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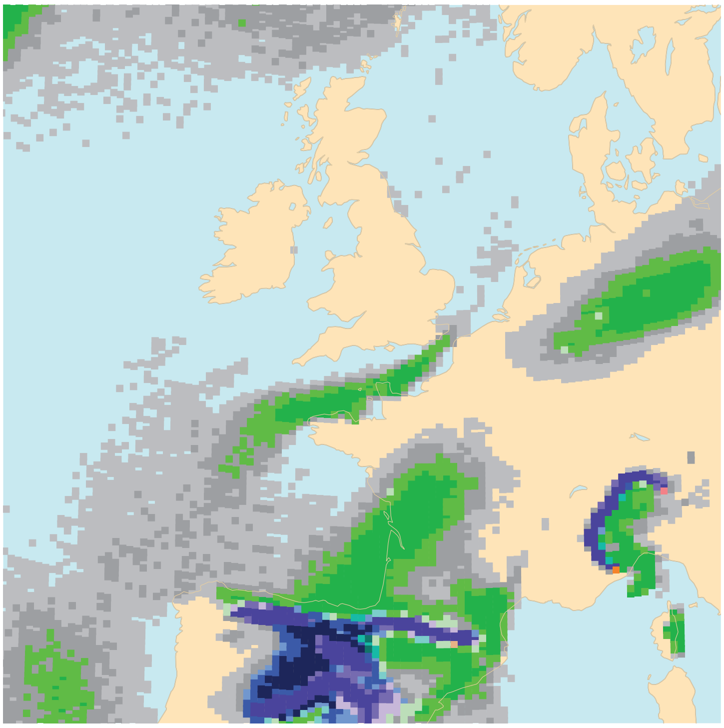
METEOROLOGY

Using EC-Earth for climate prediction research



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Using EC-Earth for climate prediction research

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Climate prediction at the subseasonal to interannual time range is now performed routinely and operationally by an increasing number of institutions. The feasibility of climate prediction largely depends on the existence of slow and predictable variations in the ocean surface temperature, sea ice, soil moisture and snow cover, and on our ability to model the atmosphere's interactions with those variables.

Climate prediction is typically performed with statistical-empirical or process-based models. The two methods are complementary. Although forecasting systems using global climate models (GCMs) have made substantial progress in the last few decades (*Doblas-Reyes et al.*, 2013), systematic errors and misrepresentations of key processes still limit the value of dynamical prediction in certain areas of the globe. At the same time, model initialisation, ensemble generation, understanding the processes at the origin of predictability, forecasting extremes, bias adjustment and model evaluation are all challenging aspects of the climate prediction problem. Addressing them requires both a large base of researchers with expertise in physics, mathematics, statistics, high-performance computing and data analysis interested in climate prediction issues and a tool for them to work with.

This article illustrates how one of these tools, the EC-Earth climate model (Box A), has been used to train scientists in climate prediction and to address scientific challenges in this field. The use of model components from ECMWF's Integrated Forecasting System (IFS) in EC-Earth means that some of the results obtained with EC-Earth can feed back into ECMWF's activities.

EC-Earth has been run extensively on ECMWF's high-performance computing facility (HPCF), among a range of HPCFs across Europe and North America. The availability of ECMWF's HPCF to EC-Earth partners, including the use of the successful ECMWF Special Project programme, means that a substantial amount of EC-Earth's collaborative work, both within the consortium and with ECMWF, takes place on this platform.

The EC-Earth Earth system model

A

Earth system models (ESMs) such as EC-Earth are one of the most powerful tools to provide society with information on the future climate. EC-Earth is a non-operational ESM that generates predictions and projections of global climate change and variability, which are a prerequisite to supporting the development of national adaptation and mitigation strategies. As a climate model, EC-Earth is closely aligned with the ECMWF seasonal forecasting system, in which the IFS atmospheric model is coupled with the NEMO ocean model.

EC-Earth is developed as part of a Europe-wide consortium, thus promoting international cooperation and access to both knowledge and data. It facilitates fruitful interaction between academic institutions and the European climate impact community. The EC-Earth model benefits greatly from IFS updates and in turn the consortium contributes to the development of the atmospheric model. EC-Earth makes significant contributions to a range of international climate modelling and service research projects, as well as to international initiatives, such as the Coupled Model Intercomparison Projects (CMIP).

