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Deliverable D4.5

Quantify impact of resolution on European climate change

Deliverable Title	Quantify impact of resolution on European climate change	
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WP number	4	
Lead Beneficiary	*MPG (MPI-M)*	
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1. Executive Summary

This report is a summary of the various comparative analysis performed with WP4 frontier and WP6 Stream 1 simulations, to investigate the impact of an eddy-resolving ocean on European climate change. We find that the eddy-resolving ocean models can behave differently from their lower resolution counterparts, particularly on changes in the Atlantic Meridional Overturning Circulation (AMOC), North Atlantic Oscillation (NAO) and weather regimes, and the resulting impact on changes in European climate such as temperature, precipitation and storminess.

Most of these changes are as a result of reducing model bias common to lower resolution models, and hence enabling different processes to happen in future. For projections of European future climate, it is therefore important to use models at these resolutions to improve the robustness of climate risk assessments.

2. Project Objectives

With this deliverable, the project has contributed to the achievement of the following objectives (DOA, Part B Section 1.1) WP numbers are in brackets:

No.	Objective	Yes	No
A	To develop a new generation of global high-resolution climate models. *(3, 4, 6)*	X	
B	To develop new strategies and tools for evaluating global high-resolution climate models at a process level, and for quantifying the uncertainties in the predictions of regional climate. *(1, 2, 5, 9, 10)*		X
C	To provide new high-resolution protocols and flagship simulations for the World Climate Research Programme (WCRP)'s Coupled Model Intercomparison Project (CMIP6) project, to inform the Intergovernmental Panel on Climate Change (IPCC) assessments and in support of emerging Climate Services. *(4, 6, 9)*	X	
D	To explore the scientific and technological frontiers of capability in global climate modelling to provide guidance for the development of future generations of prediction systems, global climate and Earth System models (informing post-CMIP6 and beyond). *(3, 4)*	X	
E	To advance understanding of past and future, natural and anthropogenic, drivers of variability and changes in European climate, including high impact events, by exploiting new capabilities in high-resolution global climate modelling. *(1, 2, 5)*		X
F	To produce new, more robust and trustworthy projections of European climate for the next few decades based on improved global models and advances in process understanding. *(2, 3, 5, 6, 10)*	X	
G	To engage with targeted end-user groups in key European economic sectors to strengthen their competitiveness, growth, resilience and ability by exploiting new scientific progress. *(10, 11)*		X

H	To establish cooperation between science and policy actions at European and international level, to support the development of effective climate change policies, optimize public decision making and increase capability to manage climate risks. *(5, 8, 10)*		X

3. Detailed Report on Progress

We address the role of resolution, particularly ocean eddy resolution, on European climate over three broad categories:

1) In relation to the Atlantic Meridional Overturning Circulation (AMOC):
    a. the influence of AMOC on surface temperature distribution [UK MetOffice]
    b. the differences in heat distribution response to CO_2 forcing, and thus AMOC stability [AWI]
    c. the impact of Nordic Seas overflows on the AMOC [MPG]
2) In relation to the North Atlantic Oscillation (NAO) and weather regimes:
    a. NAO influence on Euro-Asia surface temperature [MPG]
    b. Weather regimes and its impact on European climate [CNR]
3) Comparative analysis on:
    a. wintertime precipitation over Europe and the North Atlantic [BSC]
    b. east Atlantic storminess [NERC]

3.1 Atlantic Meridional Overturning Circulation (AMOC)

3.1.1 Influence of AMOC on surface temperature distribution in a warming world

European mean climate is strongly influenced by the Atlantic Meridional Overturning Circulation (AMOC), the ocean process that moves warm surface water northwards in the Atlantic where it cools, sinks and returns southwards e.g. (Jackson et al., 2015). To a large degree, future temperature change over Europe over the long term is determined by a balance of radiative heating from global warming via CO2 increase, set against regional processes such as storm tracks, AMOC and their impact on this warming. Shorter term variability (interannual to decadal) is also important

Two papers from PRIMAVERA (Jackson et al., 2020; Roberts et al. 2020) have examined the projected change in AMOC in the PRIMAVERA-HighResMIP multi-model ensemble and the impact of model resolution. In general, the AMOC performance at 26.5°N in the Atlantic in the historic period (and its associated northward heat transport, NHT) improves with higher ocean resolution compared to observations. However, the picture further north is rather more mixed, with both low and high resolution models having some better metrics.

