

EC-EARTH: goals, developments and scientific perspectives

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Introduction

In recent years, it has become clear that the dynamic response of the Earth's global climate system is strongly affected by the interactions between its various subsystems¹. As a result, attention has shifted to the development of Earth System Models (ESMs) that go beyond the more 'traditional' state-of-the-art coupled atmosphere-ocean general circulation models (AOGCMs). These ESMs will include additional climate components such as ocean biochemistry, dynamic vegetation, atmospheric chemistry, carbon cycle components and dynamic ice sheets. In the coming decade, ESMs will thus enable us to study the Earth's climate system and its response to perturbations in the broadest sense, with the interactions between the various subsystems most likely resulting in increased accuracy of climate predictions as well as in valuable new insights in climate variability and interactions. In addition, there is rising interest in predicting the anthropogenic climate change and natural climate variability beyond seasonal to interannual time scales.

A few years ago, it was henceforth decided by the European Centre for Medium-range Weather Forecast (ECMWF) member states that it would be imperative to initiate the development of an ESM, and the ECMWF weather prediction model was chosen as a starting point. Despite their different purposes, climate and weather forecasting are obviously based on the same physical principles. This has been recognized with the introduction of the concept 'seamless prediction'², which intends to address the predictability of the Earth's climate system (in its broadest sense) within one common framework.

These considerations have led a large number of ECMWF member states to commence with the development of a common ESM, coined EC-Earth (Figure 1), an initiative in



Figure 1. The EC-Earth logo.

which the Global Climate Division of KNMI has taken the lead. Among the various member states that participate in this initiative, three scientific and practical common goals have been identified³:

Investigate Earth system feedbacks

Currently there is significant spread in climate sensitivity among climate models, which can be attributed to inaccurate knowledge of the main climate feedbacks such as cloud feedbacks, the lapse-rate feedback and the snow/ice albedo feedback⁴. To improve on this, such processes should be studied within the framework of a detailed ESM and validated with independent observations. Additionally, adding new components to the ESM will most likely bring to light previously unknown climate feedbacks, which will affect the modelled climate sensitivity.

Study interannual to multi-decadal climate fluctuations and predictability

This aspect of climate, and especially its interaction with projected greenhouse warming, is currently not understood very well. Large ensemble integrations with ESMs are required to usefully address the possible interactions between the dominant variability patterns (e.g. the North

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Atlantic Oscillation (NAO), El Niño – Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), Atlantic Ocean meridional overturning) and climate change. These experiments are initialized using estimates from the observed state of the climate, and ocean in particular, to obtain predictions.

Develop an advanced modelling tool for making climate scenarios

There is a strong need for ESMS to accurately quantify climate change in its broadest sense and to make projections for future change. This will aid the development of mitigation policies, and will also facilitate adaptation strategies that will mostly be based on regional climate change. The latter can be obtained by coupling a global ESM such as EC-Earth to a regional model such as RACMO (Regional Atmospheric Climate Model), developed by the Regional Climate Division of KNMI⁵.

Development and tuning

The development of EC-Earth within the EC-Earth consortium started with ECMWF's Integrated Forecast System (IFS) as a well-tested atmospheric module, with different components being added over time. The current version of EC-Earth is a fully coupled AOGCM, with oceanic, sea ice and land surface components having been coupled to the IFS. The model is off-line coupled to the TMS atmospheric chemistry model.

The different demands of a climate model as opposed to

a weather prediction model forced us to seek improvements to the uncoupled version of IFS (called CY31), which was initially chosen as the starting point of EC-Earth. These improvements should be reflected in the mean current climate as well as in its variability⁶. The tuning group of the EC-Earth consortium has performed several experiments to improve the skill of the model. In the following we will highlight a few changes that significantly improved the simulated climate.

The first improvement relates to problems in the simulated tropical climate in CY31, and most prominently to the underestimation of precipitation over the Pacific warm pool region (mainly the months JJA) and over Amazonia (mainly the months DJF), and to the overestimation of precipitation in the ITCZ (Inter Tropical Convergence Zone). It was noted that IFS cycle CY33 did not exhibit these problems and the changes could eventually be pinpointed to the different entrainment formulation in deep convection. Indeed, adopting the CY33 deep-convection entrainment in CY31 greatly reduced these deficiencies (Figures 2 and 3). Obviously, the agreement still is far from perfect, with e.g. somewhat degraded Asian monsoonal precipitation rates. An interesting 'side' effect is that the changed tropical convection and the associated heat transports also significantly improved the vertical distribution of temperature (Figure 3). The latter can also be inferred from a more systematic approach to assess the effect of model changes involving a performance index (PI).

