SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Sensitivity of multi-annual forecasts to model resolution
Computer Project Account:	SPITCORT
Start Year - End Year :	2014- 2016
Principal Investigator(s)	Susanna Corti
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The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

This is a three-year project, which aims to investigate the sensitivity of multi-year forecasts to model resolution. During the first project year it was planned to assess the sensitivity to the atmospheric model resolution. In the following project years, depending on the results of the experiments carried out during the first year, it was planned to assess the sensitivity to the ocean model resolution. Such sensitivity should have been assessed by a set of integrations with a suitable versions of the ECMWF coupled system (including the Sea-Ice interactive module LIM2) where ocean resolution is kept at the standard ~1˚ or increased to ~0.25˚, while atmospheric resolution is increased from T255 (~80 km) to T511 (~40km). However, due to problems in finding an acceptable configuration for ORCA025, we decided to keep investigating the impact of model resolution in long climate hindcast simulations (atmospheric-only and coupled) using the EC-Earth model, version 3.1.

Summary of problems encountered

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

The set of experiments planned for the second project year was a set of three-year long integrations using a complete high-resolution coupled system (HRCTL 10-3-1: 10 starting dates, 3-year long, 1 ensemble member). The configuration chosen consists of IFS Cycle 40R1 integrated at T511L91 coupled with the ocean model NEMO ORCA025 (0.25˚). In this configuration we were supposed to repeat the same hindcasts as in the control (CTL 10-3-5; i.e. IFS at T255L91 coupled with NEMO ORCA1) and in the atmospheric high-resolution experiments (HRA 10-3-5; i.e. IFS at T511L91 coupled with NEMO ORCA1). These experiments were set to estimate how much the improvement of the key ocean processes, such as for example ocean convection and the representation of ocean currents, impacts the ability of the models to simulate important modes of variability (for example ENSO and the Atlantic Meridional Overturning Circulation), which in turn influence the extended range predictability over remote continental regions (via teleconnections).
However, due to serious problems in finding an acceptable configuration for NEMO ORCA025 coupled with T511L91, both in terms of computing time efficiency and in terms of stability of the configuration, we decided to change strategy and dismiss the HRCTL 10-3-1 and the HRO-22-3-5 experiments planned for the 2nd and 3rd project years. The computer time allocated for year 2015 was used to carried out two different sets of experiments: 1) Multi-year SWAP experiments with three starting dates and 2) Atmospheric seasonal forecasts of the 20th Century starting from ERA20C reanalysis. Whilst the computer time for year 2016 was used to perform coupled and atmospheric-only AMIP simulations with the EC-Earth model at different resolutions and with the inclusion (or not) of the stochastic physics parameterisations. These latter integrations integrate and complement twin simulations already carried out with the same model version on a different platform and they are currently investigated as part of the H2020 EU-project PRIMAVERA.

Experience with the Special Project framework

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

Our experience with the ECMWF Special Project framework has been more than positive. We haven't experienced any particular issues and everything went on very smoothly.

Summary of results

Impact of increased atmospheric resolution on model mean state and forecast quality in multi-year hindcasts

Here we report the results of the following experiments:

1) A control (CTL) series of hindcasts with the atmospheric model integrated at T255 (~80km) with 91 levels in vertical (this is the current resolution of the ECMWF System4 coupled model for seasonal predictions). The ocean resolution is the standard NEMO-ORCA1 (~1˚). The simulations were started on the 1st of November, once every year over the period 1988 to 2009 (i.e. 22 starting dates), they are 3-year long and for each starting date five ensemble members are available
2) The set up of the second experiment (HRA) is the same as the first one, but the atmospheric component of the coupled system is integrated at T511L91

Both experiments 1) and 2) use IFS cycle 40R1 for the atmosphere, NEMO_V3.0 for the oceanic component (Medec 2008) and the LIM2 sea-ice dynamical component (Goosse and Fichefet 1999). All the simulations were initialized with a full initialization procedure (Magnusson et al. 2013) with NEMOVAR-ORAS4 ECMWF operational analysis (Mogensen et al. 2011). The atmosphere is initialised with ERA Interim (Dee et al. 2011). The sea ice initial conditions have been obtained forcing from a 5-member sea ice reconstruction described in Guemas et al. 2014. The external forcing is based on the CMIP5 recommended historical datasets (Taylor et al. 2012).

