SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	CMIP6 BSC contribution to HighResMIP (HighResMIP_BSC)
Computer Project Account:	spesiccf
Start Year - End Year :	2017 - 2019
Principal Investigator(s)	Louis-Philippe Caron
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The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The simulations performed within the context of HighResMIP_BSC represents BSC's contribution to the HighResMIP coordinated exercise, which is part of the Sixth Phase of the Coupled Model Intercomparison Project (CMIP6). This exercise offers a framework for increasing synergies and building a large multi-model ensemble of high resolution simulations with a standard resolution counterpart following a common experimental protocol, i.e. a common integration period, forcing and boundary conditions (50 year long spin-up simulation, followed by a 100-year control simulations as well as a 100-year historical+future climate simulation (1950-2050)). The primary goal is to determine which processes can be represented reliably at typical CMIP5 resolutions and what is the minimum resolution required for an adequate representation of other processes as well as what are the limitations of representing such processes in lower resolution models.

Summary of problems encountered

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

Simulations of future climate (2015 onward) were delayed because of the delay in the CMIP6 forcings becoming available. These forcings were expected to be available in the first year of the project, but only became available during the second year of the project. These forcings are produced by a group external to this project and this delay impacts the climate community at large. Once the forcings became available, the future climate simulation could be completed. This delay put us slightly behind schedule, but because the project was granted a one-year extension, we managed to make up for the delay and produce all the simulations that had originally been planned. In fact, we could extend both the control and the historical simulations by 50 years, to cover the period 1950-2100 instead of 1950-2050, as originally planned.

Experience with the Special Project framework

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

We are generally happy with the current administrative aspects. This might be because we have become familiar with them by now. The response time of the Spanish representative is usually very short and we find him to be very helpful.

Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

We first performed a short series of experiments. The goal of these experiments were twofold; first, to test the integration of XIOS, an asynchronous parallel I/O server, into IFS, and second, to benchmark the IFS-XIOS integration and compare it against the two other types of I/O schemes present in IFS (the sequential I/O scheme and the MF I/O server).

For these tests, the IFS configuration consisted in a Tco1279L137 grid, a time step of 600 seconds, 702 MPI processes and 6 OpenMP threads, hyperthreading enabled, a 5 day forecast and a large hourly output configuration to stress the I/O (GRIB output size: 2.4 TB. NetCDF output size: 9.9 TB). In addition, the MF I/O server uses 30 servers with 3 dedicated nodes and XIOS uses 40 servers with 20 dedicated nodes.

Figure 1 shows the execution time of the sequential I/O scheme, the MF I/O server and XIOS. It is quite evident that the sequential I/O scheme is very inefficient and slow, so it is not appropriate for high resolution experiments, such as the ones performed in this project (HighResMIP). On the other hand, the two I/O servers offer good performance, with the MF I/O server being the fastest one. The difference in execution time and amount of resources between occurs for several reasons:

- XIOS performs an additional spectral transformation which takes about 290 seconds.
- XIOS outputs in netCDF format instead of GRIB, so the difference in size of the output has a considerable impact.
- GRIB can only output data, while XIOS can perform many different online post-processing operations before writing data.

For this project, the remaining simulations were performed using XIOS.

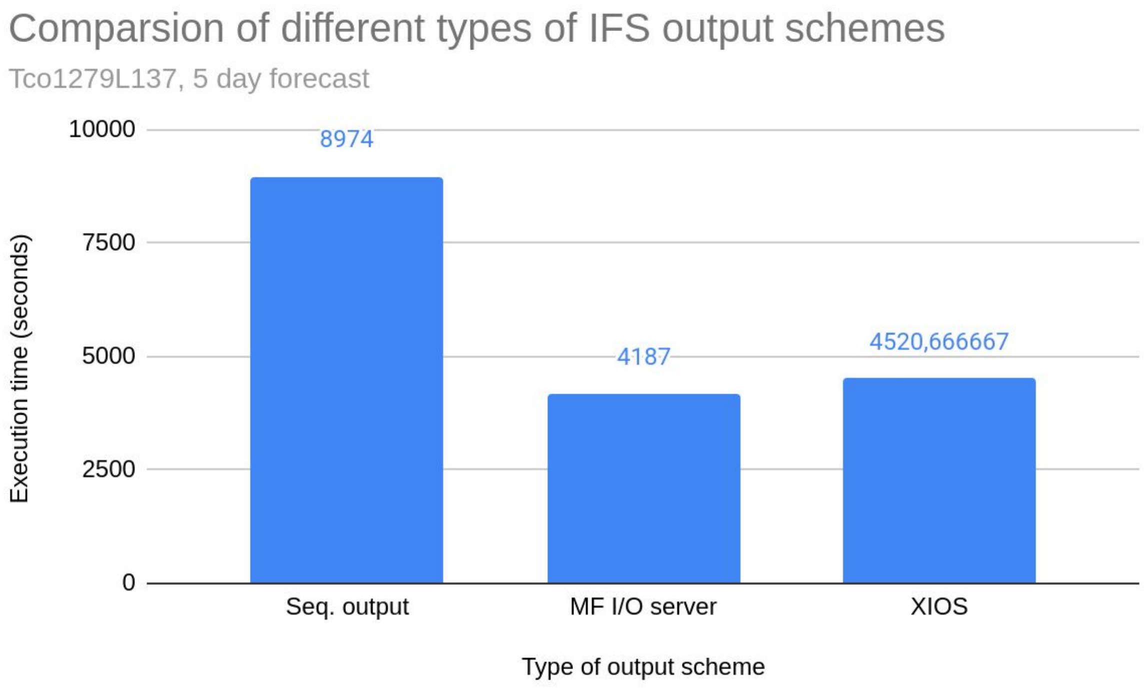


Figure 1. Execution time of IFS with the different I/O scheme.