For more information, visit the EC-Earth website at: *http://www.ec-earth.org*

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Why use EC-Earth?

There are several reasons that motivate the use of EC-Earth for climate prediction research. The following is a non-exhaustive list:

1) ***Comparison across timescales and seamless modelling:*** EC-Earth has been designed for climate research problems covering any timescale. For this reason, the model is tuned according to community standards, notably for conservation of both mass and energy. Long control experiments typical of climate change research are regularly produced with each new model version. They help to understand the characteristics of the model variability. Such a model also offers a unique opportunity to perform climate modelling experiments across timescales, from sub-seasonal climate prediction to long-term climate change or paleoclimate experiments. This means that EC-Earth is an ideal platform, albeit not the only one in the community, to investigate the physical reasons behind issues like the initial shock and drift by comparing initialised and long-term control simulations or the effects of the initialisation on the forced model response by analysing initialised and historical simulations.

2) ***Inclusion of new components:*** Although the EC-Earth model is based on the IFS and the NEMO ocean model, the consortium has introduced some modifications to ECMWF's coupled model and added new components. An example of a different component is the LIM3 sea-ice model, which has been introduced as part of the latest NEMO version, while a new component is the LPJG vegetation model. One reason why the latter has been added is to be able to take into account land-use changes and interactive vegetation in the simulations. Some of these components introduce more complexity into the system. Their use in a climate prediction context is opening up new avenues for exploring new sources of predictability and for further collaboration with ECMWF.

3) ***Portability:*** EC-Earth is a community model and, as such, it has been ported by the EC-Earth partners to their preferred computing platforms, including ECMWF's HPCF. Portability comes at a price, mainly in terms of computational performance, but it also enables the consortium to participate in very ambitious experiments. EC-Earth will, for example, make a significant contribution to the Sixth Phase of the Coupled Model Intercomparison Project (CMIP6), in particular by playing a key role in the Decadal Climate Prediction Project (DCPP; *Boer et al.*, 2016). Such endeavours would be beyond the reach of any individual partner in the consortium. To ensure that experiments performed on different computing platforms are comparable, an innovative reproducibility protocol has been designed following the example of other climate community models.

Climate prediction research with EC-Earth

EC-Earth has many uses as a climate prediction research tool. In what follows we give some examples. The details of the model characteristics and the experimental setup used in most of the simulations referred to in this section can be found in *Prodhomme et al.* (2016a) for EC-Earth2.3, also used in the CMIP5 exercise, and in *Prodhomme et al.* (2016b) for EC-Earth3, the version of the model that will be used in CMIP6.

Ensemble initialisation

Ensemble initialisation is a key aspect of all climate prediction experiments. While EC-Earth has benefited enormously from ECMWF reanalyses (both for the atmosphere and the ocean) to initialise different re-forecast experiments, the consortium is exploring ways to improve its forecasting system by either assimilating new observations or by using different initialisation methodologies. Figure 1 shows the correlation coefficient of the ensemble mean of seasonal predictions of near-surface temperature performed with EC-Earth3.2 over the period 1993 to 2008 for the boreal winter. Figure 1a gives a first impression of the skill of the EC-Earth climate prediction system at seasonal timescales (EXP1). Note that the robustness of the skill is limited by the period considered. The skill can be compared with that obtained in a similar experiment (EXP2), in which the sea ice is initialised with data from a sea-ice reconstruction (no data assimilation). The difference between them suggests that the impact of the sea-ice data assimilation is small but mainly positive, with areas of positive impact over North America, the North Atlantic, Siberia and central Europe. The latter could be related to a similar difference in skill between EXP1 and EXP2 of predictions of the North Atlantic Oscillation (NAO) index, the variability of which has an important impact over central Europe. Experiments are under way to extend the re-forecast period to confirm the robustness of these results.