Near-surface air temperature from ERA Interim (Dee et al., 2011) are used to evaluate the hindcasts. The reference climatology is taken to be the average of the entire period from 1988 to 2009. To take into account the model systematic error, forecast anomalies for each experiment are calculated as: $X'_{j\tau} = X_{j\tau} - \bar{X}_{k\tau}$ where j is the starting year (j = 1, n), τ is the forecast month (τ = 1,120) and $\bar{X}_{k\tau} = \frac{1}{n-1}\sum_{j\neq k}^{n-1} X_{j\tau}$ is the forecast average estimated in cross-validation mode (i.e., estimated removing the model climate for the specific forecast period, see Doblas-Reyes et al. 2011 for more details).
Observation anomalies are estimated using the average on the period for which both observations and hindcasts are available (per=pairs selection of the years, Garcia-Serrano and Doblas Reyes, 2012), i.e., as: $O'_{j\tau} = O_{j\tau} - \bar{O}_{\tau}$.

Model inadequacy causes forecasts to drift away from the observed climate toward an imperfect-model climate. This drift, which can be understood as the evolving systematic error, depends on the forecast time, especially when using the full-initialization approach (Magnusson et al. 2013).

Figure 1 displays the mean systematic error of near surface temperature for seasonal forecast (i.e for DJF), the first year forecast and for forecast period 1 to 3 years. Results from control and atmosphere high resolution experiments are shown on the left and right column respectively. The experiments have in general air temperatures cooler than the reference, however it is apparent an increase of the systematic error with forecast leading time and a general decrease in the systematic error with the increase of resolution. This is particularly obvious over the oceans, where the cooling is considerably alleviated in HRA, especially over the Pacific tropical band at forecast time longer than one year.