HighResMIP

The aim of the special project was to produce a set of experiments following the HighResMIP protocol (Haarsma et al., 2016). The HighResMIP coordinated exercise, which is part the Sixth Phase of the Coupled Model Intercomparison Project (CMIP6), offers a framework for increasing synergies and building a large multi-model ensemble of high resolution simulations with a low resolution counterpart following a common experimental protocol, i.e. a common integration period, forcing and boundary conditions. This coordinated aims to identify robust benefits of increased model resolution based on multi-model ensemble simulations.

The HighResMIP protocol divides the simulations in 4 distinct experiments:

- a 50-year spinup, initialized using 1950 conditions and with constant 1950 forcings (labelled spinup-1950)
- a 100-year control experiment started from the end of the spinup-1950 simulations and with constant 1950 forcings (labelled control-1950)
- a 65-year simulation (1950-2014) initialized from the end of the spinup-1950 simulations but with forcings corresponding to forcings observed during the period 1950-2014 (labelled hist-1950)
- a 36-year simulation (2015-2050) initialized from the end of the hist-1950 simulation and forced with emissions from the SSP5-85 scenario (equivalent to RSP 8.5 in CMIP5) (labelled highres-future).

The protocol is summarized in Figure 2 below.

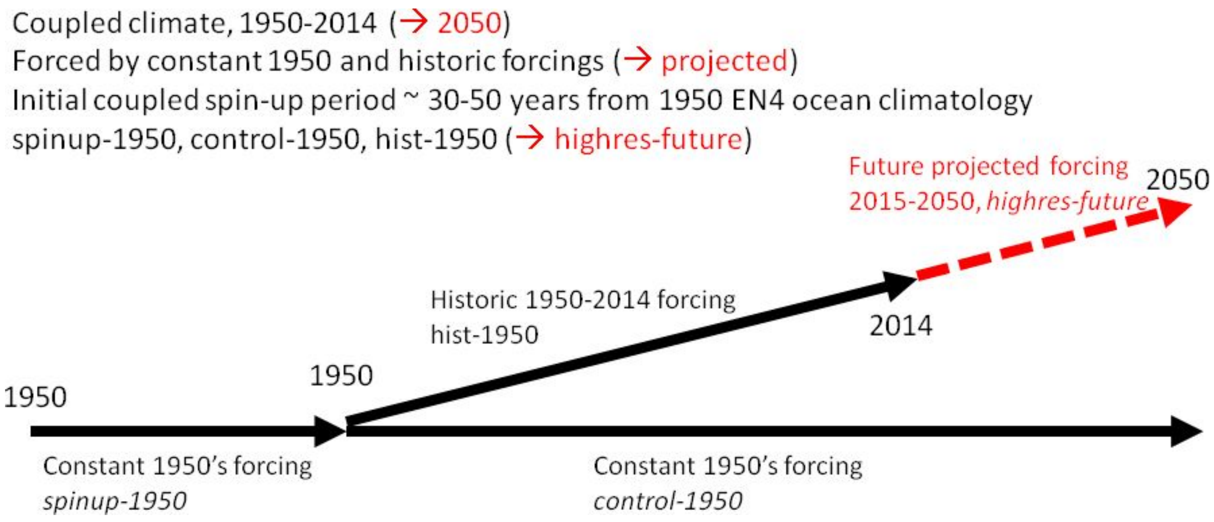


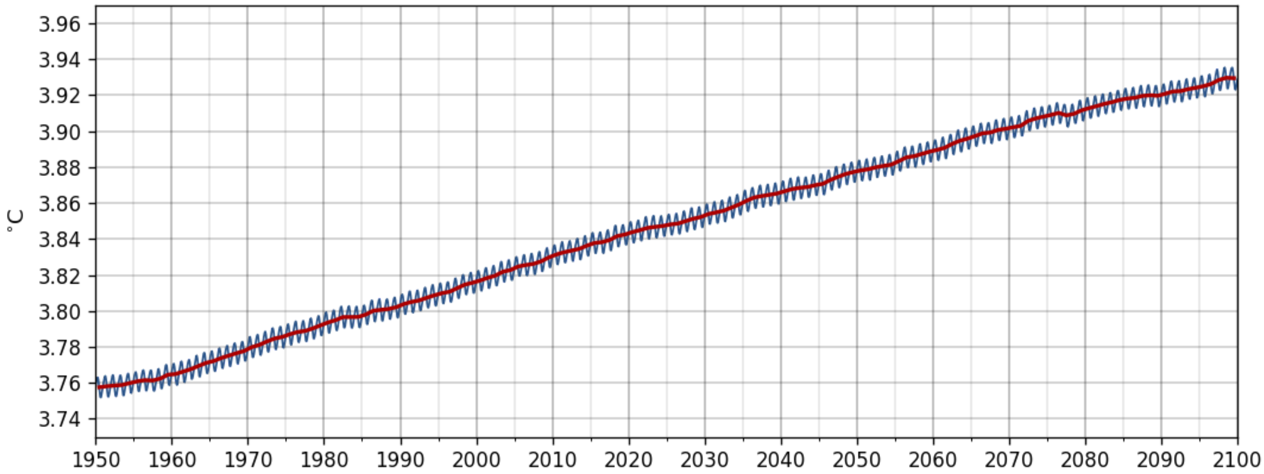
Figure 2: HighResMIP protocol.