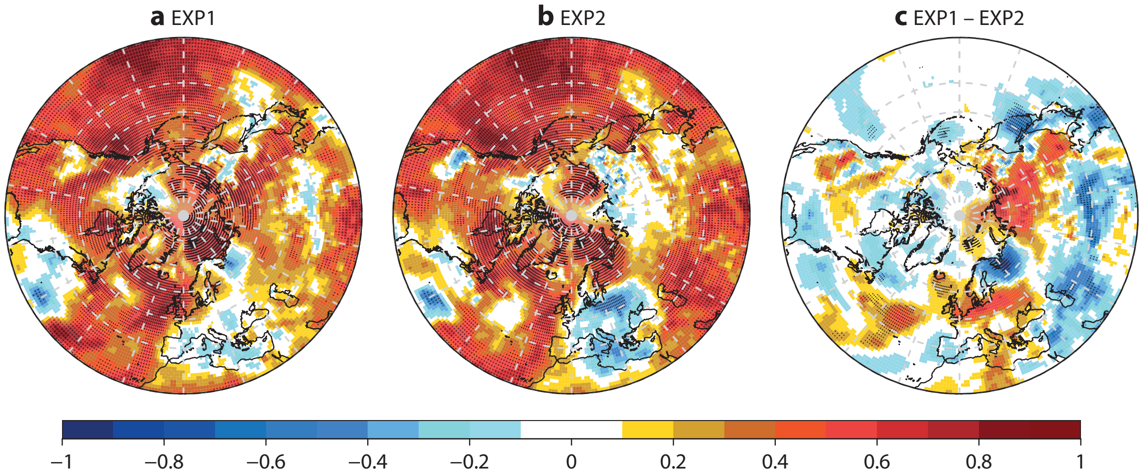

Figure 1 Correlation coefficients of the ensemble mean of 10-member ensemble seasonal predictions performed with EC-Earth3.2 over the period 1993 to 2008. The results shown are for boreal winter (December to February) near-surface temperature predictions with a starting date of 1 November. The panels show (a) the results for simulations initialised with the ERA-Interim reanalysis for the atmosphere, ORA-S4 for the ocean and a BSC (Barcelona Supercomputing Center) reanalysis using an ensemble Kalman filter approach for sea ice (EXP1), (b) the same but with sea ice initialised with data from a sea-ice reconstruction (no data assimilation) (EXP2), and (c) the difference in the correlation coefficient between the two experiments (EXP1 – EXP2). Stippling indicates statistical significance at the 95% confidence level.

Impact of model resolution

The desire to better capture physical processes in the ocean and the atmosphere, alongside the growing efficiency of the HPCFs used to run GCMs, has led to an increasing number of studies using higher-resolution components of the climate system for climate prediction (*Prodhomme et al.*, 2016b). EC-Earth, with its range of configurations with different atmospheric and ocean resolutions, has proved to be an ideal tool for this type of study. The model has been used to assess the impact of atmospheric and ocean resolution on the quality of climate predictions. Figure 2 shows a comparison of the quality of predictions (the correlation coefficient of the ensemble mean) of the sea-surface temperature (SST) index in the NINO3.4 region performed with EC-Earth3.1 in standard (TL255-ORCA1) and high-resolution (TL511-ORCA025) configurations. Although the high-resolution configuration shows sustained and statistically significant better skill with respect to the standard-resolution configuration, it is important to note that there are many sources of skill estimate uncertainty. Observational uncertainty is one of them, as Figure 2a shows in the range of correlations obtained when verifying a set of re-forecasts against different observational references.