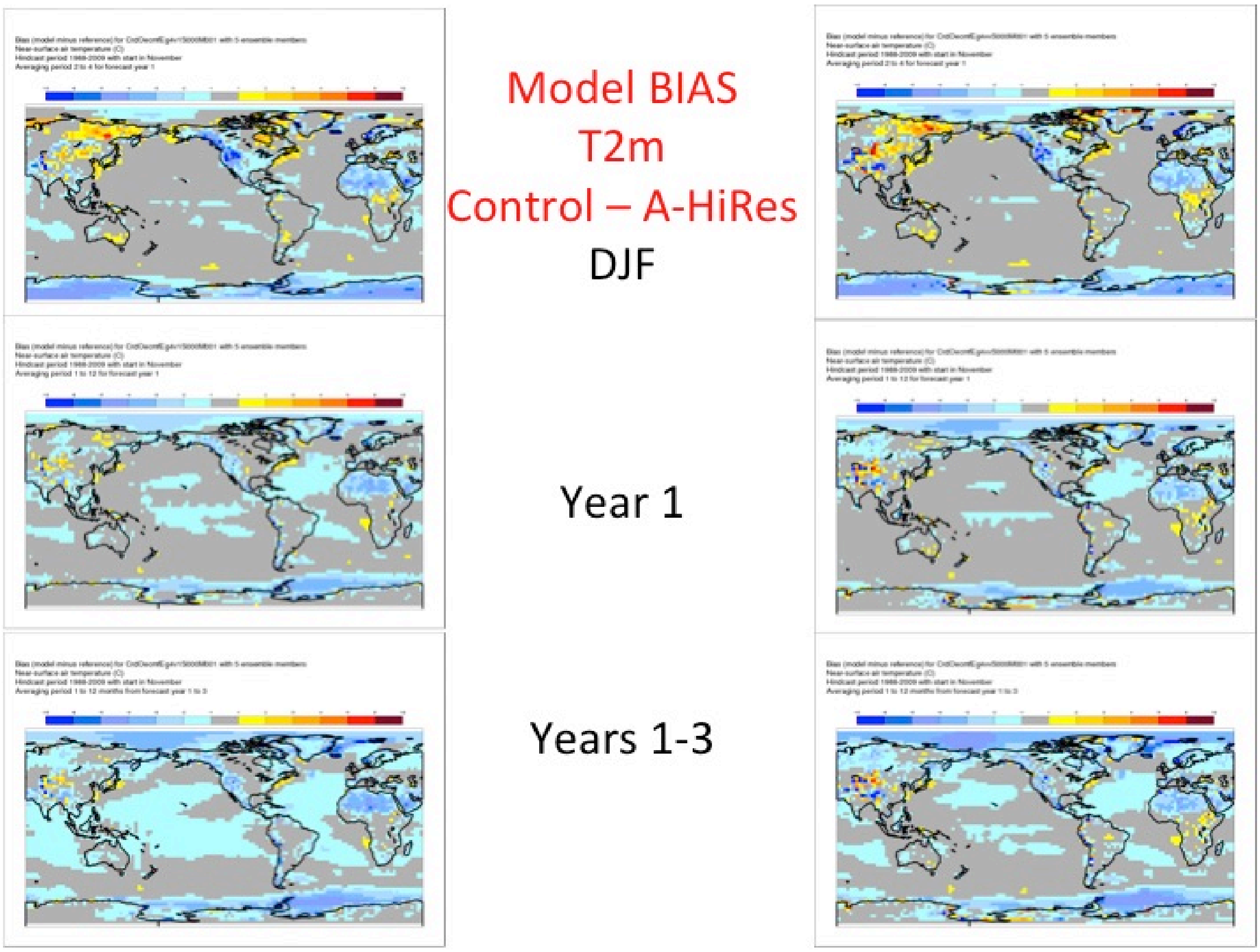

Figure 1. Near-surface air temperature (K) systematic error over the forecast period seasonal (DJF, top row), annual (middle row) and 1 to 3 years (bottom row) of the CTL (on the left) and HRA (on the right) experiments. The systematic error has been estimated with respect to the ERA-Interim dataset. Five-member ensemble reforecasts for the period 1988–2009 have been used.

Figure 2 shows the ensemble mean correlation for near-surface temperature computed for seasonal forecast (i.e. average DJF, one month lead time) and for the forecast period 2 to 3 years. As in figure 1, results from the control experiment are on the left, while the HRA counterparts are on the right. Large areas with positive skill appear in all experiments, a consequence of both correctly projected climate change and forecast initialization. The regions where the impact of high resolution is more apparent are circled in blue. For the seasonal forecast, the most evident improvement is over Europe and Africa. It is interesting to note that high resolution shows a positive (even if not always significant) positive skill over Europe, a region with no skill in the CTL experiment. Indeed, the skill of seasonal predictions over Europe for near-surface temperature in forecasts starting in November is very modest, even when more ensemble members are used. The benefits of high resolution are evident also for the multi-annual forecasts. Figure 2 shows a clear improvement in the anomaly correlation coefficients over the Atlantic sub-polar gyre region, the North Pacific and the African continent. We found similar results (not shown) when other variables (for example the 500 hPa geopotential height and the mean sea level pressure) are considered.

Overall the increase in resolution of the atmospheric component lead to a general increase of the model systematic error at different lead time and to a better forecast quality over selected regions. In general the high resolution forecasts have a better skill over Europe and Africa on a seasonal time-scale and over the North Atlantic, Southern Europe and North Pacific for multi-year forecasts (i.e. year2-3). Some improvements have been also found for the seasonal prediction of precipitation over the Northeastern South-America.