We first completed the 50-year spin-up simulation at high resolution using EC-Earth3P. This model configuration uses a spectral truncation of the atmospheric model (IFS) at T511 (approx. 40 km globally) and 91 vertical levels and a grid resolution of the ocean model (NEMO3.6) of 0.25° globally (ORCA025 grid) with 75 vertical levels, which increases thickness from 1m below surface up to 500m in the deep ocean. This simulation was compared to a different 50-year spin-up simulation performed by an EC-Earth partner (KNMI) which used a slightly different version of the model. The KNMI simulation was deemed to be closer to equilibrium and as such was selected as the starting point for the control and historical simulations. Ideally, it would have been possible to just run a very long spin up simulation until equilibrium was reached, but at the high-resolution considered here, such long spin up is not possible and a comparative approach was used to identify the model closest to equilibrium. Using the initial conditions provided by the spin-up, we then ran a 150-year control simulation using 1950s (constant) forcing and, starting from the same initial conditions, we ran a

150-year transient simulation, with observed forcing for the period 1950-2014 and projected forcings from 2015 onward. An equivalent set of standard resolution (T255; ORCA1) simulations was performed on our local machine to investigate the impact of increasing horizontal resolution.

We can see from Figure 3a that the ocean in the high-resolution control simulation is continuously warming at a rate of ~0.02K/10 year and has not yet reached equilibrium, even after 200 years of simulations (the situation is similar at standard resolution - not shown). Figure 3b shows that while some of that warming occurs near the surface, most of that warming occurs between 500m and 1000m. This warming is also somewhat compensated by a cooling in the 50-250m layer. This is not entirely surprising given the short length of the spin-up (50 years only; spin-up excluded from the figure). For the deep ocean to reach quasi-equilibrium, a very long spin-up (thousands of years) would probably be necessary, which is not realistic in the current configuration. To circumvent this problem and to remove the climate drift, a suite of ensemble simulations is needed, which can be used to estimate and remove the climate drift, particularly in locations where it is very strong, such as the deep ocean.

a



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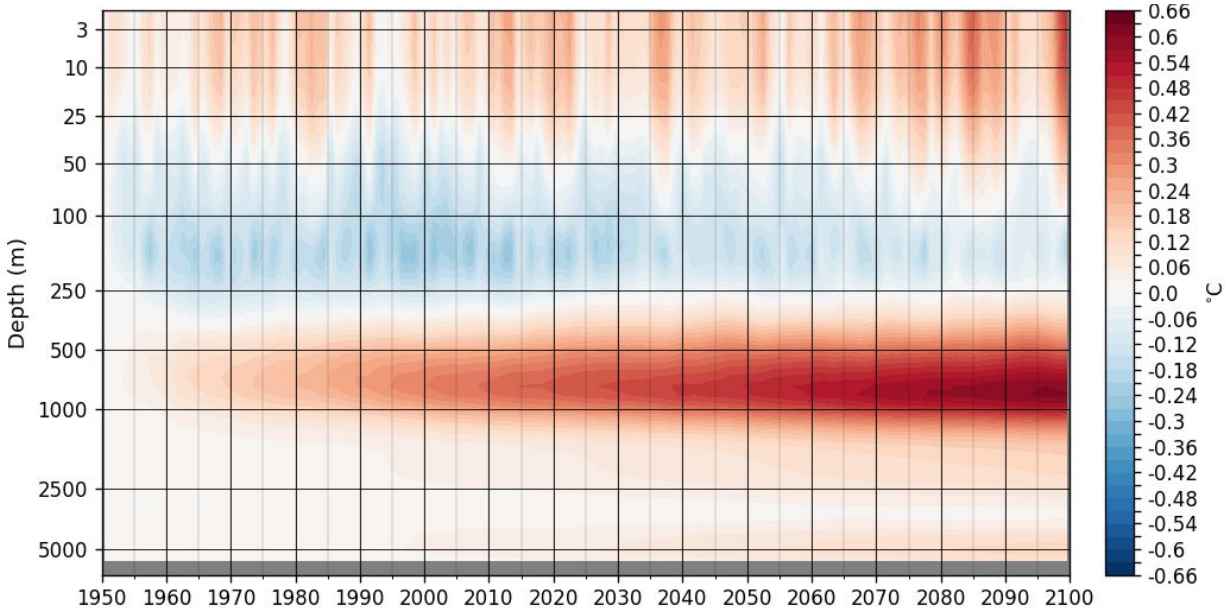
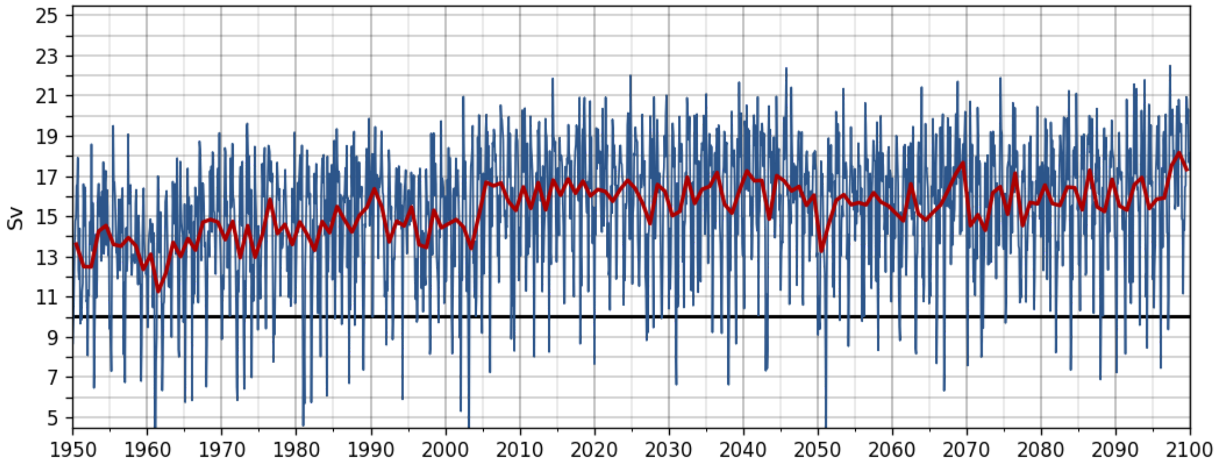


Figure 3: a) Globally averaged ocean temperature of the control simulation. b) Evolution of temperature anomalies between the surface and 5km depth in the control simulation.