The stronger AMOC at higher resolution is primarily driven by enhanced dense water formation in the Labrador Sea. As the climate warms, this region reduces its dense water formation, as the surface warms and freshens, more quickly than in the Nordic Seas north of

Iceland where the convection can migrate northwards. This means that the higher resolution models typically have a stronger decline in AMOC than the lower resolution models.

What impact does this have on the surface climate? Focusing on one model initially, Figs. 1 and 2 (top left) show the annual mean surface air temperature change in the HadGEM3-GC31-LL model comparing 2030-2050 against the mean 1950 control state in the control-1950 simulation, both globally and in the Atlantic region. One can note common features of enhanced warming over land compared to ocean, Arctic polar amplification as sea ice recedes, and a minimum in warming in the northern North Atlantic.

For the higher resolution models, Figs. 1 and 2 show the difference between warming compared to LL. Globally in the low latitudes there is very little difference in warming with resolution, with the largest differences in the North Atlantic and around Antarctica. In the northern Atlantic we see considerably less warming south of Greenland (the so-called "warming-hole"), slightly reduced warming over Scandinavia and Eastern Europe. There are increases in warming in the Nordic Seas in some models, and next to the east coast of the USA in the eddy-rich simulations (those with ocean resolution of 1/12°). The impact of this latter warming will be described elsewhere in this document.

The AMOC decline is associated with the warming hole, since reduced northward heat transport with the AMOC means a reduced heat convergence into this region. It has been found to have an influence on projected future European summer climate e.g. (Haarsma, Selten, & Drijfhout, 2015) via a change in the large-scale pressure patterns over the Atlantic. These can then produce a reduction in precipitation and cloud over Europe during future summers. This analysis is ongoing for the PRIMAVERA-HighResMIP simulations (van der Wiel et al., in prep).

In addition to the long-term changes, the relationship of AMOC to large-scale variability in Northern Hemisphere surface temperatures was examined in D2.4 (Fig. 3.4.1.1), suggesting a smaller warming over Europe for a given increase in AMOC with an eddy-rich ocean. Ongoing work will attempt a similar analysis to (Wills, Armour, Battisti, & Hartmann, 2018) to further look at the relationship between AMOC, AMV (Atlantic Multidecadal Variability) and NAO (north Atlantic Oscillation), all of which are important for European climate.

In terms of the multi-model surface temperature changes, Fig. 3 shows the same as Fig. 2 but here for the PRIMAVERA model ensemble – here high resolution ocean only reaches to 1/4°. For the models with a change in ocean and atmosphere resolution (HadGEM3-GC31, EC-Earth3P, CNRM-CM6-1), there is a similar reduction in the warming over the northern North Atlantic and a warming in the Nordic Seas. The signal over Europe is more uncertain.

