SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	High-resolution climate prediction with EC-Earth
Computer Project Account:	SPESICCF
Start Year - End Year :	2015- 2016
Principal Investigator(s)	Francisco J. Doblas-Reyes
Affiliation/Address:	Barcelona Supercomputing Centre
Other Researchers (Name/Affiliation):	Eleftheria Exarchou, Chloé Prodhomme, Virginie Guemas, Juan Camilo Acosta Navarro, Neven Fučkar (Barcelona Supercomputing Centre)

The following should cover the entire project duration.

Summary of project objectives
(10 lines max)

The main objective of SPESICCF has been to investigate the impact of increased resolution in both the ocean and the atmosphere on seasonal prediction quality. We have compared seasonal predictions performed with the high and standard resolution configurations of EC-Earth3. This corresponded to an increase in horizontal and vertical resolutions by a factor of 4 and 2 approximately. Motivated by the important role of the ocean in seasonal prediction, we have also investigated the impact of ocean initialisation by using initial conditions from three different ocean reanalysis datasets, namely GLORYS2V1 (produced by MERCATOR, Toulouse, France), ORAP5 (produced by ECMWF, Reading, UK), and GLOSEA5 (produced by MetOffice, UK). We illustrate below the results in terms of skill and drift behaviour in the tropics and the extratropics.

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

We found an unexpected behaviour of some simulations using the CCA platform. In particular, one experiment using our high-resolution configuration did not work. We noticed in this experiment that the MPI communications, used to transfer information among components that are using different binaries, did not work correctly, missing some of the messages from the senders to the receivers. This produced a blocking where some MPI processes are waiting indefinitely for messages which never reach the destination, wasting at the same time our simulation hours produced by this blocking.

We think that this problem could be related to the platform, the compiler version and the IntelMPI libraries for two reasons. The first one is that the standard configuration works, using the same model and configuration environment to compile and run. The only difference would be the input data and the number of processes used. The second one is that we run the same high-resolution configuration using another platform (Marenostrum3 at BSC) without any problem.

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

We had a very good experience with this framework. It offers to us some additional computing resources beyond what we use from the BSC and PRACE to perform climate experiments. Besides, having access to a different platform helps us to single out computational problems in the code. Finally, the access to the ECMWF systems favours the collaboration with the rest of the EC-Earth partners.

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.)

I. Model and experiments

The seasonal forecasts performed for this project have been run with the EC-Earth climate model version 3.1. An earlier version of the EC-Earth, which was used in CMIP5, is described in detail in Hazeleger et al. (2012). The main differences between these two versions are an improved radiation scheme (Morcrette et al., 2008) and a new cloud microphysics scheme (Forbes et al., 2011). We use EC-Earth3.1 on two different horizontal resolution configurations, the high and standard resolution (hereafter HR and SR), respectively.

The atmosphere component of EC-Earth3.1 is the Integrated Forecasting System (IFS) cycle 36r4, of the ECMWF. HR and its T511 spectral resolution, corresponds to approximately 0.35◦ in latitude and longitude, while for SR (T255 spectral resolution) this number is about 0.7◦. Both HR and SR use 91 vertical levels (up to 1 Pa).

The ocean component of EC-Earth3.1 is the version 3.3.1 of NEMO (Madec, 2008), at the ORCA025 (HR) and ORCA1 (SR) configurations, which correspond to a resolution of about 0.25◦ and 1◦, respectively. The Louvain-la-Neuve Sea Ice Model version 2, LIM2, (Fichefet and Maqueda, 1997; Bouillon et al., 2009) is included in NEMO, with dynamics based on Hibler (1979) and thermodynamics based on Semtner (1976). The atmosphere and ocean sea-ice components of EC-Earth are coupled with the Ocean Atmosphere Sea Ice Soil coupler version 3 (OASIS3; Valcke, 2006).