Figure 4 shows the evolution of the Atlantic Meridional Overturning Circulation (AMOC) for both the control (a) and the transient (b) simulations. We see from Figure 4a that the AMOC strengthened over the first 50 years of the control and stabilized in the range of 15-17 Sv afterward. By comparison, the AMOC of the transient simulation spends the first 50 years in the 13-15 Sv range and starts decreasing afterwards. This decrease in the AMOC becomes more pronounced after 2060, with the circulation reaching mean annual values below 10 Sv in the last few years of the simulation.

a



b

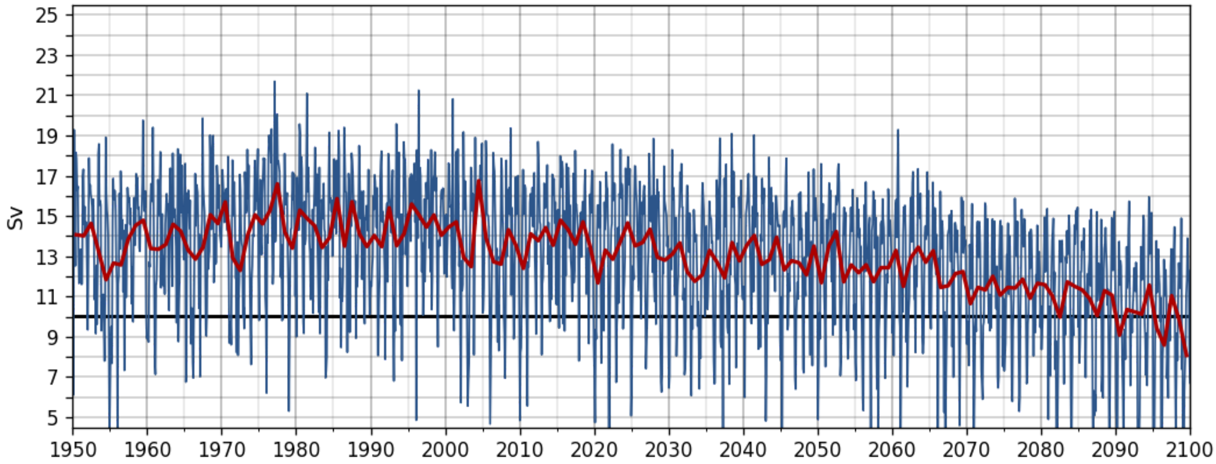


Figure 4. Atlantic Meridional Overturning Circulation (between 40N and 43N) for a) the control simulation and b) the transient simulation. The thin blue line represents the monthly mean value while the red line represents the annual mean.

This decrease in AMOC over the last ~40 years is accompanied by a sharp decrease in ocean salinity in the top 100m of the ocean (Figure 5b). This is in sharp contrast with the control simulation for which the ocean salinity is still increasing in the same corresponding period (Figure 5a).

