

EC-Earth

A Seamless Earth-System Prediction Approach in Action

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THE CHALLENGE. Climate and weather forecasting applications share a common ancestry and build on the same physical principles. Nevertheless, climate research and numerical weather prediction (NWP) are commonly seen as different disciplines. The emerging concept of “seamless prediction” forges weather forecasting and climate change studies into a single framework. At the same

time, it has been recognized that biogeochemical and human processes interact with the physical climate system, and these interactions are thus explicitly incorporated into extended climate models, now referred to as Earth-system models (ESMs). Merging weather and climate prediction with Earth-system science is a new challenge that is of considerable scientific interest and societal relevance.

There is increased societal interest in climate information for the next few decades to guide adaptation strategies. Initialized climate forecasts and scenario integrations with climate models can generate relevant climate information. Advances have been made to increase the prediction horizon of initialized forecasts to decades. The quality of long-term predictions relies on accurate simulation of slow components of the Earth system, accurate simulation of interactions between fast and slow processes in the Earth system, and the initialization procedures.

The prediction problem lies at the heart of NWP. Hence, scientists working on decadal predictions can learn from experiences in initialization, perturbation, and verification in short-term-to-seasonal forecasting. Also, joint model development in NWP and Earth-system modeling can be mutually beneficial. Atmospheric model development is generally more advanced in NWP than in ESMs and new developments can also be implemented in Earth-system models. Conversely, NWP models increasingly include Earth-system components. These include modules of atmospheric composition and the land surface that are generally developed by Earth-system modeling groups.

The EC-Earth consortium is a grouping of meteorologists and Earth-system scientists from 10 European countries, put together to face the chal-

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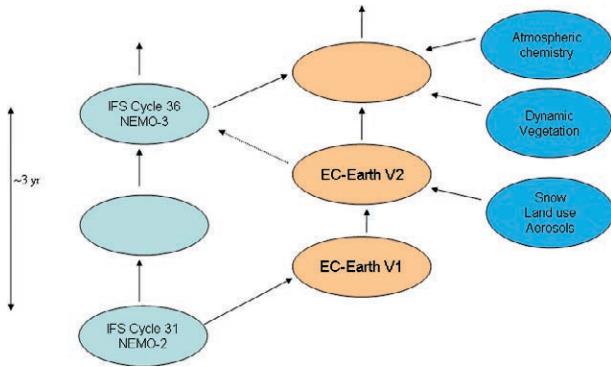


Fig. 1. Strategy of EC-Earth model development. Left-hand side: ECMWF model development, ensuring up-to-date fast processes parameterizations. Center: EC-Earth development. Right-hand side: Independent Earth-system component developments (e.g., academia), ensuring up-to-date slow-processes parameterizations.

lenges mentioned above. The consortium consists of scientists from national meteorological services, academia, and high-performance computing centers, designed to bridge the gap between NWP and Earth-system modeling. The EC-Earth model, described below, will be used for basic research, developing climate projections and predictions, and delivering climate information to users.

STRATEGY OF EC-EARTH MODEL DEVELOPMENT. The NWP system of the European Centre for Medium-Range Weather Forecasts (ECMWF) forms the basis of the EC-Earth Earth-system model (hence the name EC-Earth). NWP models are designed to accurately capture short-term atmospheric fluctuations. They are used for forecasts at daily-to-seasonal time scales and include data assimilation capabilities. Climate models are designed to represent the global coupled ocean-atmosphere system. They are used for different purposes and time scales than NWP models, but could benefit from several best practices from the NWP community. To our knowledge, this approach is currently only followed in the Unified Model of the UK Met Office and the ARPEGE system at Météo-France.

A central element of our strategy is to continually synchronize the atmosphere, land, and ocean modules between the EC-Earth model and a reference configuration of the ECMWF forecast system (see Fig. 1). To serve climate science and prediction, the EC-Earth consortium improves or adds different

Earth-system modules to the model, which can be taken over by or developed in close cooperation with ECMWF. This procedure requires a strict version-management strategy and the coordination of the development of new versions by a single partner. In order to facilitate code merging, we keep a repository of the EC-Earth code at ECMWF.