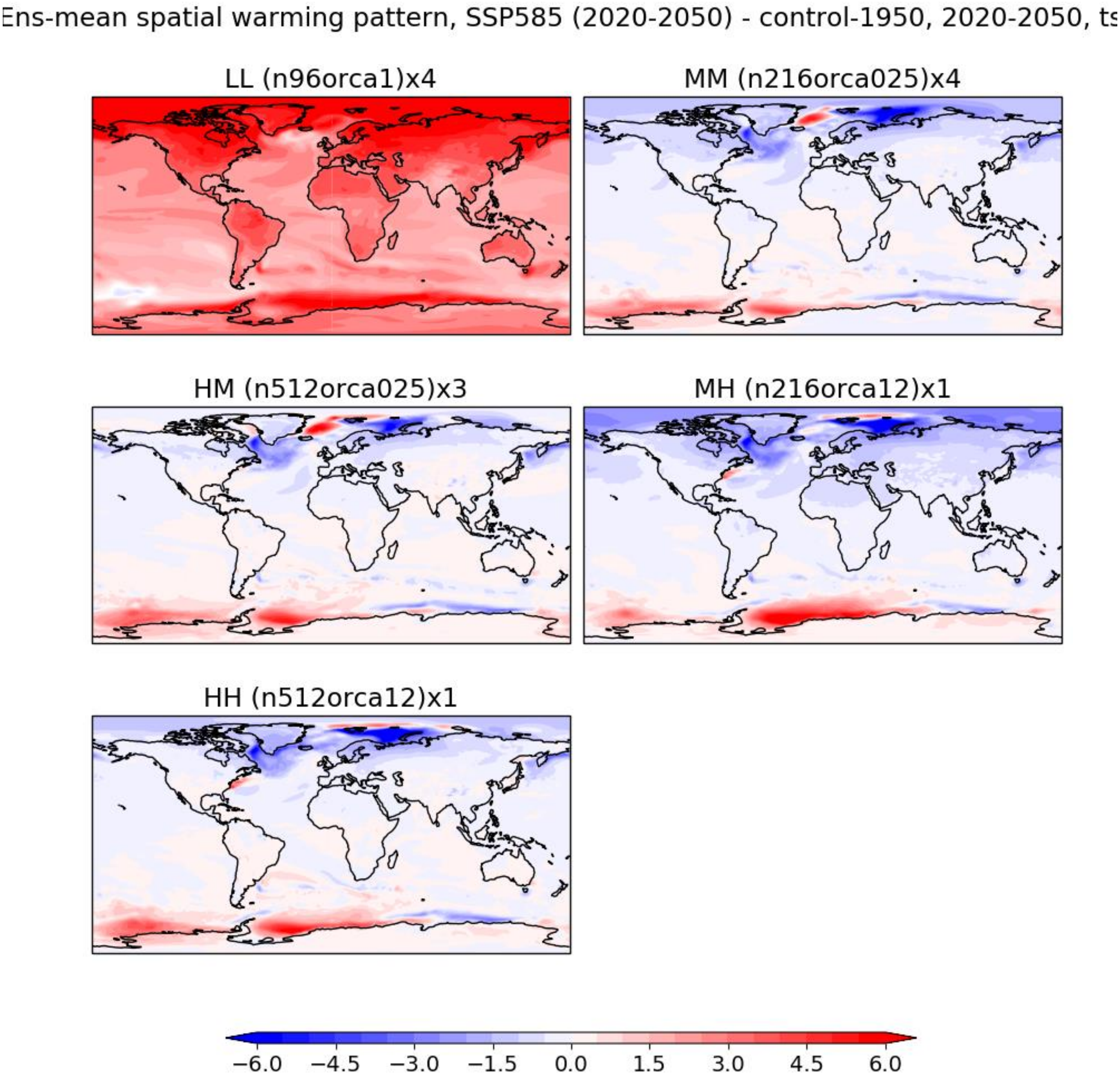

Figure 1: Global change in surface air temperature (tas) between 2030-2050 compared to the control-1950 mean for HadGEM3-GC31 models at different resolutions. Top left shows the mean change, other figures show how the different resolutions differ from the LL low resolution model. Scale is Kelvins.