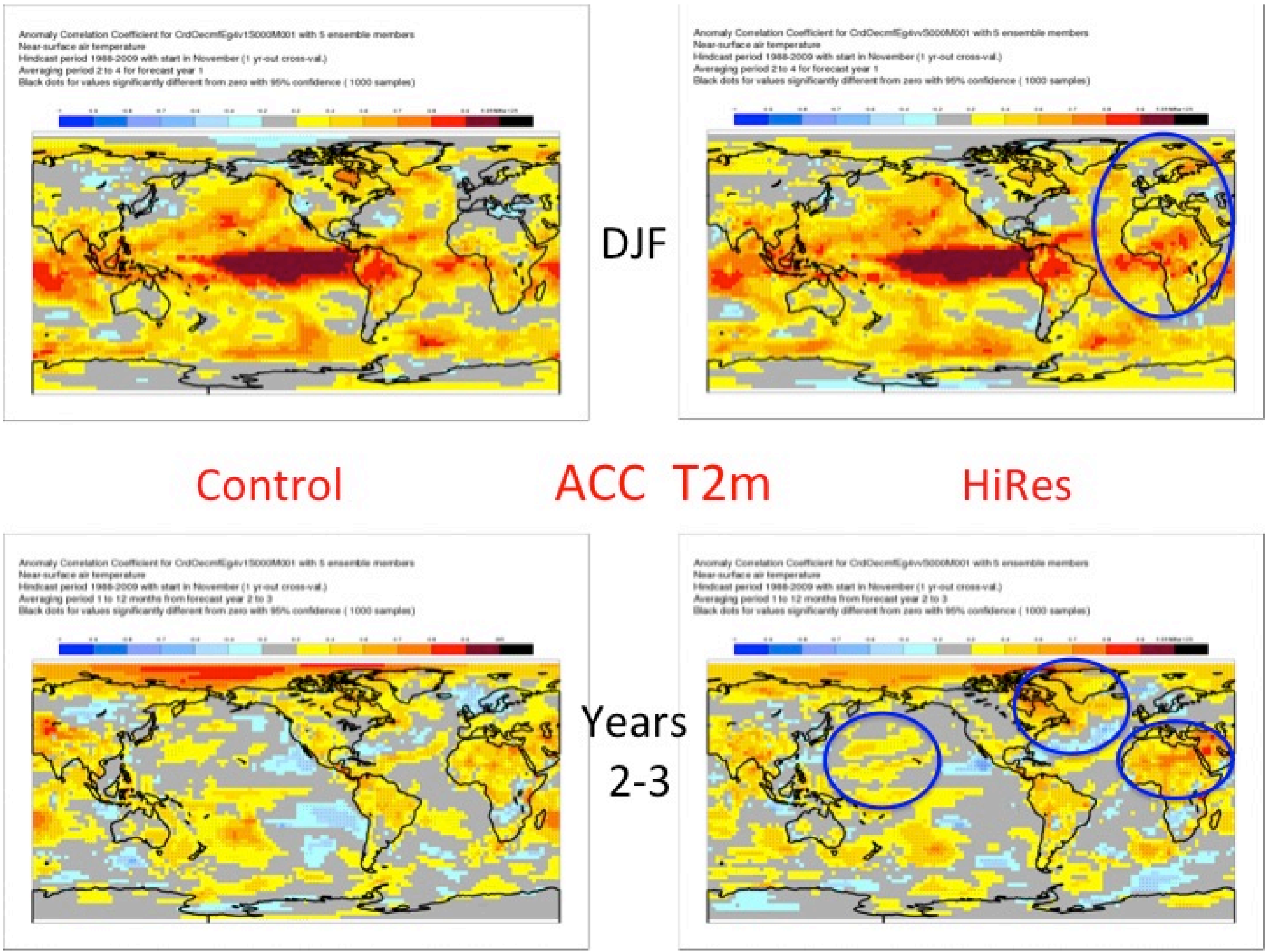

Figure 2. Ensemble mean correlation for near-surface air temperature with respect to the ERA Interim data set over the forecast periods 1 season (DJF top row) and 2 to 3 years of the CTL (left column) and HRA (right column). Five-member ensemble reforecasts for the period 1988–2009 have been used. The black dots depict the grid points where the correlation is significantly different from zero with 95% confidence. Blue circles highlight regions where the impact of resolution is more apparent.

Impact of initial conditions relative to external forcings in multi-year integrations

The Multi-year SWAP is a specifically designed sensitivity experiment set up to assess the impact of initial conditions relative to external forcings in 3-year long integrations. It complements the CTL and HRA series of hindcasts described in the previous section. It consists, for each atmospheric resolution, of three sets of ensemble hindcasts for three initial dates in 1988, 1994 and 2002 (1st of November) using either the external forcings from the "correct" 3-year period or swapping the forcings between the 3-year periods. By comparing the three sets of integrations, the impact of external forcing versus initial conditions on the predictability over multi-annual time scales is estimated. In particular we estimate the sensitivity of the model to initial conditions in predicting the multi-year climate oscillations that modulate the global warming trend. As mentioned above, the Multi-year SWAP experiment has been carried out in the two model configurations, that is at standard resolution with the atmospheric model integrated at T255 (~80km) with 91 levels in vertical, and at high horizontal resolution with the atmospheric component integrated at T511. The oceanic component resolution is the standard NEMO-ORCA1 (~1˚). We run 5 ensemble members for each starting dates.

The Multi-year SWAP integrations extend to three starting dates the experimental setup described in Corti et al. 2015. In that study two sensitivity ensemble integrations were carried out: a decadal hindcast starting in November 1965 was integrated with the forcing from the 1995 decade; similarly a decadal hindcast starting in November 1995 was run with the forcing from the 1965 decade. By comparing the reference and the sensitivity integrations, the relative importance of initial conditions versus the external forcing was assessed. In particular, two estimates of the decadal predictability arising from initial conditions only and two estimates of the predictability driven by the external forcing were obtained.