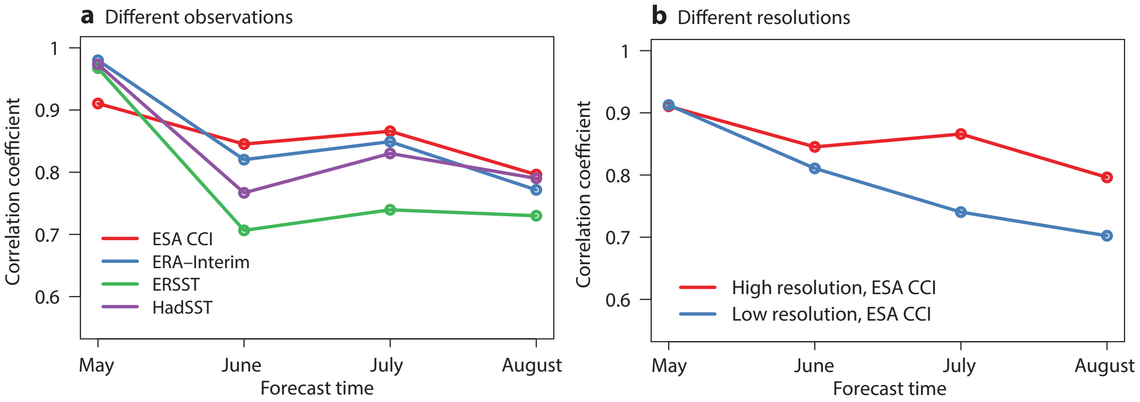

Figure 2 Correlation coefficient as a function of forecast time of ensemble-mean predictions of NINO3.4 sea-surface temperature performed with EC-Earth3.1 and initialised on 1 May using (a) the TL511-ORCA025 resolution configuration over the re-forecast period 1993 to 2009, for four different observational datasets, and (b) TL511-ORCA025 and TL255-ORCA1 re-forecasts verified against the ESA CCI dataset. All correlations are significant at the 5% confidence level and differences in the correlations in (b) are significant at the 1% confidence level.

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Observational uncertainty

Observational uncertainty has traditionally been neglected in climate prediction quality assessments. In fact, when a comprehensive skill uncertainty analysis is performed (Figure 3), the observational uncertainty is found to be a substantial contributor to the total uncertainty. In this analysis, three sources of uncertainty of a skill assessment are considered: 1) uncertainty due to the limited number of re-forecasts available resulting from the limited set of robust initial conditions, 2) uncertainty due to the limited ensemble size resulting from limited computational resources, and 3) observational uncertainty. The uncertainties are assessed by resampling the ensemble members of the re-forecast prior to computing the ensemble mean and resampling the years in the verification period, both with replacement.

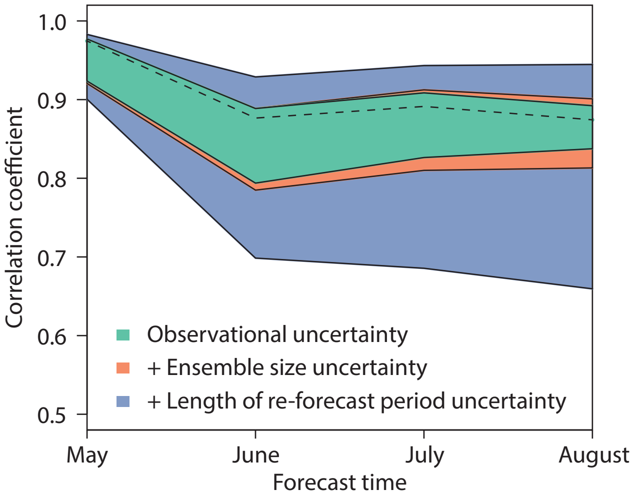

Figure 3 Correlation coefficient as a function of forecast time of ensemble-mean predictions of NINO3.4 SST performed with EC-Earth2.3 over the re-forecast period 1993 to 2009, initialised on 1 May. The shaded areas show the 5–95% range of the bootstrapped uncertainty around the correlation coefficient, broken down into the uncertainty in the observational reference using the CCI SST, and the uncertainties due to a limited ensemble size and limited re-forecast length. The entire shaded area corresponds to the total uncertainty obtained by resampling all sources (see text) at the same time.

Model inadequacy

Another aspect of uncertainty relevant in climate prediction is model inadequacy, which is one of the sources of the overconfidence of ensemble forecasts over some areas of the globe. The Stochastically Perturbed Parametrization Tendencies (SPPT) method developed at ECMWF was tested in EC-Earth3 to investigate this issue. Several sets of boreal summer and winter 10-member ensemble seasonal re-forecast experiments were run over the period 1993 to 2009. The summer re-forecasts were initialised on 1 May and the winter re-forecasts on 1 November. The experiments explored different options for the time and spatial scales of the perturbations. Figure 4 shows the impact of two combinations of SPPT patterns on the root-mean-square error (RMSE) and ensemble spread as a function of the forecast time for the May initialisations for SST averaged over the NINO3.4 area. While the SPPT3 option uses parameters similar to the ECMWF Seasonal Forecast System 4, SPPT2L favours longer and larger time and spatial scales to take into account the misrepresentation of a number of global-scale atmospheric patterns. These experiments are compared to a reference (REF) ensemble with only initial perturbations. As expected, the SPPT perturbations increase the ensemble spread, and in the case of the NINO3.4 index, they improve the RMSE (as well as other forecast quality measures) of the re-forecast with respect