We have adopted the performance index of Reichler and Kim (RK)⁷, which has been used to compare the performance of various models contributing to the Coupled Model Intercomparison Project CMIP3. It is based on the squared differences of a number of simulated parameters with observations, such as 2 meter temperature (T2m), mean sea level pressure (MSLP), precipitation and vertical distributions of various quantities, scaled with the interannual variance in the observed quantity. Figure 4 graphically depicts the RK performance of some selected

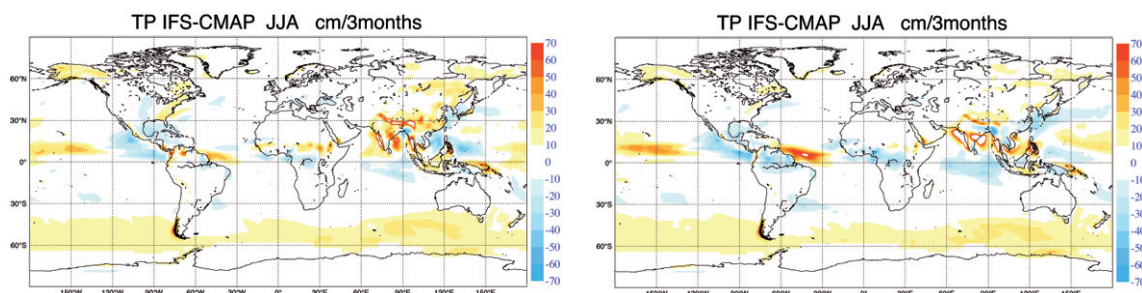


Figure 2. Geographical distribution of June-July-August (JJA) precipitation (simulated minus observed) for a) CY31 convection, b) CY33 deep convection. The difference between a and b is indicative of the effect of including the CY33 deep convection scheme. Units are cm per 3 months.

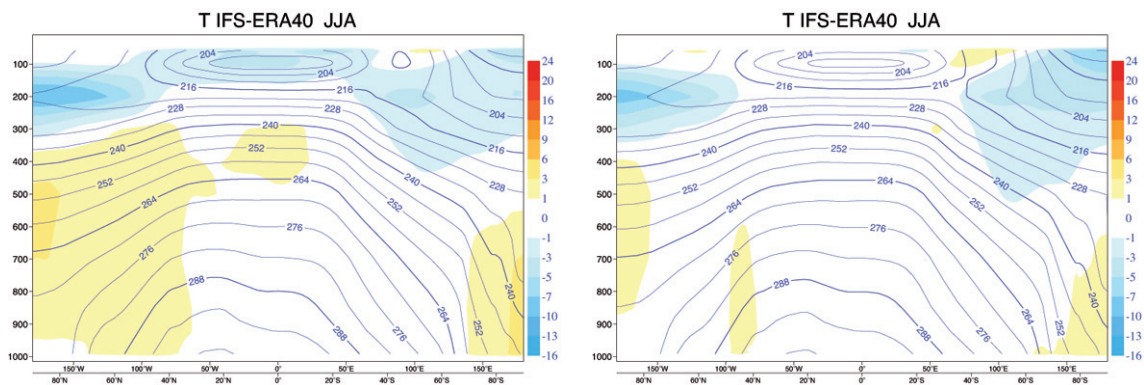


Figure 3. As in Fig. 2 but for vertical distribution of zonal mean temperature; lines denote absolute temperature (K), colours denote differences with ERA40 (K).

key model experiments. The top three entries depict the mean, best and worst CMIP3 AOGCMs, which are included for reference (being a next-generation model, one would expect that EC-Earth would generally outperform the CMIP3 models). The next four entries show the results for cumulative changes to the CY31 model version, for which it is important to note that these employ prescribed Sea Surface Temperatures (SST). The final two entries relate to the latest version of EC-Earth, which is a fully coupled AOGCM. The different colours depict four selected parameters, and the total (in black) reflects all variables (ten in total) combined. All values are scaled with the ‘mean CMIP3’ results to facilitate comparison between variables.

The uncoupled version CY31 in T95L40 resolution already yields results that are far better than the mean CMIP3, and are even comparable with the best CMIP3 model. While this seems reassuring, it should be noted that this

is for a large part due to the fact that uncoupled models always outperform coupled models for obvious reasons. A notable result is that increasing the resolution to T159L62 significantly increases the performance of all variables. This is an expected result, but it is instructive to infer which variables benefit most from the increase in resolution (MSLP and T2m); generally it seems that variables associated with the dynamics depend stronger on model resolution than those connected to the physics. Including CY33 convection yields, as explained above, better precipitation rates and associated vertical distributions of temperature, in particular in the equatorial region. As shown by the black bar, its inclusion significantly increases the total performance. For this reason, and also because improved precipitation rates may favourably affect the climate of the model after coupling to an ocean component, this change was incorporated in the final version.