In the experiment performed here three initial dates, namely, 1988 and 2002 (preceding years of pauses in global warming) and 1994 (preceding years of accelerate global warming), were chosen, and the following nine 3-year-long hindcasts were produced:

1 IC88F88 for 1988 initial conditions and correct observed forcing from 1988;
2 IC94F94 for 1994 initial conditions and correct observed forcing from 1994;
3 IC02F02 for 2002 initial conditions and correct observed forcing from 2002;
4 IC88F94 for 1988 initial conditions and swapped observed forcing from 1994;
5 IC88F02 for 1988 initial conditions and swapped observed forcing from 2002;
6 IC94F88 for 1994 initial conditions and swapped observed forcing from 1988;
7 IC94F02 for 1994 initial conditions and swapped observed forcing from 2002;
8 IC02F88 for 2002 initial conditions and swapped observed forcing from 1988;
9 IC02F94 for 2002 initial conditions and swapped observed forcing from 1994;

The same 9 experiments were repeated at high resolution. By comparing 1) with 6) and 8), 2) with 4) and 9) and 3) with 5) and 7) we have three estimates of the decadal predictability arising from having different initial conditions and the same forcing. By comparing 1) with 4) and 5), 2) with 6) and 7) and 3) with 8) and 9), we have three estimates of the impact of forcing (since initial conditions are identical) on the predictability of climate variables. A schematic of the nine experiments is given in Table 1.

Table 1

Standard Res & High Res	**Boundary Conditions (Forcing)**			
Initial Conditions		**1988**	**1994**	**2002**
	1988	**IC88F88**	**IC88F94**	**IC88F02**
	1994	**IC94F88**	**IC94F94**	**IC94F02**
	2002	**IC02F88**	**IC02F94**	**IC02F02**

***Table 1** Sensitivity experiments. Comparing experiments in the same row gives the impact of forcing. The comparison in the same column gives the impact of initialisation.*

In Corti et al. 2015, where two initial dates were swapped, namely November 1965 and November 1995, it was found that during the first year of integration, the predictability of surface temperature on a global scale arises mainly from the initial conditions. Here in Figure 1 and Figure 2 it is shown that, the previous statement might be not totally independent on the specific initial states (and corresponding forcings) chosen. When 1988 (or 1994) are swapped with 2002, the effect of the forcing in the global mean temperature from the first year of integration is apparent. In both cases (see Figure 1) the simulated global near-surface air temperature anomaly increases when the 2002 forcing is applied to 1988 and 1994 starting dates (and correspondently it decreases when 1988 or 1994 forcing is applied to 2002). On the other hand when 1988 and 1994 forcings are swapped, the simulation of the global mean temperature is almost unchanged (Figure 2).