Exploratory studies on feedbacks in the Earth-system are carried out mainly by academic institutions. To ensure that newly developed knowledge is included in the Earth-system model and tested in an integrated Earth-system environment, meteorological services serve as a facilitator to academic partners. A number of examples of new Earth-system components that are incorporated in the EC-Earth model are listed in Fig. 1.

By working in a large network of distributed centers, the EC-Earth consortium is able to share computational facilities. In this way, the consortium can efficiently build up extensive datasets based on large ensembles of simulations. The EC-Earth consortium will contribute to the next Coupled Model Intercomparison Project (CMIP5), coordinated by the World Climate Research Programme, using hardware at 10 different sites. Within this project, simulations with scenarios of future emissions, land use, and decadal predictions, initialized from the observed climate state, will be run in a coordinated fashion by different modeling groups.

THE EC-EARTH MODEL SYSTEM. The atmospheric model of EC-Earth version 2, which is the current reference version, is based on ECMWF's Integrated Forecasting System (IFS), cycle 31R1, corresponding to the current seasonal forecast system of ECMWF. The standard configuration runs at T159 horizontal spectral resolution with 62 vertical levels. In fact, some aspects of a newer IFS cycle have been implemented additionally, including a new convection scheme and the new land surface scheme H-TESSEL. The ocean component is based on version 2 of the NEMO model, with a horizontal resolution of nominally 1 degree and 42 vertical levels. The sea ice model is the LIM2 model. The ocean/ice model is coupled to the atmosphere/land model through the OASIS 3 coupler.

Earth-system components can be coupled to the EC-Earth model through the coupler. In particular, coupling to a detailed atmospheric aerosol-chemistry module (TM5) has already been accomplished. The next versions of the EC-Earth model will contain ac-

tive coupling of this component with the radiation and clouds microphysics parameterizations. Other Earth-system components that are planned to be coupled online are terrestrial and marine ecosystem modules.

The model is ported to different high-performance hardware systems: IBM P6 AIX, CRAY XT-5, Intel-based Linux Clusters, and SGI Altix at different sites around Europe. An interactive application, implemented through Web services, can be used on ECMWF hardware systems to set up, compile, and monitor runs. We use standardized experimental setups to check hardware dependency of the results.

EC-EARTH: CLIMATE AND WEATHER METRICS.

In line with the seamless prediction strategy discussed above, we assess here the performance of the EC-Earth model using both climate metrics (e.g., long-term means, radiative balance, and slow processes) and weather metrics (e.g., short-term forecast skill and fast processes). Any metric is somewhat subjective, including the choice of variables, the filtering applied, and the choice of datasets to which model results are compared. In weather prediction, prediction skill scores for up to a few weeks are considered. At these time scales, fast atmospheric processes are important. In climate studies, often long-term means are considered, and changes in, for instance, the oceanic heat content are relevant. However, distinguishing weather from climate metrics is also somewhat artificial. Since fast processes can shape slow feedbacks (e.g., through the surface radiation budget affecting ocean heat content), both short- and long-term model performance should be considered.

To assess the performance of the EC-Earth model at long time scales, both the atmosphere-only and the fully coupled model have been used. Atmosphere-only runs have been performed with prescribed sea-surface temperature and sea ice distribution representing the end of the twentieth century. We consider runs of at least 10 years duration. The fully coupled model has been run for 250 years, with twentieth-century boundary conditions (greenhouse gases,