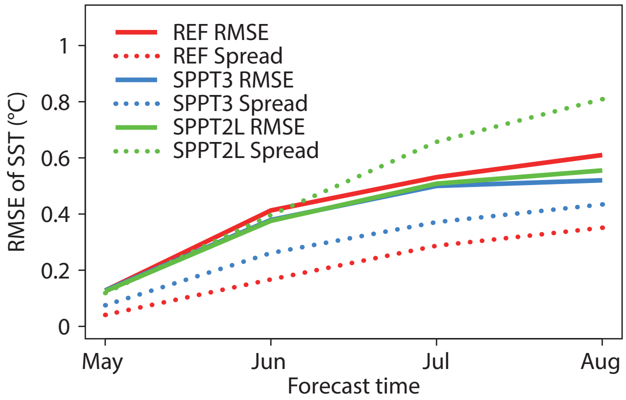

Figure 4 Root-mean-square error (RMSE) of SST predictions averaged over the NINO3.4 region and ensemble spread computed as the standard deviation around the ensemble mean for three 10-member ensemble EC-Earth 3.0.1 re-forecast experiments initialised on 1 May over the period 1993 to 2009 with initial perturbations only (REF) and with additional Stochastically Perturbed Parametrization Tendencies (SPPT) perturbations using different time and spatial correlation scales.

to REF. However, the larger-scale SPPT2L perturbations lead to over-dispersion of the ensemble at longer forecast times, which reflects results found for most variables over the tropical Pacific basin.

Land-surface initialisation

Many EC-Earth experiments have been performed to investigate sensitivity to the initialisation of model components. These include seasonal forecast experiments in which the land-surface scheme of the model is initialised with either climatological or realistic data (taken from a reanalysis). The objective is to estimate the role of the land-surface initialisation in seasonal forecast quality, recognising that the land surface is an untapped source of predictability for near-surface air temperature predictions over land in the mid-latitudes. The experiment showed that the model manages to capture a positive feedback between high temperature and low initial soil moisture content. Such feedback tends to dominate over other processes in re-forecasts of the warmest summers in Europe. This result has been confirmed using both versions of the model at both standard and high resolutions.

An innovative exercise that can be undertaken with this type of sensitivity experiment is to estimate to what extent the resulting differences in forecasts are relevant for climate prediction users. Such an exercise was carried out by formulating seasonal maize yield predictions for European countries based on empirical climate-yield relationships and using the re-forecasts of the two land-surface sensitivity experiments as climate input. Figure 5 shows re-forecasts of maize yield in 2003 and 2007 calculated using an empirical stress index that estimates the impact of heat and drought stress events on maize yield anomalies.

In 2003, the observed yield anomalies were in the lowest quartile for all countries except the former Yugoslav Republic of Macedonia and Romania. The predictions obtained with the experiment with realistic soil moisture initialisation suggest an anomalously low yield for re-forecasts starting as early as May. The forecast probability of a low yield event increases when using re-forecasts initialised in June, particularly over south-eastern Europe. Yield estimates that use re-forecasts initialised with climatological soil moisture show lower probabilities for the observed category.