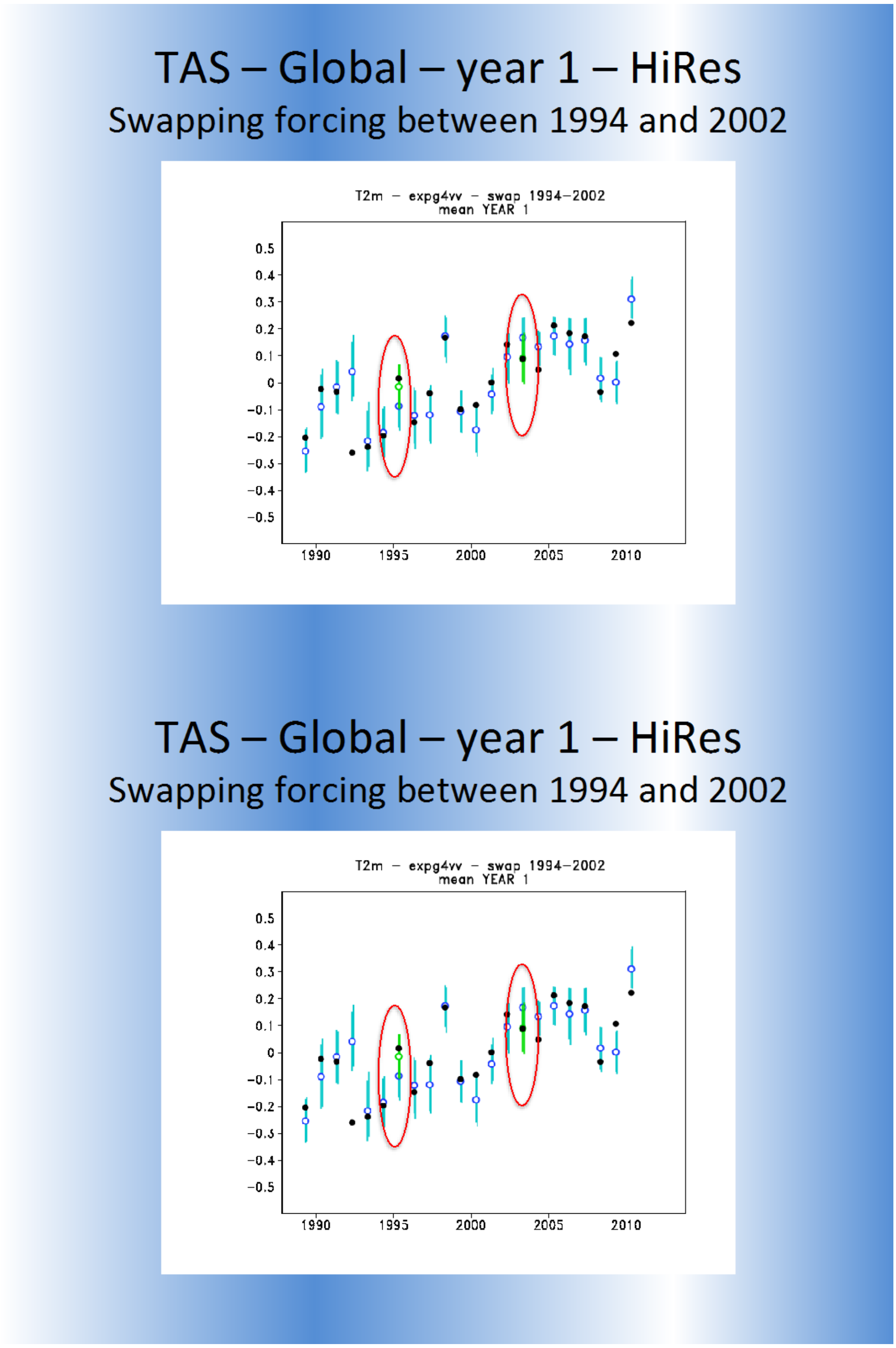

Figure 1. Time series of the near-surface air temperature (K) global mean anomalies observed (black dots) and simulated ensemble means (blue/green dots). Shown are annual means (observations) and the means of the first year of the high-resolution integrations (year-1 means). Bars represent the spread (standard deviation over the 5 ensemble members). Green dots and bars refer to integrations in which the forcing is swapped. Top panel: swapping between 1988 and 2002 forcing. Bottom panel: swapping between 1994 and 2002.