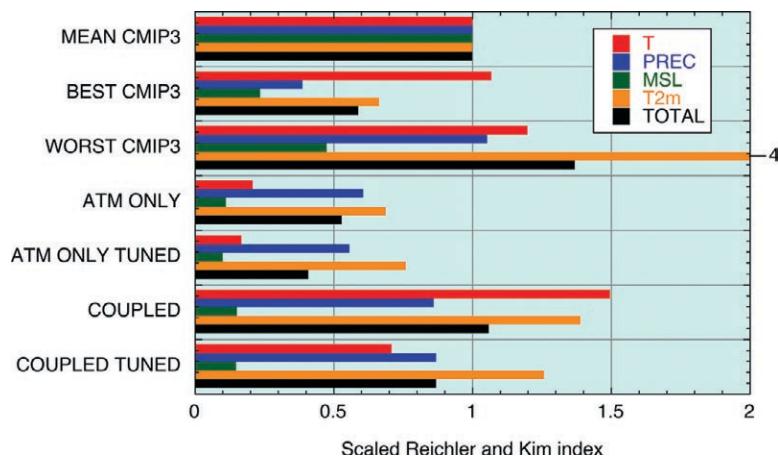


FIG. 2. Performance indicators (root-mean-square errors) of the long-term mean climate of the EC-Earth model according to the metrics of Reichler and Kim (2008). Metrics are shown for the atmosphere-only models (“ATM Only” and “ATM Only Tuned”) and the coupled models (“Coupled” and “Coupled Tuned”). The performance is compared to the averaged CMIP3 coupled model performance, which is normalized to 1. Metrics are computed separately for vertical distribution of zonal mean temperature (T), precipitation (PREC), mean sea level pressure (MSL), surface air temperature (T2m), and a combination of 14 parameters (TOTAL; only 4 of the individual parameters are shown). Changes larger than 0.04 are statistically significant at the 95% level according to a t-test, determined from the performance indicator of 17 slices of 10 years of the control run of EC-Earth.

aerosols, land use, and solar activity). We use a set of metrics developed by Reichler and Kim in a 2008 *BAMS* article to compare the EC-Earth model results to observations and to other coupled climate models of CMIP3. This set of metrics consists of a weighted root-mean-square error of 14 variables. Other measures, such as representation of the seasonal cycle, surface, and top-of-the-atmosphere energy balances and representation of patterns of natural climate variability were used as well. In general, we use the performance indicators to inform the optimization process. We discarded parameter changes that gave a strong degradation in the general performance of the model.

The atmosphere-only model (ECMWFs IFS cycle 31R1) performs well for most variables compared to CMIP3 coupled models (Fig. 2, bars labeled “ATM Only”). This is not surprising, because sea surface temperature is prescribed and strongly constrains the mean climate. Nevertheless, a small number of parameters (inhomogeneity scaling factor for short-wave cloud optical thickness, autoconversion rates in clouds, and the gravity wave drag parameterization) were optimized with the atmosphere-only model in

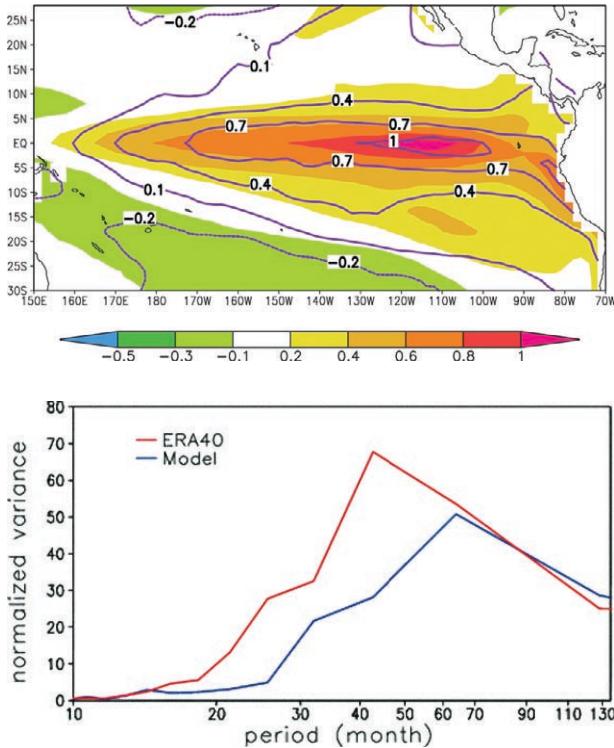


FIG. 3. (top) First empirical orthogonal function (EOF) of monthly averaged sea surface temperature (SST, °C) in the tropical Pacific in EC-Earth (colors) and observations (contours). (bottom) Power spectra of the first EOF of SST in reanalysis data (red) and EC-Earth (blue).