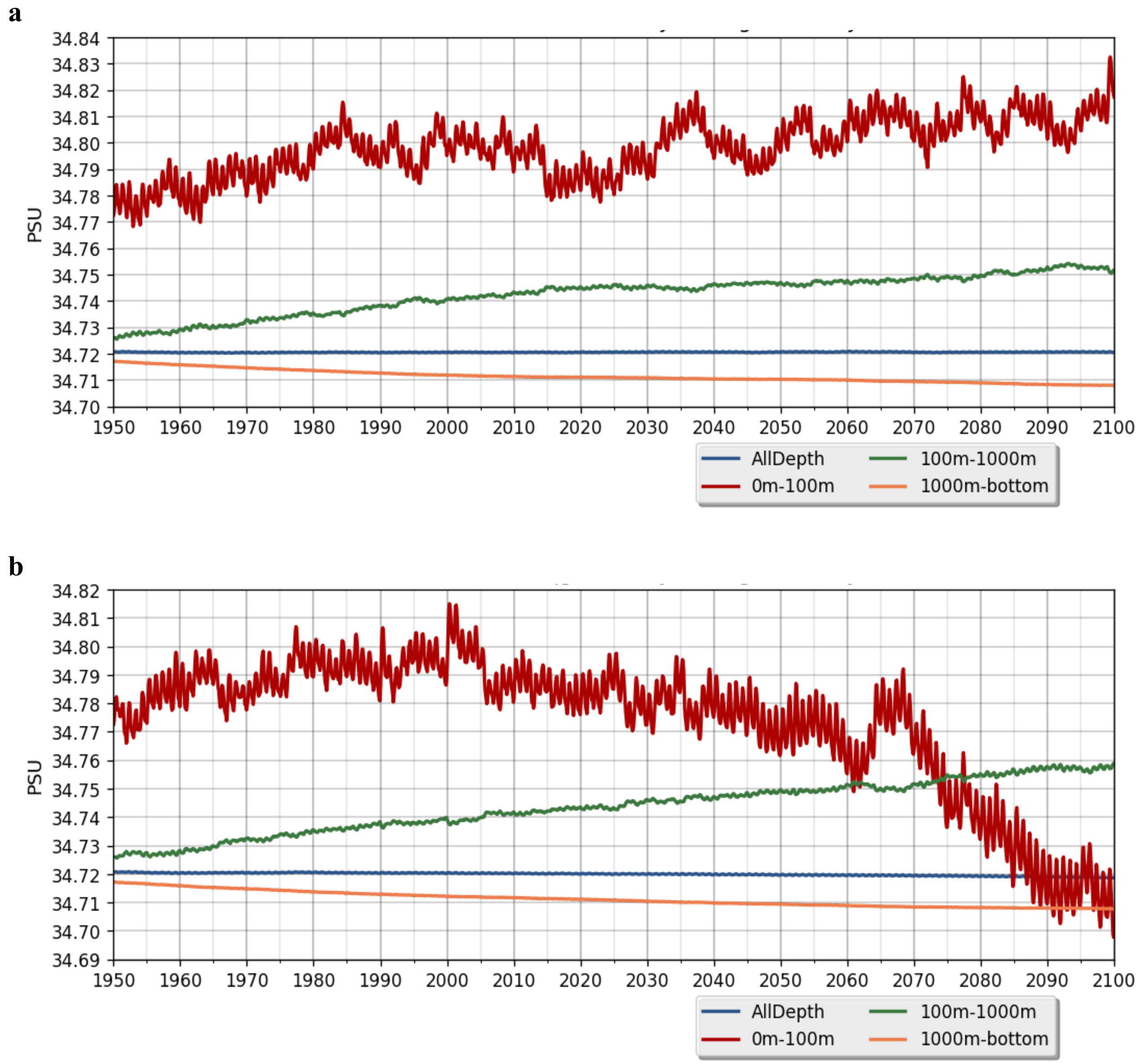


Figure 5. Global mean salinity for 4 different layers of the ocean for a) the control simulation and b) the transient simulation.

During the last ~40 years of the simulation, we also observe an ice free Arctic during the summer (Figure 6c). In this case, we detect a relatively constant decrease in sea-ice volume, starting in 1980, which is consistent with a decrease in ocean salinity. A similar decrease in sea ice is observed during the winter (Figure 6d), but in the latter case, we don't quite reach an ice free Arctic during the simulation. While we detect a significant amount of interannual variability in the control simulation, no such downward trend is observed (Figure 6a, 6b).

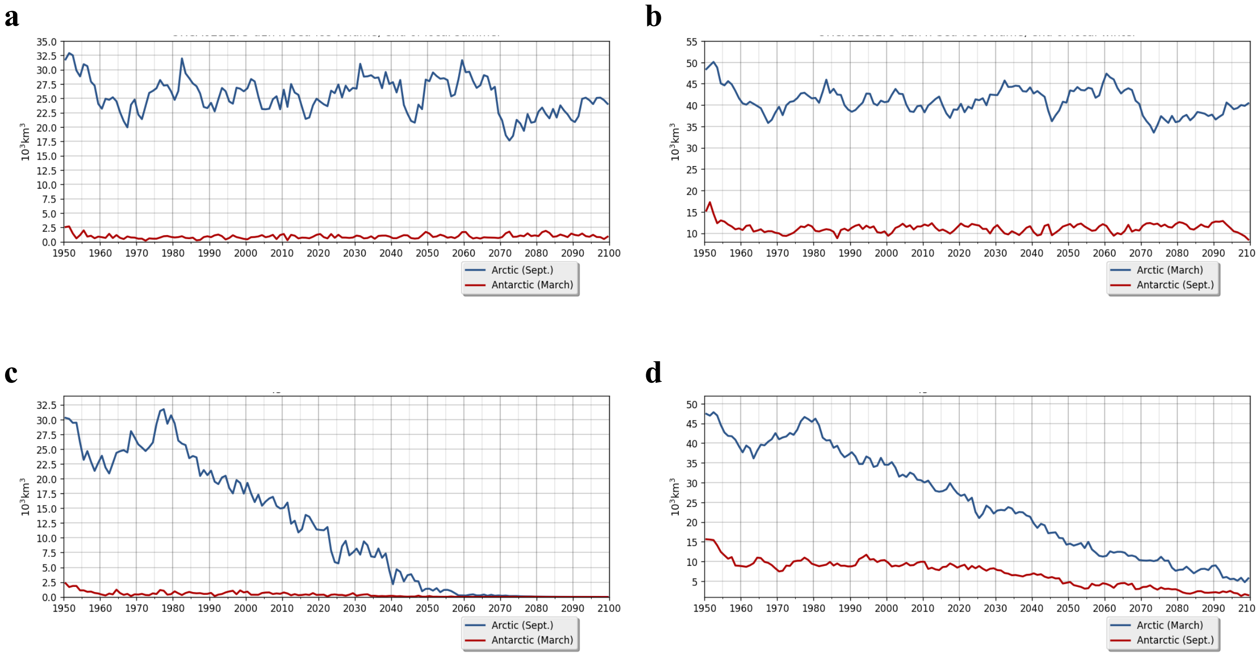


Figure 6. Sea-ice volume at the end of local summer (first column) and the end of the local winter (second column) for the control simulation (top) and the transient simulation (bottom).