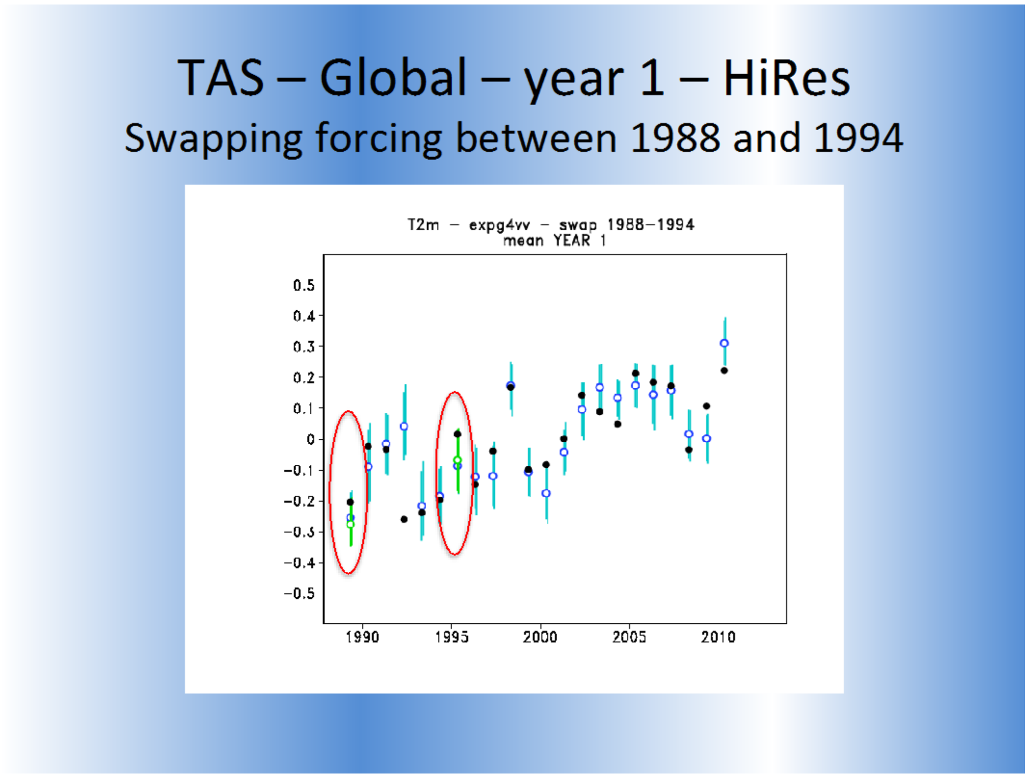

Figure 2. As in Figure 1 for the swapping between 1988 and 1994.

A similar behaviour, i.e. a dependency of the major driver of predictability on the specific chosen dates for the swap, can be found on regional anomalies (not shown). For example over the North Atlantic it was found a high sensitivity to changes in the forcing since the first year of integration for the forecasts initiated in Nov1994 (when the forcing is swapped with Nov1988). On the other hand the swap of forcings between 1988 and 2002 doesn't affect the model simulations for the all length of the integrations. Over the north-western Pacific, consistently with the global case, the forecast sensitivity to the forcing is more pronounced when 1988 (or 1994) are swapped with 2002. Further analyses are necessary to understand what causes this year-sensitive sensitivity of the forcing with respect to initial conditions in different portion of the phase space of the climate attractor.

Increased atmospheric model horizontal resolution doesn't affect the results of the Multi-year SWAP experiment.

Impact of increased model resolution on the Northern Hemisphere blocking

Here we describe the results of a subset of simulations carried out within the Climate SPHINX project (Davini et al., 2017). These are an ensemble of atmospheric-only simulations for 30 consecutive years, from 1979 up to 2008, with forcing according to the historical CMIP5 protocol (*Moss et al.*, 2010). The runs were performed with version 3.1 of the atmosphere-ocean Earth System Model EC-Earth (Hazeleger et al., 2010, 2012) at 5 different horizontal resolutions (from 125 km to 16 km).

The top row of Figure 1 shows the climatology of blocking events frequency averaged over the extended winter season (December to March, DJFM) for the 1979-2008 period. The e
mean of the five resolutions explored in Climate SPHINX is here plotted.
areas of blocking are identified, over the Pacific and the Atlantic basins. Th
events frequency is found over the Pacific at high latitudes. Conversely over the Atlantic sector a first relative maximum is seen over Greenland -which is as
and a second one over Europe - which (Masato ... defining the well k

al., 2011). In both basins over the low l
found, mainly associated (Davini et al., 2012). Rossby wave Breaking
the lowest resolution (T159, Fig. 1f), when compared to recent CMIP5 models [e.g.,
2013, which used a similar index], EC-Earth shows a limited -bias. However the
GCM bias characterized by an underestimation of blocking over Central Europe and by an overestimation at lower latitude is clearly visible. In addition, EC-Earth presents a considerable negative bias over the North Pacific. The impro
over the Euro-Atlantic region. In this area the bias decreases monotonically as resolution is increased up to 25km. In this configuration (i.e. T799) the blocking bias is actually negligible over most of the Euro-Atlantic sector (Fig. 1i). On the other hand, over the Pacific region the negative bias - albeit reduced - is still evident even at higher resolutions.