We have completed four sets of ensemble seasonal hindcasts, also referred to as retrospective forecasts. Each set comprises of 4 month-long simulations initialized every 1st of May and every 1st of November between 1993 and 2009. Each ensemble consists of at least 3 different members, with some ensembles reaching up to 10 members (the details are summarized in Table 1). These sets of forecasts differ in two aspects: three sets of forecasts, which are run with the HR configuration, are initialized from different oceanic initial conditions, namely GloSea5 (MacLachlan et al., 2015), ORAP5 (Zuo et al, 2015) and GLORYS2V1 (Ferry et al., 2010). These experiments are referred to as HR-GLOSEA5, HR-ORAP5, and HR-GLORYS, respectively. Also, one set of forecasts is run with the SR configuration, and its ocean is initialized from GLORYS2v1 interpolated to the 1◦ grid (this experiment is referred to as SR-GLORYS).

In all experiments, the sea ice is initialized from GLORYS2V1 and the atmosphere from ERA-Interim (Dee et al., 2011). We assess these forecasts in their bias in sea surface temperature and in their skill in predicting the tropical climate variability (section II) and in their skill in predicting the surface air temperature in the Northern Extratropics (section III).

Exp name	Ocean resolution	Atmosphere resolution	Initial conditions for the ocean	Number of ensemble members
HR-GLOSEA5	ORCA025L75	T511L91	GLOSEA5	5
HR-ORAP5	ORCA025L75	T511L91	ORAP5	3 (November start dates) - 5 (May start dates)
HR-GLORYS	ORCA025L75	T511L91	GLORYS	10
SR-GLORYS	ORCA1L46	T255L91	GLORYS	10

Table 1: Summary of the experiments discussed. All experiments are four-month-long forecasts, initialized every 1st May and every 1st November from 1993 to 2009.

Regarding storage space, the experiments have been run using Autosubmit, the launching and monitoring solution developed by the BSC group that allows the remote submission of EC-Earth

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and NEMO experiments. Autosubmit includes in the workflow of the experiments a job that retrieves the data back to the local storage at the BSC Earth Sciences Department as soon as each chunk of simulation has completed, releasing space in both the scratch filesystem and the permanent storage at ECMWF. This means that we ended up not using any permanent storage at ECMWF for the experiments.

II. Model bias and prediction skill in the tropics

The model sea surface temperature (SST) bias, defined here as the difference between the average of the ensemble-mean predictions starting at different dates (1993-2009) and the observed mean SST over the same period (the reference observational dataset is HadISST1, Rayner 2003) is shown in Figure 1. The main features that systematically appear in all experiments and in all start dates (only simulations initialised in May and November are shown here) comprise a pronounced cold bias in the equatorial Pacific and a pronounced warm bias in the southeastern subtropical Atlantic. Both biases are stronger in the summer months (JJA, top row in Figure 1) than in winter months (DJF, bottom row in Figure 1).