Impact of Resolution on Mean Temperature Biases

As mentioned above, one of the goals of HighResMIP is to investigate the impact of increasing horizontal resolution on the simulation of the climate. As such, we also compared the impact of increasing the resolution from the standard configuration (ORCA1; T255) to the high-resolution configuration (ORCA025; T511) on the model's biases. Figure 7 (top row) shows the mean bias of the high-resolution configuration in 2m temperature and the impact of increasing resolution on the 2m air temperature bias. We detect a cold bias over the northern North Atlantic, the Arctic and northern Africa as well as a strong positive bias over Antarctica (Figure 7a). Increasing the resolution doesn't appear to impact the bias over Northern Africa or the North Atlantic, and even seems to worsen the biases over the poles (Figure 7b). The omission of specific tuning for the high resolution might be responsible for this.

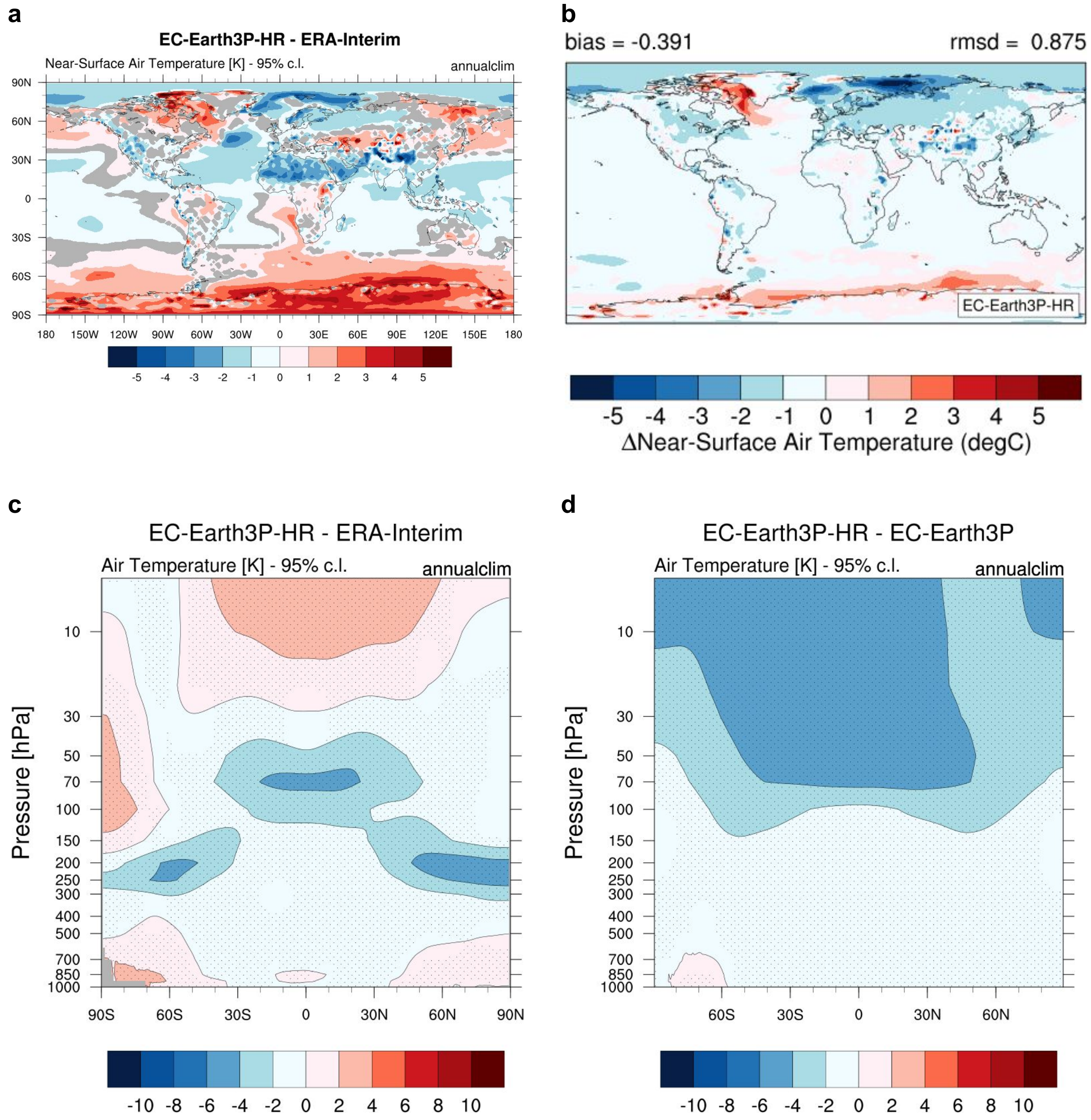


Figure 7. a) Mean annual bias in 2m temperature between EC-Eart3P at high resolution and ERA-Interim. b) Difference in the mean annual climatology of 2m temperature between the high-resolution simulation and the standard resolution simulation. c) Zonal mean annual bias in air temperature between EC-Eart3P at high resolution and ERA-Interim. d) Difference in the zonal

annual mean temperature between the high-resolution simulation and the standard resolution simulation. The period 1980-2014 is used to compare all the averages.

The high-resolution version of EC-Earth3P also shows cold biases in the upper troposphere over both poles and in the lower stratosphere over the tropics. It also shows a positive bias in temperature in the upper stratosphere over the tropics and most of the stratosphere over the south pole. The high-resolution version of the model tends to be colder over much of the stratosphere compared to the standard resolution (Figure 7d), which suggest that increasing resolution reduced the warm bias over the tropics in the upper stratosphere but worsen the cold bias in the lower stratosphere.