terms of this metric, as shown by the performance of the atmosphere-only model used in EC-Earth V2 (“ATM Only Tuned” vs. “ATM Only”). The radiative imbalance at the top of the atmosphere and at the surface is less than 0.5 Wm^{-2} , which is considered acceptable for climate models. However, the interaction with the slow components of the climate system can still lead to severe biases.

When coupling the atmosphere model to the ocean model with the adjusted parameters mentioned above, the EC-Earth model still performs well, but initially somewhat worse than the average of the CMIP3 models (Fig. 2, bars labeled “Coupled”). Additional optimization led to an improved coupled model (Fig. 2, bars labeled “Coupled Tuned”). The changes were mainly confined to internal oceanic processes, the coupling interface to the ocean and sea ice (fresh-water exchanges), and not in parameterizations related to the fast atmospheric processes in the NWP model. The model performs well in tropical regions, where the atmospheric circulation and lapse rate are well simulated. Also, the mean sea

level pressure is well simulated. In the Arctic, the sea ice distribution is realistic. Major warm biases are still found over Siberia and Canada in winter. When coupling to dynamic vegetation models, anomaly coupling will need to be employed, as in most current ESMs. Also, the ocean surface is too warm in the Southern Ocean, which can likely be attributed to ocean processes and circulation, because other coupled models with the same ocean module show very similar biases and surface fluxes tend to damp warm anomalies in ocean-only simulations. The results show the potential of using NWP models in a climate setting.

Next, the model’s interannual variability was investigated. This has to be well represented for successful seasonal-to-decadal predictions. The dominant climate pattern of interannual variability is the El Niño–Southern Oscillation (ENSO). The model captures the spatial variability of ENSO very well (Fig. 3). For example, the model shows a good connection between the anomaly in the central Pacific and South American coast. Also the temporal variability is well captured with a broad peak at interannual time scales, although the variance may be too small.

The concept of seamless prediction fails if the additional tuning required to simulate a good mean climate and its variability in a fully coupled setting degrades the prediction skill on short time scales. Since primarily slow processes were affected when optimizing the fully coupled system, this is not expected. Indeed, weather reforecasts with the current atmospheric component of EC-Earth show that the model has good forecast skill. As an illustration, we present the anomaly correlation and the standard error of geopotential height at 500 hPa (Fig. 4). Forecasts made by the consortium with the ECMWF model (IFS cycle 31R1) and the EC-Earth model (at the same T159 spectral resolution) show comparable levels of skill. The slightly increased level of skill in the EC-Earth system likely arose from the revisions made by ECMWF to their convection and land-surface schemes (see above), which were implemented in later cycles of the forecast model.

SYNERGISTIC WEATHER AND EARTH-SYSTEM ACTIVITIES. A merit of using an NWP model for climate studies is that insights and developments in NWP modeling can be taken over in Earth-system studies and vice versa. Some examples of this “cross fertilization” are given here.

Within the EC-Earth consortium, the land module has been further developed. One of the motivations was to investigate the cause of warm biases in the winter over Siberia and Canada. As part of the land-surface module, a new snow scheme has been implemented by Dutra et al. in their 2010 *Journal of Hydrometeorology* article. The new scheme, which reformulates the density of snow and the representation of liquid water in the snowpack, reduces warm biases (Fig. 5). The new module was also tested in the operational NWP environment, with a positive effect on medium-range forecast skill. It has been implemented in new operational cycles at ECMWF. Other developments by the EC-Earth consortium along this track are the implementation of direct and indirect aerosol effects and more detailed vegetation dynamics (e.g., seasonal leaf area index).

