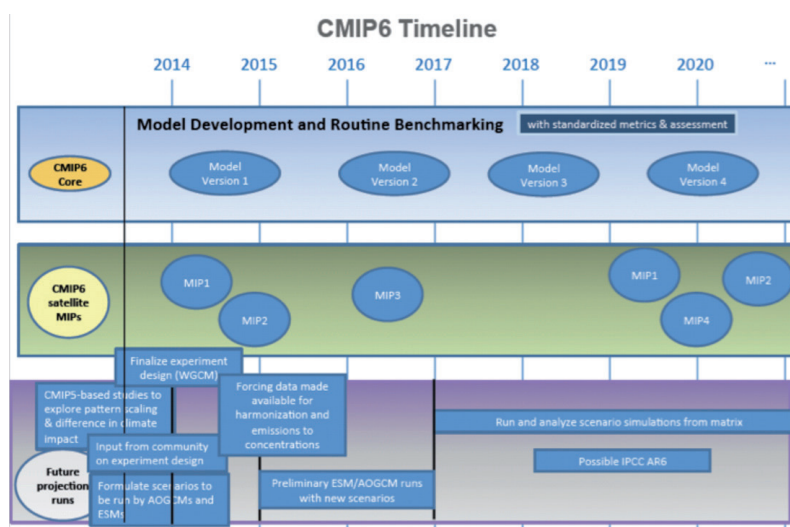


Figure 6. General timeline of the CMIP6 initiative.

that includes biogeochemical cycles and atmospheric chemistry.

Currently, EC-Earth V3 does not yet include chemical and biogeochemical components. The roles of aerosols and different nutrient cycles are essential for the development of the Earth System. In EC-Earth V2.4 couplings

between terrestrial ecosystems, atmospheric chemistry and physical modules are explored. A full coupling is foreseen before 2016, such that EC-Earth will include biogeochemical cycles and atmospheric chemistry modules, and can as such be used as a full ESM within CMIP6 and in H2020 projects (Figure 7).

Timeline of EC-Earth V3 development, tuning and deployment

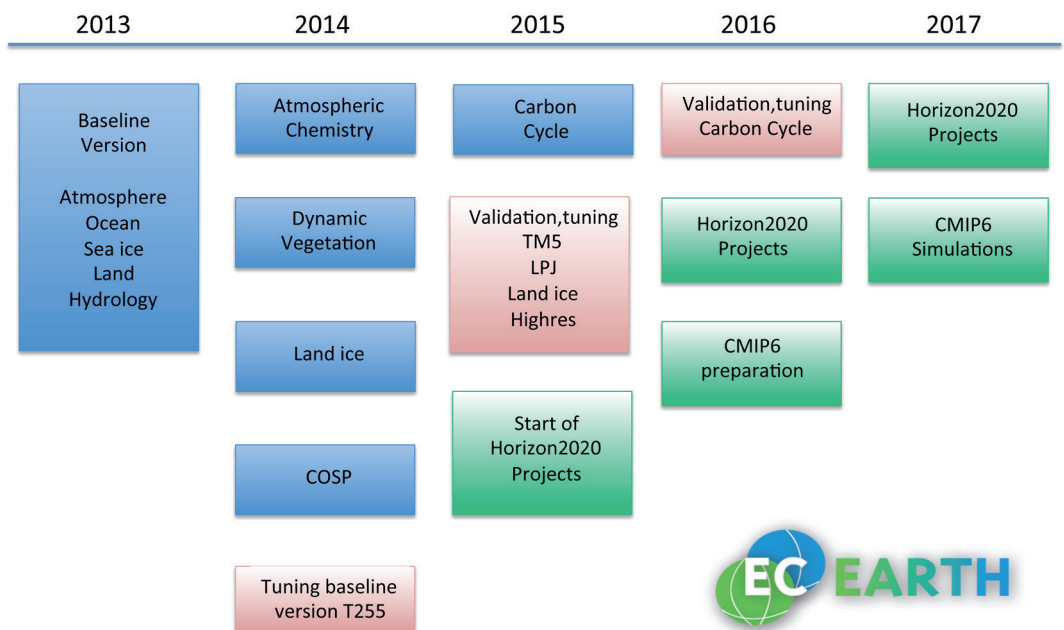


Figure 7. Timeline of EC-Earth V3 in terms of development, tuning and use within CMIP6 and H2020 projects. A key development goal will be the inclusion of modules representing the carbon cycle.



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Cover photo

The Cabauw mast seen from the remote sensing site. On the left the Humidity and Temperature Profiler (HATPRO), a microwave radiometer from KNMI. To the right of the mast a microwave radiometer from the European Space Agency: the Atmospheric Propagation and Profiling System (ATPROP). On the foreground a CT75 Lidar Ceilometer from KNMI and behind it a Present Weather Sensor from the Wageningen University & Research centre. On the right on top of the small mast a GPS receiver from the Delft University of Technology for Integrated Water Vapour measurements.

Photo: Jacques Warmer, KNMI, 2011.

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