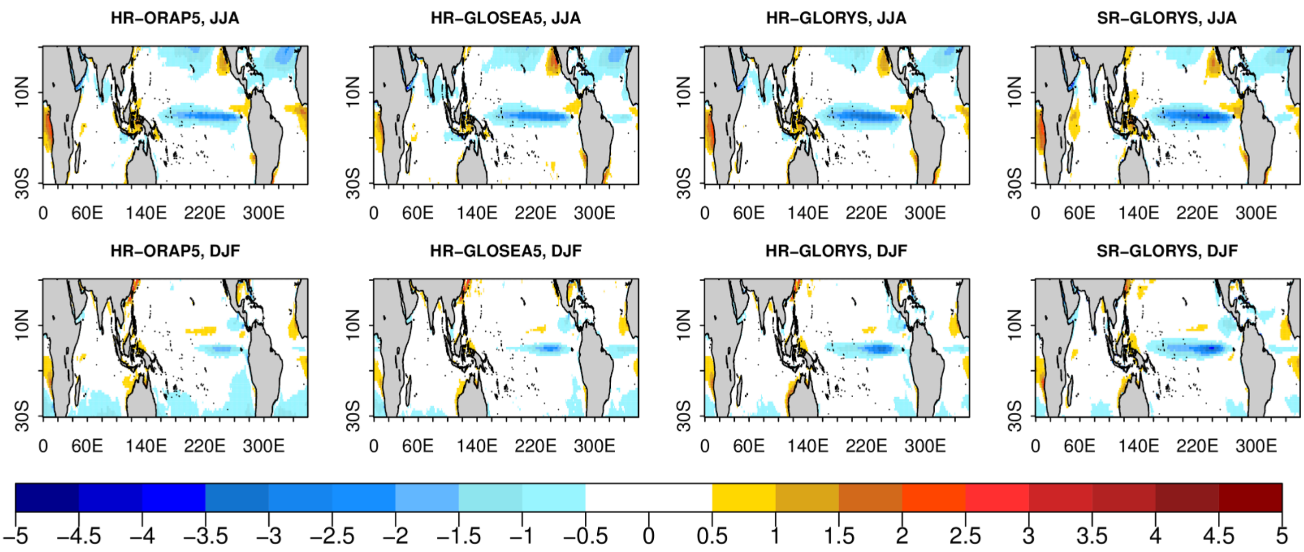

Figure 1: Model bias in SST during boreal summer (JJA, top row) and boreal winter (DJF, bottom row), defined as the difference between the seasonal forecasts initialized on 1st May (top row) or 1st November (bottom row) and observations from HadISST for 1993-2009.

The largest impact on those biases comes from the selection of ocean initial conditions rather than the model resolution. There is only a modest improvement in the cold equatorial pacific bias and in the warm southeastern atlantic bias caused by the increase in resolution (HR-GLORYS with respect to SR-GLORYS). The cold bias, however, is notably improved in HR-ORAP5 and in HR-GLOSEA5 with respect to both HR-GLORYS and SR-GLORYS. Similarly, the warm bias is significantly reduced in HR-GLOSEA5 with respect to the other three forecasts.

We assess the forecast skill in predicting climate variability in the tropics using the anomaly correlation coefficient (ACC) between the ensemble mean predictions and observations (Figure 2). We further show the forecast skill in predicting the SST in the Niño3.4 (5S-5N and 170-120W) and in ATL3 (3S-3N and 20W-0) regions (Figure 3). There is no robust relationship between skill and model resolution: HR-GLORYS has higher skill in Niño3.4 in JJA than SR-GLORYS (Figure 3), but a lower skill in the Southeastern Atlantic and Southwestern Pacific in DJF (Figure 2). Skill in the Atlantic does not relate to skill in the Pacific. For example, the highest skill in Niño3.4 in the May-initialized forecasts is achieved in HR-GLOSEA5 and HR-ORAP5, which have the lowest skill

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in ATL3 (Figure 3). Finally, weaker model biases, do not imply higher model skill in the tropics: HR-GLOSEA5 has particularly low skill in the tropical Atlantic (Figures 2 & 3), despite having the smallest bias among all forecasts in this region (Figure 1).