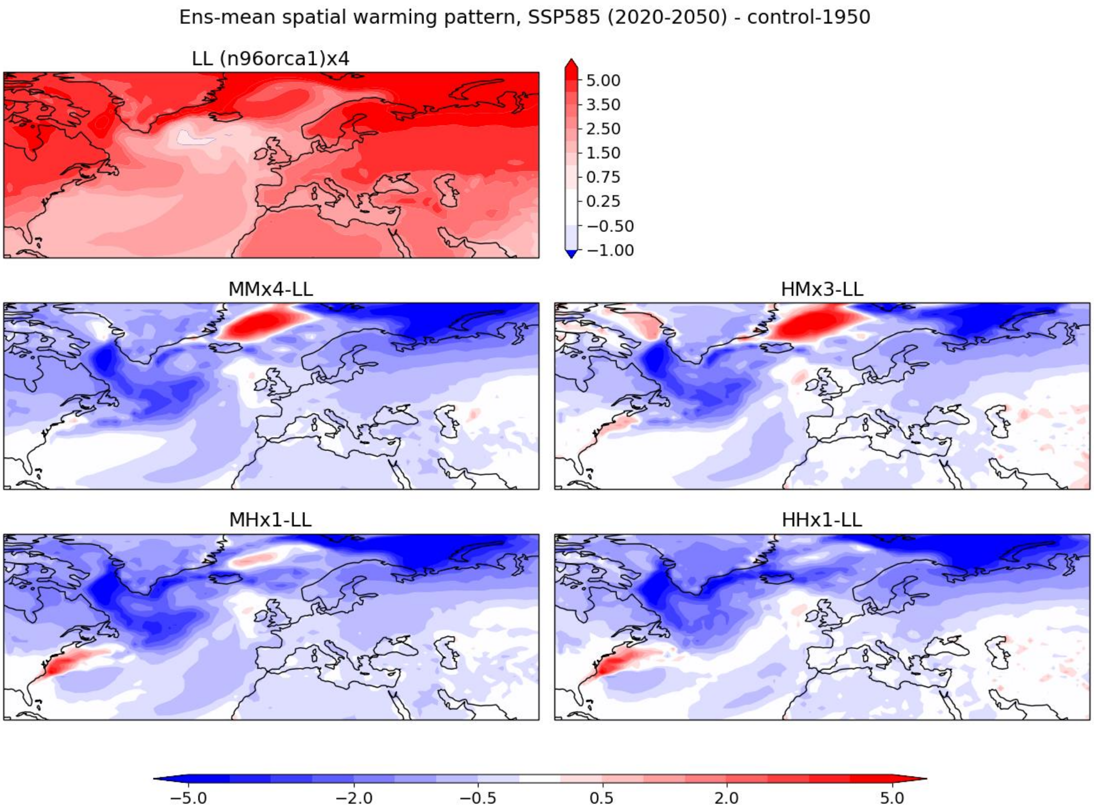

Figure 2: As Fig. 1 but for the European region only.

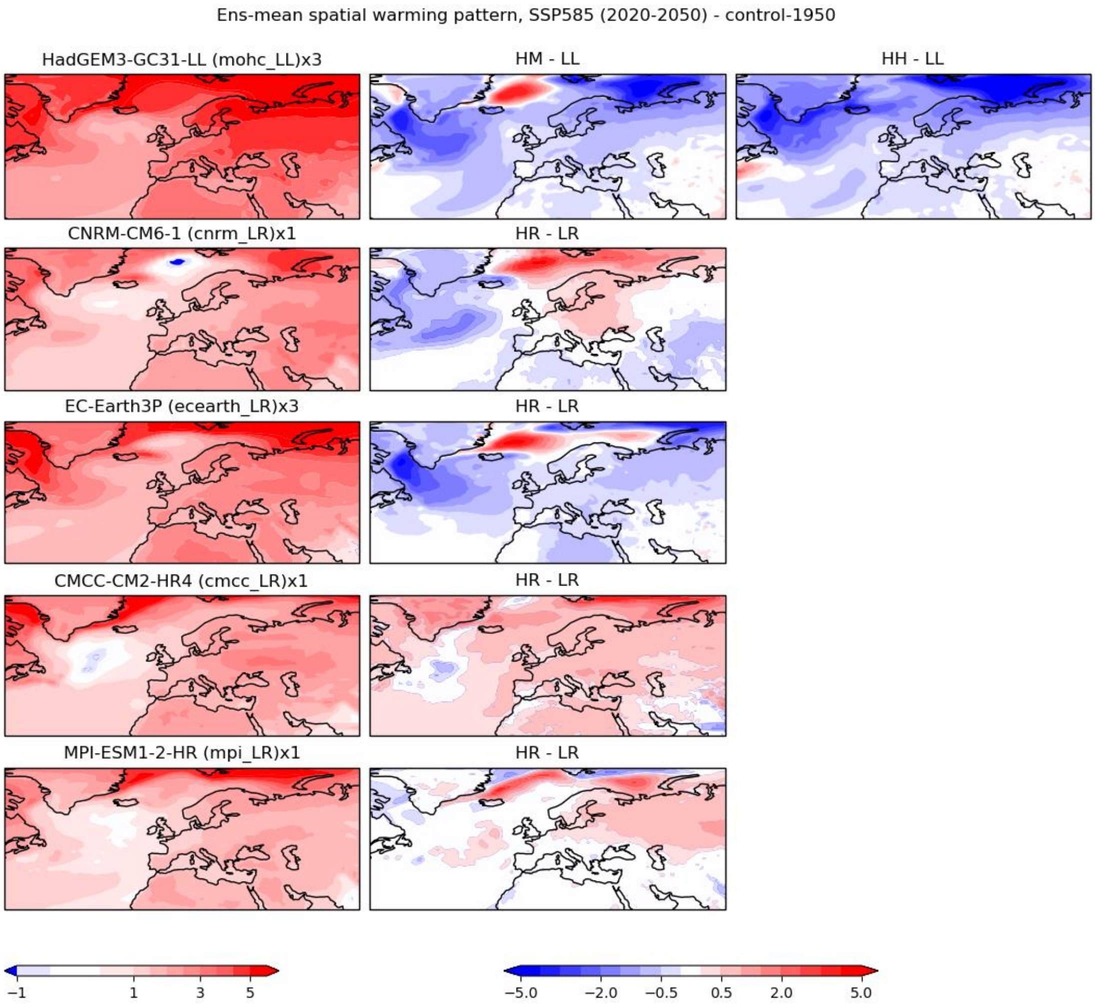

Figure 3: As Fig. 2 but for the different models used in PRIMAVERA. (left) are the 2030-2050 minus control-1950 changes, middle and right the relative resolution change. Note that the last two rows are models in which the ocean resolution is unchanged between low and high resolution.