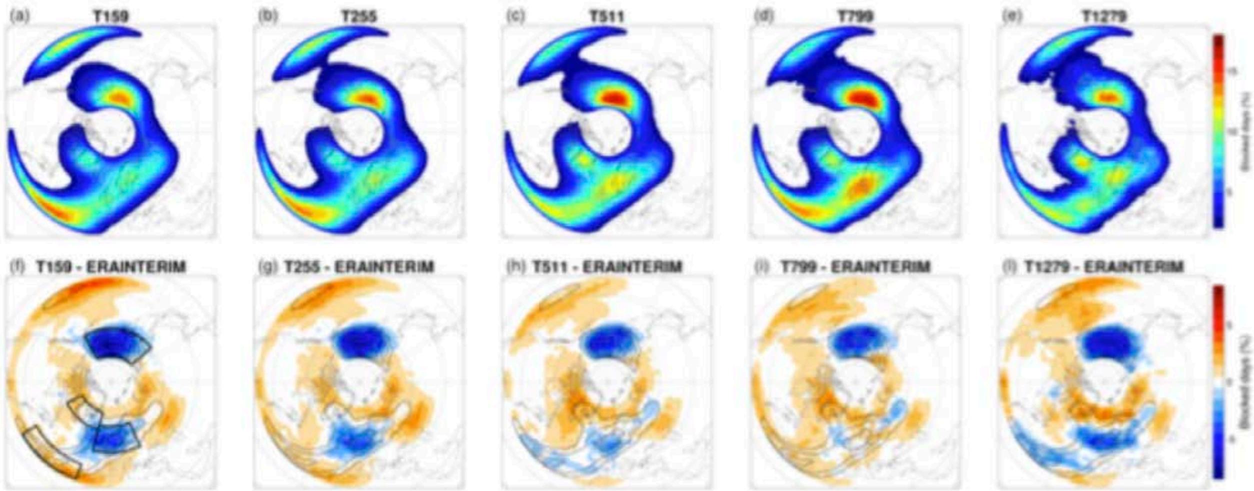

Figure 1. (a,b,c,d,e) DJFM 1979-2008 blocking events (blocked days) for the EC-Earth ensemble mean at 5 different resolution. (f,g,h,i,l) EC-Earth model biases (colors) against ERA Interim reanalysis (contours). Contours are drawn every 3%. Boxes identifying the different regions used in Figure 3 are shown in (f).

The causes of this improvement in blocking frequency over the Euro-Atlantic sector have been explored in a recent study (Davini et al. 2017b). It was found that a combined effect by the more resolved orography and by a change in tropical precipitation is the tropospheric planetary wave. At the sa
gradient reduces the upper level baro
in the high resolution configurations the Atlantic eddy-driven jet stream is weakened and less penetrating over Euro
ridge and thus
stream is too weak and the blocking duration is still underestimated, suggesting that the optimal blocking frequencies are achieved through a compensation of errors.

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List of publications/reports from the project with complete references

The results of the *Impact of increased atmospheric resolution on model mean state and forecast quality in multi-year hindcasts* have been presented at the Joint MiKlip/SPECS Meeting on Decadal Climate Prediction held in Offenbach the 23-26 February 2015
http://www.fona-miklip.de/_media/MiKlipSPECS_workshop_leaflet_final_for_web.pdf
A publication based on that presentation is in preparation.

The results of *Impact of initial conditions relative to external forcings in multi-year integrations* have been presented at :
UNESCO Conference “Our common future under Climate Change” held in Paris the 6-10 July 2015.
http://cfcc.event.y-congress.com/ScientificProcess/Schedule/index.html?setLng=en
CLIVAR-ICTP International Workshop on “Decadal Climate Variability and Predictability: Challenge and Opportunity” held in Trieste the 16-20 November 2015.
http://www.clivar.org/dcvp2015
A publication based on that presentation is in preparation.

The results of *Impact of increased resolution on the Northern Hemisphere blocking* have been presented at the EGU2017 held in Vienna the 23-28 April 2017
The following publication is currently under review:
Davini P., S. Corti, F. D’Andrea, G. Rivière, J. von Hardenberg (2017) Improved winter European atmospheric blocking frequencies in high-resolution global climate simulations. *JAMES*, under review.

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.)

The research activities started under the SPITCORT umbrella is currently going in collaboration with other institutions and in the framework of the European Project PRIMAVERA. New special projects related to this activity (i.e. the study of impact of increased resolution in the simulation of weather and climate) have been submitted this year by our group at ISAC-CNR and in collaboration with Oxford University.

In the largest one, titled: “EC-Earth Decadal Global high-resolution prEdiction (EC-EDGE)” and proposed by Paolo Davini, we plan to explore the role of North Pacific and North Atlantic Sea Surface Temperatures (SST) in modulating the global surface temperature trends and in driving regional climate variations. It is proposed to carry out a sensitivity experiment (at low and high resolution) with the EC-Earth model with a large number of ensemble members in order to correctly sample the natural variability, which is a key element for reliable forecast especially on the decadal time window. The experiments outlined in this proposal will follow the protocol of the Decadal Climate Prediction Project C (DCPP-C) of the World Climate Research Project (WCRP).