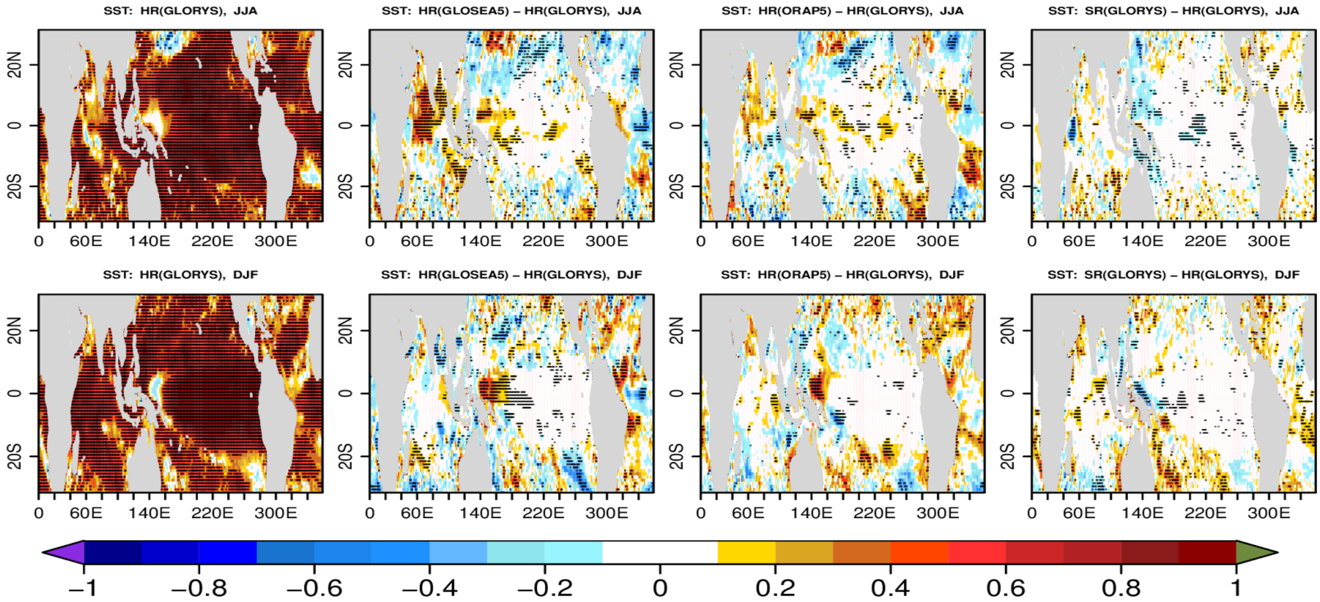

Figure 2: Prediction skill in SST for the summer forecasts (top) and the winter forecasts (bottom), shown as the correlation between anomalies of the ensemble mean predictions with the ERA Interim SST. From left to right: HR-GLORYS, HR-GLOSEA5 minus HR-GLORYS, HR-ORAP5 minus HR-GLORYS, SR-GLORYS minus HR-GLORYS. Hatched patterns indicate where the differences are statistically significant at the 95% confidence level.