Conversely, new developments from ECMWF operational cycles have been taken over in the EC-Earth model. Numerical schemes are frequently more efficient in NWP models than those in ESMs. Also, some atmospheric physics parameterizations are more advanced in NWP models. We implemented a convection parameterization from a newer NWP model cycle that strongly improved the midlatitude sea level pressure distribution over the Pacific and Atlantic, showing that new developments in NWP can improve the climate simulated with EC-Earth.

Seasonal-to-decadal prediction bridges the gap between weather and climate applications. The EC-Earth consortium and ECMWF are collaborating on development of initialization procedures to improve long-term predictions. Prediction experiments in the GLACE-2 project, including EC-Earth model simulations, show potential in initializing soil moisture for seasonal prediction. Also, sea ice initialization procedures for decadal predictions are being developed in joint projects.

Aside from improving modeling techniques in both NWP and climate contexts, insights from NWP are applied in Earth-system sciences within the EC-Earth project—for instance, the occurrence of episodes of midlatitude atmospheric blocking conditions. Blocks are synoptic weather patterns that have been studied in detail at “weather” time scales. There is increased interest in blocking in future climate conditions because blocking is associated with extreme warm summer or cold winter conditions. Insights into the dependence of simulated blocking frequency on model resolution have helped to interpret future changes simulated in coarse-resolution climate runs. Long runs at different

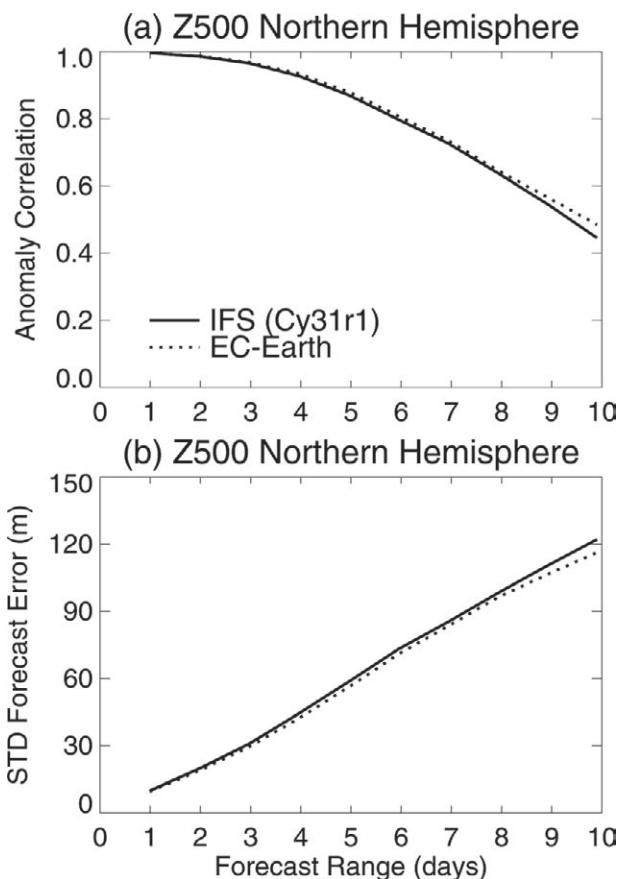


FIG. 4. (a) Anomaly correlation of analyzed and predicted (10-day forecasts, winter 2005) geopotential height at 500 hPa with IFS cycle 3IR1 and with the atmospheric version of EC-Earth at identical resolution. (b) Root-mean-square error of the IFS cycle 3IR1 and EC-Earth forecasts.

horizontal resolutions with the atmospheric component of EC-Earth have been carried out and confirm the resolution-dependence found in NWP.

FUTURE OF SEAMLESS EARTH-SYSTEM MODELING WITH EC-EARTH.