Contribution of internal climate variability to the ocean heat uptake and its sensitivity to the model resolution

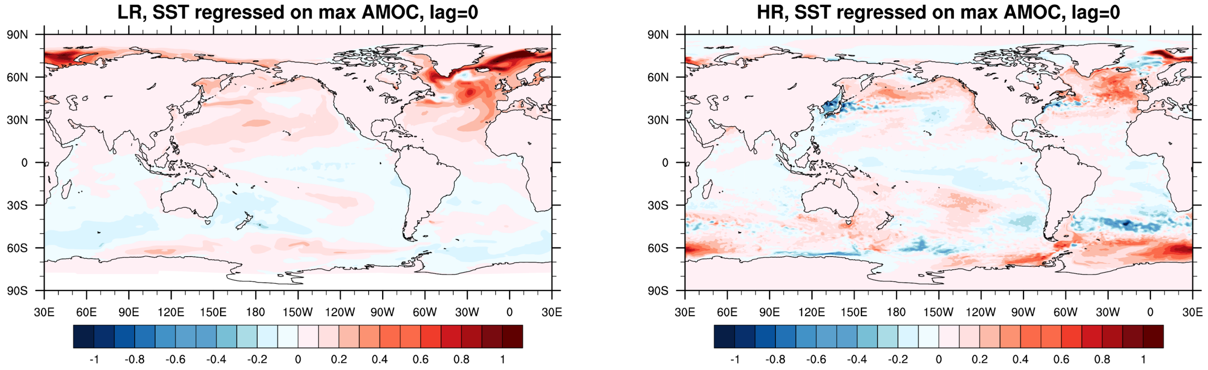
We also analysed and compared the energy budget in high and standard resolution sets of present-day control HighResMIP experiments. In particular, we looked at the potential contributions of the Atlantic Meridional Overturning Circulation, which largely controls the ocean energy transport from the Equator to the Arctic, to the global and local heat uptake. Gregory et al. (2004) have been shown that in a forced climate there is a linear relationship between the radiative forcing F and the global mean surface temperature change T, $F = \boldsymbol{\rho}T$. The net top-of-the-atmosphere (TOA) radiation N, equal to the difference between F and the radiative feedback λT, can be written as

$$N = F-\lambda T = (\boldsymbol{\rho}-\lambda)\ T= \kappa T = dH/Dt \quad \text{(Eq 1)},$$

where H is the ocean heat content (OHC). During hiatus periods ($dT/dt <= 0$), Equation 1 implies $dN/dt=dF/dt$, i.e. there is an accelerated ocean heat uptake. It is unclear from observations whether accelerated heat content uptake or increase in TOA radiation occurs in the case of a hiatus. Recent studies revisited the energy budget discussing that the previous relationships are different under a context of internally generated variability than in a forced climate (Xie et al., 2016; Drijfhout, 2018). These studies analysed CMIP5 simulations in the most commonly used resolutions of about 1 deg in both the ocean and the atmosphere. The impact of increased model resolution on the energy budget has not been addressed.

The change in resolution leads to different model biases in the polar region (see previous figure), associated with different biases in sea-ice volume and polar temperature and rather distinct variability in the AMOC (not shown), which shows substantially higher variability at subpolar latitudes in the standard resolution version. This could be related to the fact that the main regions of deep convection are different in the two configurations: convection occurs in the Labrador Sea in the high-resolution simulation, and in the Nordic Seas in the standard-resolutions simulation. The standard resolution simulation is also warmer in the northern high latitudes and has comparatively less sea ice (not shown).

The regression patterns in Figure 8 provides information about the concomitant changes between the AMOC strength and the upper ocean temperatures, and thus about the global impact that the AMOC can play on the heat uptake by the ocean. Important differences can be observed between the two resolutions. While in the standard resolutions simulation, the impact of AMOC on sea surface temperature (SST) is almost exclusively restricted to a warming in the North Atlantic subpolar gyre and over the Arctic, the high resolution experiment (which is eddy-permitting) seems to additionally represent other key processes and interactions. The associated regression exhibits, for example, a region of substantial cooling in the Atlantic downstream of the Agulhas Current, as well as massive warmings over the Southern Ocean. These results thus suggest that the model resolution plays an important role in the representation of the AMOC, and by extension of its contribution to the global heat budget.


LR, SST regressed on max AMOC, lag=0

HR, SST regressed on max AMOC, lag=0

Figure 8. Regressions of sea surface temperature on the maximum AMOC strength (at any latitude and depth) for standard resolution (left) and high resolution (right). Data have been smoothed using a 13-year running means.

The lead-lag correlations between global mean SST and the different components in the surface fluxes (Figure 9) reveal that, in the low resolution model, on decadal timescales, the solar fluxes heat (cool) the ocean about 5 years before the SST warming (cooling), and the turbulent and long wave respond with upward (downward) heat flux anomalies to dampen this warming (cooling) 5 years later. For the high resolution, there is a different type of variability, the reason for which we are currently exploring.

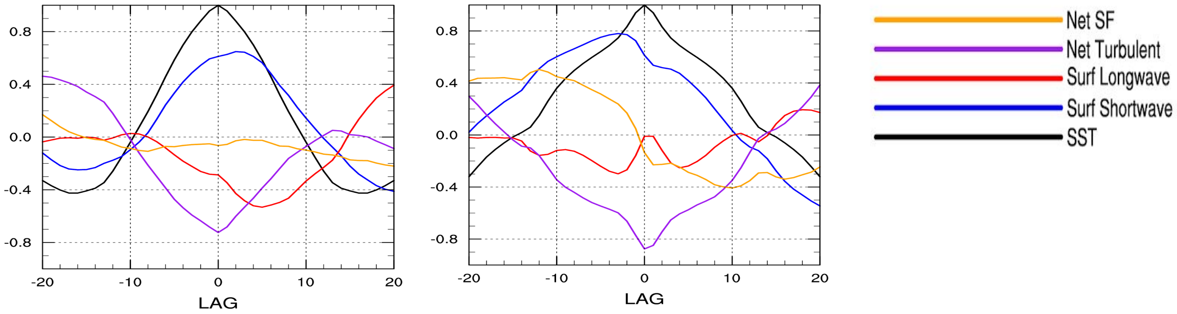


Figure 9: Lead-lag correlation between SST and the different components of the surface fluxes (positive lags when the SST leads) for the high (left) and low (right) resolution. The black line shows the autocorrelation of the SST. A high-pass filter of 13 years has been applied to the time series in order to remove interannual variability.