The model version denoted by ‘V2_coupled_1’ is identical to the V1_final but for the coupling to the ocean (NEMO3) and sea ice (LIM2) components, and therefore represents the first coupled version of EC-Earth prior to tuning the coupled system. Not unexpectedly, the performance degrades significantly for all variables. Note, however, that the average performance of the first untuned coupled system of EC-Earth is only slightly worse than that of the mean CMIP3 model. Coupled model ‘V2_coupled_6’ represents the state after several bug fixes as well as changes to the snow albedo scheme and to the ocean. Clearly an improvement in most variables and in the total performance has been achieved. The process of development and tuning the coupled system is still ongoing, so further improvements can be expected.

An example of the state of the latest coupled model is

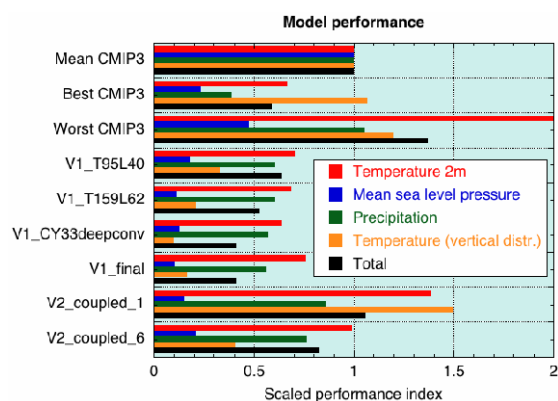


Figure 4. Scaled performance indices (based on squared differences of model and observations) for the various model versions (including mean, best and worst CMIP3 models), scaled with the results from the mean CMIP3 models.

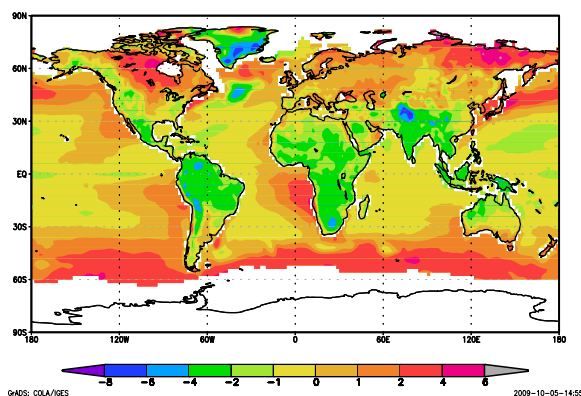


Figure 5. Geographical distribution of annual mean 2m temperature over land, and sea surface temperature over the oceans. Plots show simulated minus observed values (K) against the respective observations. White areas indicate that observations are absent.

The current version of EC-Earth will participate in the next CMIP5 initiative, and the model will also contribute to the next Intergovernmental Panel on Climate Change report

given in Figure 5. Annual T_{2m} has a positive bias over the Northern Hemisphere (NH) continents, in particular in the subarctic regions (excluding regions permanently covered by land ice, such as Greenland). Analysis shows that this feature is due mainly to too warm winters, a feature present not only in the IFS model but also in many other climate models⁴. The reason for this bias may lie in the treatment of snow physics and/or the parameterization of vertical transports in the stable boundary layer. Attempts to address this issue have so far been largely unsuccessful. Another important bias is present in the sub polar sea surface temperatures (SST), in particular in the Southern Ocean. Also this bias is a fairly common feature among coupled climate models; attempts to reduce this are ongoing.

First scientific results

Even though the model has only recently been finalized, already some studies have been carried out with preliminary versions of EC-Earth. As an example of the kind of issues EC-Earth will be able to address, we will here briefly discuss the results of a recent paper by Haarsma et al.⁸. This paper focuses on possible causes of anomalously warm Western European summers under future climate change. The hypothesis is that warming of the Mediterranean region in concert with drier soils

induces a large-scale heat low that causes easterly winds over Central Europe. This has been tested in the uncoupled (atmosphere only, prescribed SST) version of EC-Earth by applying an artificial net downward surface flux of energy over the Mediterranean that mimics conditions under the SRES A1B scenario for 2100. The results (Figures 6 a, b, c and d) show a strong increase in T_{2m}, which is attributed to the depletion of soil moisture and a consequent decrease in latent heat flux. A heat low indeed develops, causing more easterlies in Western/Central Europe, as well as increased subsidence, less clouds, reduced precipitation and increased solar warming: all aspects of a more continental summer climate in Western Europe. This example nicely illustrates how EC-Earth can be used in a case-study manner to investigate specific aspects of climate in more detail, thereby bringing to light possible causes of (regional) climate change.