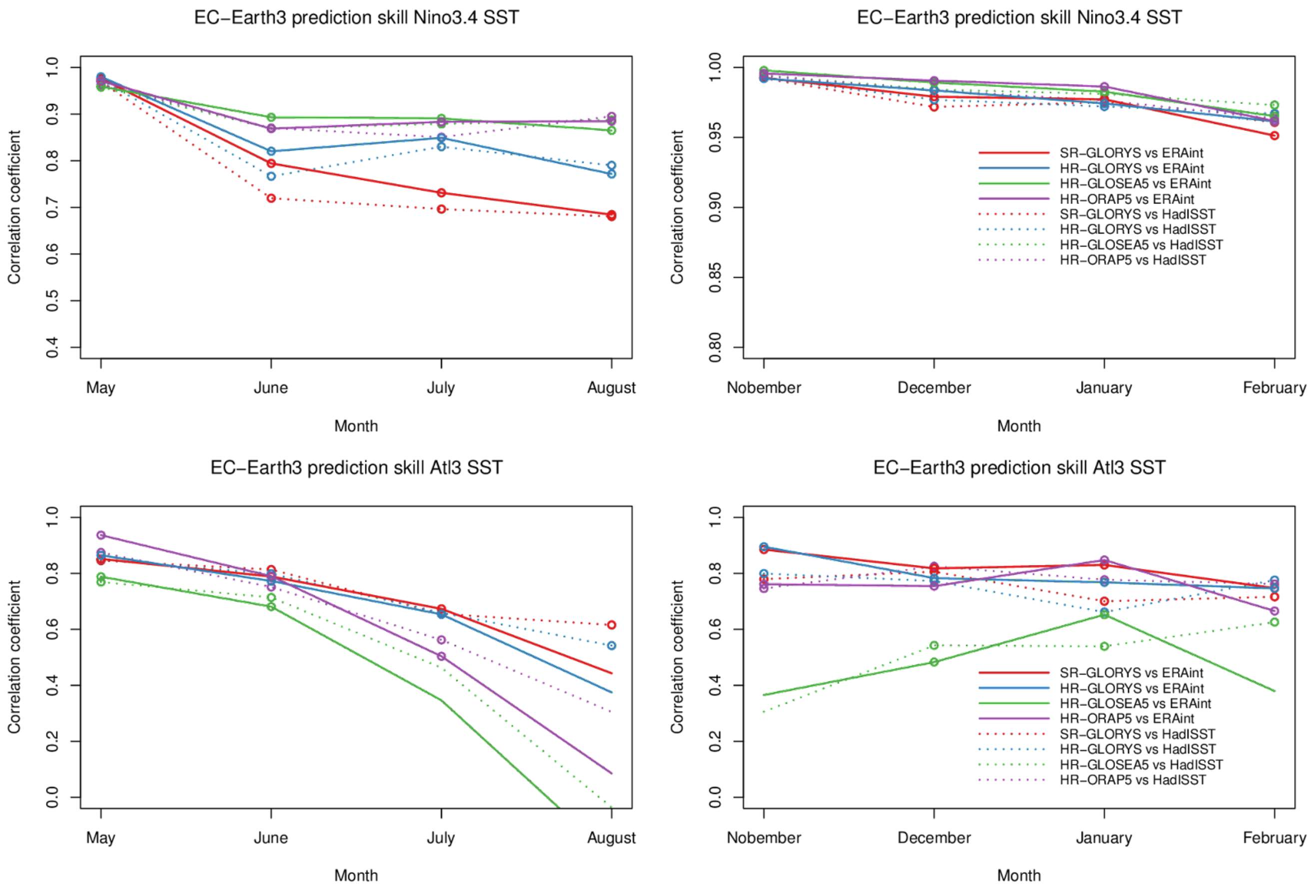

Figure 3: Prediction skill in SST in the Niño3.4 region (top row) and amd the ATL3 region (bottom row) for the summer forecast (left) and the winter forecast (right), shown as the correlation of the ensemble mean prediction with two different

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observational datasets (ERA Interim and HadISST). Circles denote statistically significant values at the 95% confidence level.

III. Model prediction skill in the Northern Hemisphere Extratropics

Finally, we examine the forecast skill of summer (JJA) and winter (DJF) surface air temperature (SAT) in the Northern Hemisphere (NH) extratropics with ACC between the ensemble mean predictions and HadCRU4 observations (Figure 4).