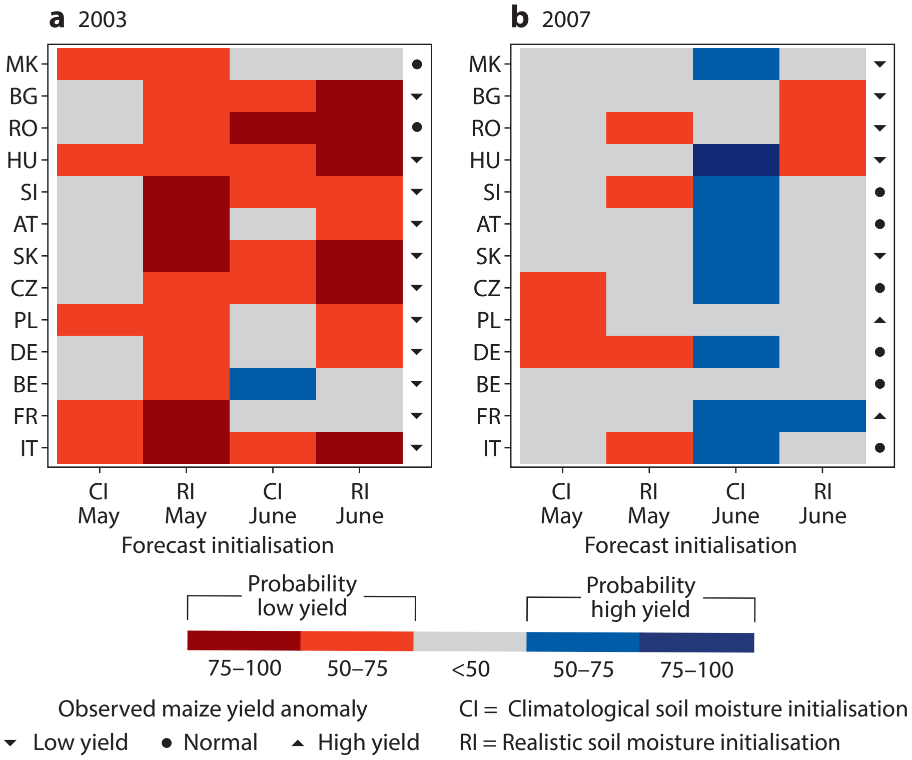

Figure 5 Forecast probabilities for low- or high-yield events (maize yield anomaly in the lower quartile or the upper quartile, respectively) in different countries in (a) 2003 and (b) 2007. The shading indicates the probability of such events from different seasonal re-forecast experiments performed with EC-Earth2.3 initialised with land-surface climatological (CI) and realistic (RI) conditions on 1 May and 1 June. The observed maize yield anomaly is indicated on the right-hand side of each panel. The countries listed from top to bottom are the former Yugoslav Republic of Macedonia, Bulgaria, Romania, Hungary, Slovenia, Austria, Slovakia, the Czech Republic, Poland, Germany, Belgium, France and Italy.

In 2007, south-eastern Europe experienced a severe summer drought and a heat wave, resulting in substantially negative maize yield anomalies. Yield estimates that use re-forecasts initialised in June with climatological soil moisture fail to indicate high probabilities for low yield in the region, while those from the re-forecasts with realistic land-surface initial conditions show slightly higher probabilities for a low yield anomaly. At the time of the re-forecast initialisation in both May and June, soil moisture levels were depleted due to a persisting drought from the preceding winter in most of central and south-eastern Europe. A forecast quality assessment over the period 1981–2010 clearly demonstrates the overall benefit of land-surface initialisation of climate predictions for maize yield forecasting in Europe. It also illustrates the benefits that can be obtained when climate modellers work with users.

Decadal predictions

EC-Earth has been one of the pioneering models used in the development of decadal climate prediction, defined as climate simulations for forecast periods up to ten years into the future. Decadal prediction relies on the combined result of a forced component due to changes in atmospheric composition, such as greenhouse gases, aerosols and other species of anthropogenic and natural origin, and an internal variability component that is initialised with current conditions. Decadal forecast systems have shown skill in predicting global near-surface air temperatures compared to climate projections for the same forecast period. The skill of EC-Earth2.3 as a decadal forecast system is illustrated in Figure 6. Skill is particularly high over the North Atlantic and Europe, among other regions. A large part of the predictable signal in temperature is due to the forced component of temperature variations associated with recent changes in atmospheric composition. This is also reflected in climate projections. However, decadal predictions offer a more credible estimate of the amplitude of the forced signal than climate projections. More regionally, the North Atlantic has been singled out as one of the main regions that can benefit from decadal prediction. This is due to the ability of current systems to correctly predict the phase and amplitude of the Atlantic Multidecadal Oscillation, which impacts on the multiannual climate variability of the neighbouring continents, for at least several years ahead.