Conclusion

While the current version of EC-Earth is essentially a state-of-the-art AOGCM, a number of additional components are currently under development and will be added to EC-Earth in the coming years. These include dynamic vegetation, ocean biochemistry, carbon cycle components and dynamic ice sheets. We work actively with academia where there is expertise on these earth system components. As such, we provide the EC-Earth model to various research groups, in order to facilitate studying earth system feedbacks in an integrated earth system model. An important component that will probably be added already in the next version is an atmospheric chemistry module, which consists of an online version of the atmospheric chemistry and transport model TM5⁹. Being developed at KNMI's Chemistry and Climate division in collaboration with Wageningen University and Research Centre (WUR) and (inter)national partners, this module calculates the concentrations of reactive gases and various aerosol types for the meteorological conditions simulated by the atmospheric module of EC-Earth (IFS). The concentrations of the simulated greenhouse gases and the concentrations and relevant optical properties of the aerosols will be fed back into the atmospheric module to calculate the associated direct and indirect radiative forcings.

The current version of EC-Earth will participate in the next CMIP5 initiative, and the model will also contribute to the next report of the Intergovernmental Panel on Climate Change (~2013). The experiments will include traditional projections of future climate change in response to changes in greenhouse gasses, aerosols and land use, and novel decadal predictions. Obviously, this

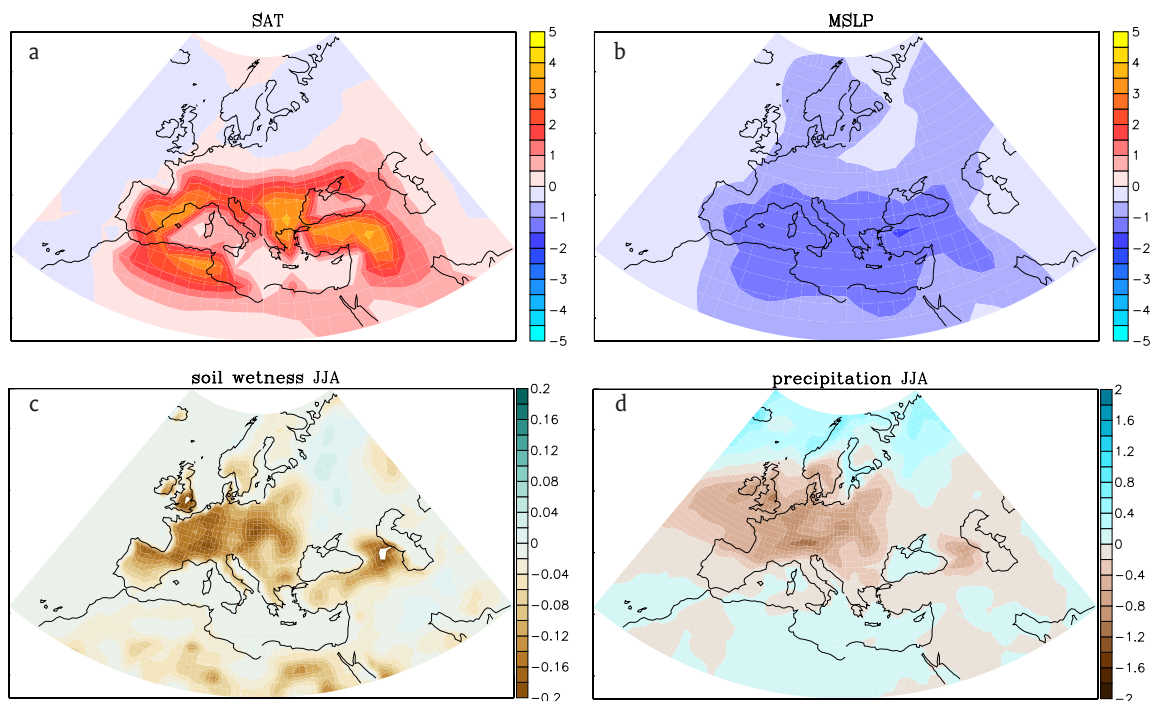


Figure 6. Simulated JJA fields of a) surface air temperature (K), b) mean sea level pressure (hPa), c) soil wetness (the average moisture content of the upper meter of the soil), and d) precipitation (mm day^{-1}), for the experiment with an enhanced surface flux in the Mediterranean⁹⁾. Plots depict the difference between the model runs with and without the artificial energy flux.

fits with the goals to address future climate change and contribute to climate scenarios as specified above. Preparations for this are already under way, as quite a number of (long) model runs are required for this purpose. To address regional (e.g. Western European) climate change, also in the framework of the climate scenarios, the output of EC-Earth simulations will most likely also be used as boundary conditions for regional climate models such as RACMO.

To conclude, we anticipate that EC-Earth will be used extensively in the near-future for all kinds of climate (change) applications, and will as such provide KNMI's climate activities a strong strategic position, both nationally and internationally.

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