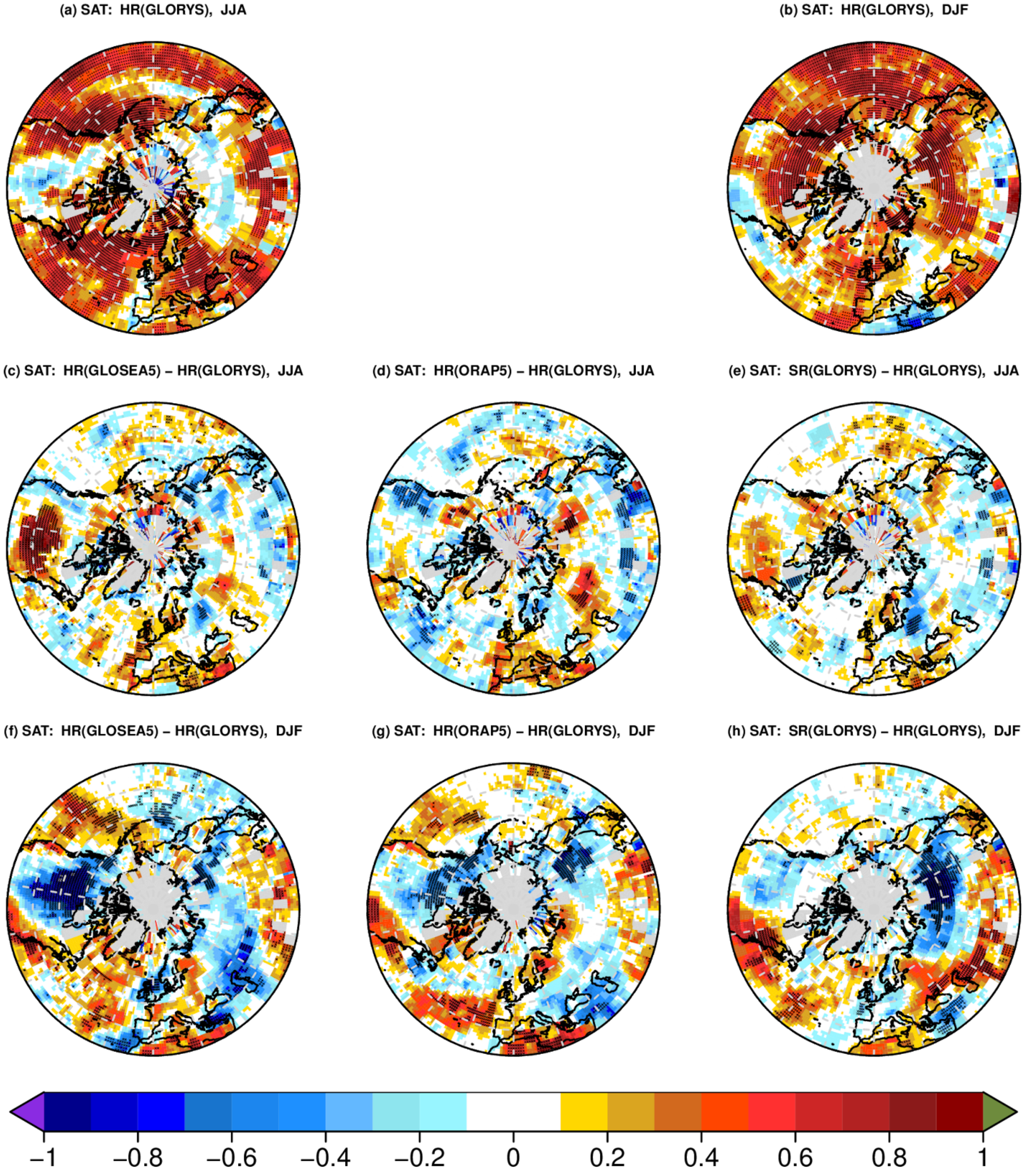

Figure 4: Prediction skill of surface air temperature (SAT) for the summer forecasts (JJA) and the winter forecasts (DJF), shown as the anomaly correlation coefficient (ACC) between anomalies of the ensemble mean predictions and HadCRU4 SAT, as well as some of their differences. Presented panels are organized in the following manner: (a) and (b) show HR(GLORYS), (c) and (f) show HR(GLOSEA5) minus HR(GLORYS), (d) and (g) show HR(ORAP5) minus

HR(GLORYS), (e) and (h) show SR(GLORYS) minus HR(GLORYS). Stippled patterns show where the ACC and selected differences are statistically significant at a 95% confidence level.

The ACC in HR-GLORYS is positive and significant in central and eastern Europe as well as western North America in summer (Figure 4a), while during winter positive and significant skill is found in northern North America and over Asia (Figure 4b). Over the North Atlantic (North Pacific) ocean, the ACC tends to be higher in summer (winter) than in winter (summer) in HR-GLORYS. Figures 4c and 4f show that the change of oceanic initial conditions from HR-GLORYS to HR-GLOSEA5 has a significant impact on ACC over North America: ACC is mostly increased (decreased) in summer (winter). Changing the initial conditions from GLORYS to either GLOSEA5 or ORAP5 improves the summer ACC in the Mediterranean sector and some parts of the Atlantic sector just off the coast of western Europe (Figures 4c-d-f-g). Decreasing the resolution (Figures 4 e-h) significantly decreases the winter ACC in the north of Asia, but simultaneously increases the ACC over the northeastern North America. Overall, the middle and bottom panels in Figure 4 show that the choice of ocean initial conditions has a stronger impact on the forecast skill of JJA and DJF SAT than the forecast resolution.