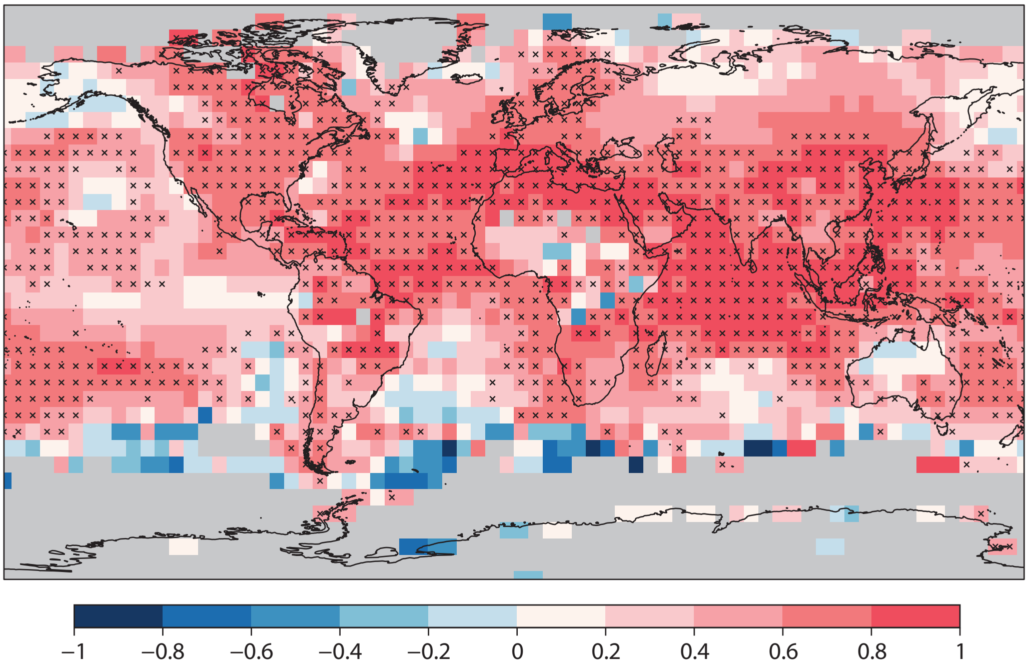

Figure 6 Correlation of five-member ensemble-mean predictions of near-surface temperature averaged over the forecast years 1 to 5 performed with the EC-Earth model over the period 1960–2016. One start date per year starting on 1 November was used. The observational reference is HadCRUT4. Areas with statistically significant correlation at the 95% level are marked by crosses.

Extreme event attribution

Climate prediction systems are increasingly considered in the context of the attribution of extreme events. Extreme event attribution deals with similar challenges as climate prediction (e.g. systematic errors, lack of reliability) albeit from an ex-post perspective instead of the ex-ante stand adopted by climate prediction. Both communities are quickly learning to work together on aspects such as the importance of the initialisation or the reliability of the simulations. Extreme event attribution uses a multi-method approach to make probabilistic statements about the physical mechanism that might explain events with scientific interest and social impact. EC-Earth regularly contributes to this kind of exercise, not only in coordinated studies such as the annual report on 'Explaining Extreme Events from a Climate Perspective' of the Bulletin of the American Meteorological Society, but also to address specific questions from users. Figure 7 shows an example of the latter where the probability distribution of the 10-metre wind speed over a region in south-western North America has been drawn from three different ensemble simulations with specified SSTs and sea ice covering the late winter of 2015. That year an important negative wind anomaly highly relevant to the wind energy industry occurred. In one ensemble simulation the atmospheric component of EC-Earth was forced with observed SSTs and sea ice (INI). In a second experiment (TROP), the SSTs were as observed in the tropics and SSTs were climatological elsewhere, and in a third one (CLIMSST), climatological SSTs were used. The CLIMSST distribution shows that without the SST anomalies such a low wind speed episode would have been very unlikely, while the tropical SSTs play a central role in generating the anomaly. Singling out the role of the extra-tropical SSTs requires additional simulations where the observed SSTs are only specified in the North Pacific.