Conclusion

The sample of results presented here cover only a small fraction of the analyses that have been done or currently being performed using EC-Earth3P at high resolution. For example, Haarsma et al. (2020) reports a deteriorating impact of increasing horizontal model resolution on the representation of Euro-Atlantic weather regimes, but a clear improvement in the spatial structure of El Niño-Southern Oscillation.

By making the simulations available to the wider scientific community through the ESGF node, we ensure that they will be analysed for the many years to come and by groups that have expertise that go much beyond what is available in our department. Because a doi number has been assigned to this set of experiments, we will be able to monitor the many different studies that are making use of this dataset.

References

Drijfhout, S (2018) The relation between natural variations in ocean heat uptake and global mean surface temperature anomalies in CMIP5. Scientific Reports, 8(1), [7402]. doi: 10.1038/s41598-018-25342-7.

Gregory, J M, et al. (2004) A new method for diagnosing radiative forcing and climate sensitivity. Geophysical Research Letters 31.3.

Haarsma et al. (2016) High resolution model intercomparison project (HighResMIP). Geoscientific Model Development Discussions, doi: https://doi.org/10.5194/gmd-2016-6.

Haarsma R. et al. (2020) HighResMIP versions of EC-Earth: EC-Earth3P and EC-Earth3P-HR. Description, model performance, data handling and validation. Geoscientific Model Development. https://doi.org/10.5194/gmd-2019-350

Xie, S-P, Y Kosaka and YM Okumura (2016) Distinct energy budgets for anthropogenic and natural changes during global warming hiatus. Nature Geoscience 9.1 : 29.

List of publications/reports from the project with complete references

The dataset presented here is available on the ESGF portal. The reference is:

- EC-Earth Consortium (EC-Earth) (2019). EC-Earth-Consortium EC-Earth3P-HR model output prepared for CMIP6 HighResMIP. Earth System Grid Federation. doi:10.22033/ESGF/CMIP6.2323

A more complete analysis of the EC-Earth3P simulations is available in

- Haarsma R. et al. (2020) HighResMIP versions of EC-Earth: EC-Earth3P and EC-Earth3P-HR. Description, model performance, data handling and validation. Geoscientific Model Development. https://doi.org/10.5194/gmd-2019-350

The following manuscripts, which rely on these simulations, are also under development by members of the Earth Science department of the Barcelona Supercomputing Center:

- Caron et al. (2020) Impact of increasing model resolution on climate model long standing biases.

- Exarchou, E. and S. Drijfhout (2020) The relationship between surface climate, and the ocean heat uptake arising from natural variability , and the impact of the resolution. In preparation for Climate Dynamics.

- Kreussler et al. (2020) Tropical Cyclone Integrated Kinetic Energy in HighResMIP simulation.

Finally, the simulations have already been included in many analyses performed within the context of the PRIMAVERA project. For example:

- Docquier, D., R. Fuentes-Franco, T. Koenigk, T. Fichefet, 2020: Sea ice - ocean interactions in the Barents Sea modeled at different resolutions. Front. Earth Sci., 8, 172. https://doi.org/10.3389/feart.2020.00172.
- Hariadi, M et al. (2020) Evaluation of the Southeast Asia rainy season in CMIP5 regional climate model results and HighResMIP datasets. ERL, submitted.
- Hirschi, J et al. (2020) The Atlantic meridional overturning circulation in high resolution models. J. Geophys. Res., accepted.
- Koenigk, T. et al. (2020) Deep water formation in the North Atlantic Ocean in high resolution global coupled climate models. Ocean Science, submitted https://www.ocean-sci-discuss.net/os-2020-41/
- Roberts, MJ, J Camp, J Seddon, PL Vidale, K Hodges, B Vanniere, J Mecking, R Haarsma, A Bellucci, E Scoccimarro, L-P Caron et al. (2020) Projected Future Changes in Tropical Cyclones using the CMIP6 HighResMIP Multi-model Ensemble. Geophys Res Lett. https://doi.org/10.1029/2020GL088662
- Roberts, MJ and et al. (2020) Sensitivity of the Atlantic Meridional Overturning Circulation to Model Resolution in CMIP6 HighResMIP Simulations and Implications for Future Changes. JAMES. https://doi.org/10.1002/essoar.10501560.1
- Schiemann et al. (2020) Northern Hemisphere blocking simulation in current climate models: evaluating progress from the Climate Model Intercomparison Project Phase 5 to 6 and sensitivity to resolution. Weather Clim. Dynam., 1, 277–292. https://doi.org/10.5194/wcd-1-277-2020

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 simulations done for this project were performed within the context of the H2020 PRIMAVERA project which is coming to an end in July 2020. However, the simulations will remain available on the ESGF nodes for the foreseeable future and will continue to be exploited for years to come. Furthermore, the model developed to perform these high-resolution simulations (i.e. EC-Earth3) will be used to perform initialized climate simulations within the context of the H2020 EUCP project.