References

Zuo, H., M.A. Balmaseda and K. Mogensen, 2015. The new eddy-permitting ORAP5 ocean reanalysis: description, evaluation and uncertainties in climate signals. Climate Dynamics, doi:10.1007/s00382-015-2675-1.

Dee, D. et al., 2011. The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society, 137, 553-597.

Ferry, N. et al., 2010. Mercator global eddy permitting ocean reanalysis GLORYS1V1: Description and results. Mercator Ocean Quart. Newsl 36, 15-27.

Forbes, R.M., A.M. Tompkins and A. Untch, 2011. A new prognostic bulk micro-physics scheme for the IFS. ECMWF Tech Memo 649.

Morcrette, J., H. Barker, J. Cole, M. Iacono and R. Pincus, 2008. Impact of a new radiation package, mcrad, in the ecmwf integrated forecasting system. Monthly Weather Review, 136, 4773-4798.

Hazeleger, W. et al., 2012. EC-Earth v2.2: description and validation of a new seamless earth system prediction model. Climate Dynamics, 39, 2611-2629.

MacLachlan, C., A. Arribas, K.A. Peterson, A. Maidens, D. Fereday, A.A. Scaife and J. Camp, 2015. Global Seasonal forecast system version 5 (GloSea5): a high-resolution seasonal forecast system. Quarterly Journal of the Royal Meteorological Society, 141, 1072-1084.

Rayner, N.A., 2003. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. Journal of Geophysical Research, 108, 4407, doi:10.1029/2002JD002670.

Madec, G., 2008. Nemo ocean engine.

Fichefet, T. and M. Maqueda, 1997. Sensitivity of a global sea ice model to the treatment of ice thermodynamics and dynamics. Journal of Geophysical Research, 102, 12609-12646.

Bouillon, S., M.A.M. Maqueda, V. Legat and T. Fichefet, 2009. Sea ice model formulated on Arakawa B and C grids. Ocean Modelling, 27, 174-184.

Hibler, W. D., 1979. A dynamic thermodynamic sea ice model. J. Phys. Oceanogr., 9, 815-846.

Semtner, A.J., 1976. A model for the thermodynamic growth of sea ice in numerical investigations of climate. J. Phys. Ocean., 6, 379-389.

Valcke, S., 2006. OASIS3 user guide (prism_2-5). PRISM support initiative report, 3, 64.

List of publications/reports from the project with complete references

Exarchou, E., C. Prodhomme, L. Brodeau, V. Guemas and F.J. Doblas-Reyes, 2017. Origin of the warm eastern tropical Atlantic SST bias in a climate model. Submitted to Climate Dynamics.

Massonnet, F., O. Bellprat, V. Guemas and F. J. Doblas-Reyes, 2016. Using climate models to estimate the quality of global observational data sets. Science, 6311, 452-455, doi:10.1126/science.aaf6369.

Prodhomme C., L. Batte, F. Massonet, P. Davini, O. Bellprat, V. Guemas and F.J. Doblas-Reyes, 2016. Benefits of increasing the model resolution for the seasonal forecast quality in EC-Earth. Journal of Climate, 29, 9141-9162.

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 follow-up special project has been submitted and accepted: HighResMIP_BSC. This project also focuses on the impact of increased resolution in both the atmosphere and the ocean, comparing similar resolutions as the one considered in SPESICCF. However, the context and experimental setup are different: this time the focus is on historical simulations and climate change projections until 2050 rather than climate predictions. Instead of assessing the role of resolution on seasonal forecast quality, we evaluate the role of resolution on the representation of climate variability on interannual to decadal timescales, teleconnection and climate sensitivity using EC-Earth3. We follow the common experimental protocol of the HighResMIP project endorsed by CMIP6 (Coupled Model Intercomparison Project Phase 6). Our experiments will be therefore publicly distributed and contribute to the CMIP6 database, as well as the model intercomparison studies to be carried out using this database.