While working on these examples and many more, a number of young scientists have been trained in the formulation, validation and use of climate predictions. These scientists could at the same time engage in discussions and research projects involving users, offering them a wider perspective of what research in climate prediction might become in the near future.

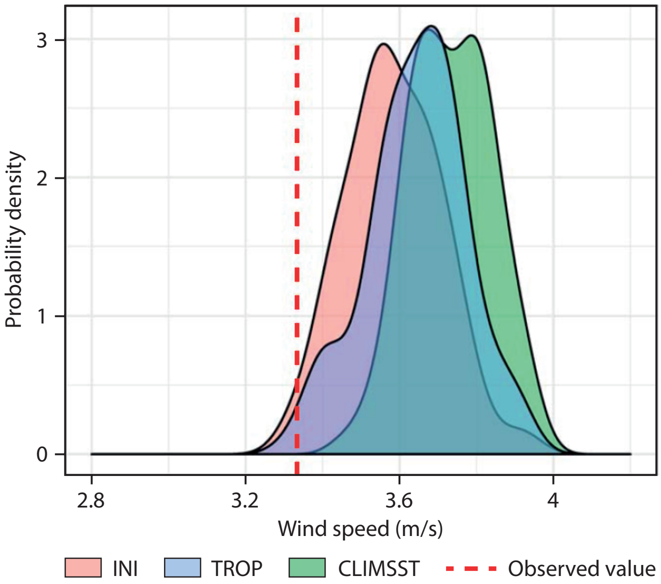

Figure 7 Probability distribution of mean wind speed in the south-western North America region (124°W–95°W, 26°N–44°N) for three different ensemble EC-Earth3.1 simulations with prescribed sea-surface temperature and sea ice covering the period January–February–March 2015. INI was forced with observed SSTs and sea ice, CLIMSST with climatological SSTs, and TROP with observed SSTs in the tropics only. The vertical dashed line indicates the ERA-Interim observed value.

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Outlook

The possibilities that EC-Earth as a climate prediction research tool offers to the community are immense. As an ESM with state-of-the-art complexity, EC-Earth is now used to explore the predictability of the carbon cycle, one of the key aspects of the global stocktake process currently under discussion; the role of interactive aerosols; the complex relationship between sea ice and atmospheric circulation in lower latitudes to improve forecasts for the next few weeks; the sensitivity of forecasts to the specification of some forcings (e.g. volcanic aerosol load). These and many other issues were beyond the reach of most European climate scientists until recently.

While EC-Earth has been, and will continue to be, used as a research tool for climate prediction, there is a way in which EC-Earth is providing real-time information. One of the objectives of the World Climate Research Programme's Grand Challenge on Near-Term Climate Prediction is to set standards for the operationalisation of decadal prediction. One of the activities in this context is the exchange of decadal predictions issued once a year between institutions with this capability. The BSC (Barcelona Supercomputing Center) is contributing decadal predictions performed with EC-Earth to this exercise and plans to become a contributing centre to the future Lead Centre on Near-Term Climate Prediction.

The use of a frozen atmospheric model, largely outdated for ECMWF's purposes, has limited the feedback that EC-Earth could offer ECMWF. The use in the near future of OpenIFS for the atmospheric component in EC-Earth will strengthen the links between ECMWF and the consortium. OpenIFS is based on more recent IFS model cycles. Results obtained by EC-Earth using an ESM that incorporates OpenIFS cycles will thus be more relevant for IFS development work. The possible feedback that EC-Earth can offer with this new approach goes well beyond the development of physical aspects in the model. There is also intense collaboration already taking place on computational aspects. For instance, a substantial amount of work is already being carried out to improve the computational performance of both EC-Earth and OpenIFS. In particular, substantial efforts are being made to assess the impact of different coupling strategies to achieve an optimal load balance of the coupled model and to incorporate a portable I/O server into the IFS that could soon be inherited by OpenIFS.

This article should be read not as a comprehensive summary of the large amount of climate prediction research activities for which EC-Earth is used, but rather as an illustration of the advantages that developing a European community model can offer and of the opportunities brought by continuing and enhancing the close collaboration between EC-Earth and ECMWF.

Further reading

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