The EC-Earth project shows that a bridge can effectively be made between weather and seasonal forecasting and Earth-system modeling. The EC-Earth model displays good performance from daily up to interannual time scales and for long-term mean climate. We have designed a strategy to take advantage of new developments in NWP, particularly to incorporate advances in parameterization of fast processes that shape crucial aspects of long-term climate characteristics, such as climate sensitivity. Evidently, for long-term climate simulations, slow processes must be considered as well. It is expected

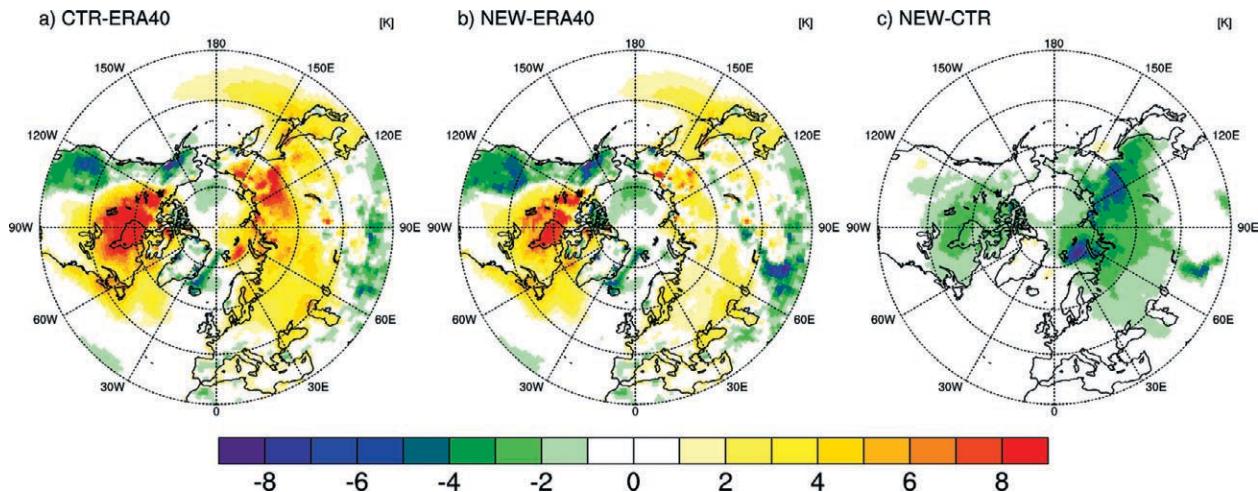


FIG. 5. Impact of new snow scheme on 2-m temperature (K) during winter (Dec–Jan–Feb) in the coupled EC-Earth runs (last 20 yr from a 40-yr run). (a) Coupled model compared to ERA40 reanalysis data. (b) Coupled tuned EC-Earth model compared to ERA40. (c) Difference between tuned and control-coupled EC-Earth model.

that exploratory work on this topic will be done by university groups involved in the project. EC-Earth allows these groups to study new components in an integrated setting in full interaction with other components of the Earth system. Clear examples of these synergistic activities are the development of modules for ice sheets, dynamic vegetation, and atmospheric chemistry. Some of these new Earth-system components will be taken over in new cycles of the weather forecasting system and may lead to improvements in weather and seasonal forecasting skill.

National meteorological services will use the EC-Earth model primarily as a tool to construct seasonal-to-decadal predictions and climate projections in line with the recently established Global Framework for Climate Services (GFCS) at the World Climate Conference-3 (WCC-3). EC-Earth can be run efficiently at high spatial resolution. The consortium will participate in the CMIP5 project with both near-term decadal predictions and century-scale projections. We use boundary conditions from the global model for our regional climate models to explore regional feedbacks. One particular application is the use of the atmosphere-only version at very high resolutions (e.g., similar to the current ECMWF NWP system, about 16 km) with future boundary conditions. In such a system, synoptic weather information in a future climate setting can be assessed.

In this paper we have shown that the EC-Earth project bridges the gap between NWP and climate modeling and has a wide range of applications, from

basic Earth-system research to providing practical climate information for a wide variety of users.

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