3.1.2 Differences in heat distribution response to CO_2 forcing and thus AMOC stability

MPG and AWI use exactly the same atmosphere model ECHAM6.3 but a different ocean model in their coupled systems: MPG use MPIOM which operates on a traditional structured mesh and AWI use FESOM which runs on an unstructured mesh allowing to focus on dynamically active regions such as North Atlantic Current, Kuroshio and Southern Ocean or coastal areas. Effort has been put into developing a mesh dependent on sea surface height variability (Sein et al., 2016).

Probably the representation of aerosol cloud interactions has one of the strongest influences on climate sensitivity in climate models. However, here we show that the ocean representation can have an influence not only on the near-surface temperature but throughout the atmosphere (Fig. 4).

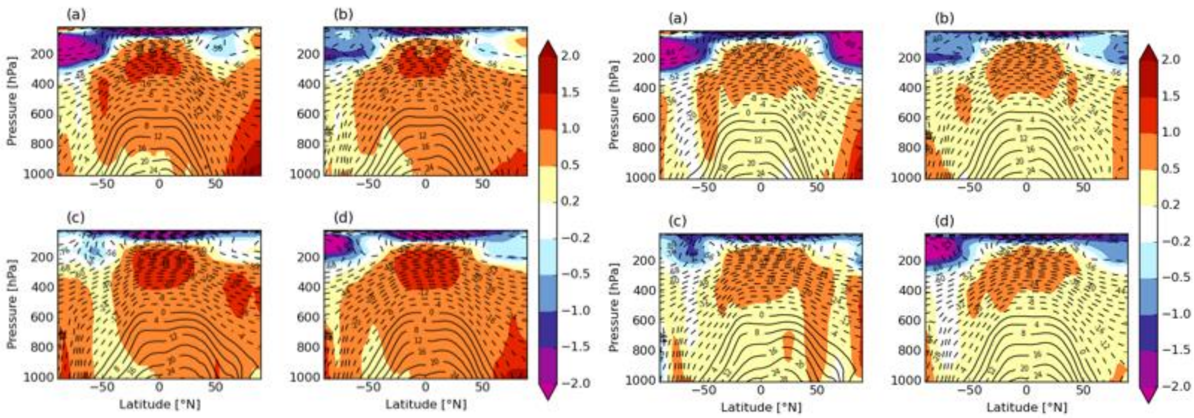

Figure 4: Zonally averaged atmospheric temperature response in the PRIMAVERA-HighResMIP simulations of AWI-CM-HR (left) and MPI-ESM-HR (right) historical 1984-2013 minus control-1950. (a) DJF, (b) MAM, (c) JJA, and (d) SON.

Indeed both the equilibrium climate sensitivity (ECS) and the transient climate response (TCR) are higher in AWI-CM compared to MPI-ESM: The ECS amounts to 3.2 K in AWI-CM-MR and to 3.0 K in MPI-ESM-HR while the TCR is 2.0 K in AWI-CM-MR and 1.7 K in MPI-ESM-HR (Meehl et al., 2020). It turns out that the anomalous heat distribution as a response to greenhouse gas forcing in the ocean is different. Fig. 5 shows that the amount of heat increases in the North Atlantic subpolar gyre as a response to greenhouse gas forcing in AWI-CM but decreases in the MPI-ESM. This could be related to a more stable AMOC in AWI-CM compared to MPI-ESM. In the CMIP6 DECK simulations we have found that when assuming the strongest emission scenario the AMOC declines by about 25% in AWI-CM and by about 40% in MPI-ESM until the end of the century compared to present-day. This would have clear implications for the European climate. A weakening AMOC is known to cause a cooling in the subpolar North Atlantic, reduced cloudiness over Europe (Laurian et al., 2010), an increase in surface pressure over Western Europe (Haarsma et al., 2015; Gervais et al., 2019), and a strengthened midlatitude jet in winter (Gervais et al., 2019) and a weakened midlatitude jet in summer (Jackson et al., 2015). This leads to milder, more maritime winters and warmer, more continental summers in Europe (Jackson et al., 2015). Therefore, a more stable AMOC would prevent such changes.

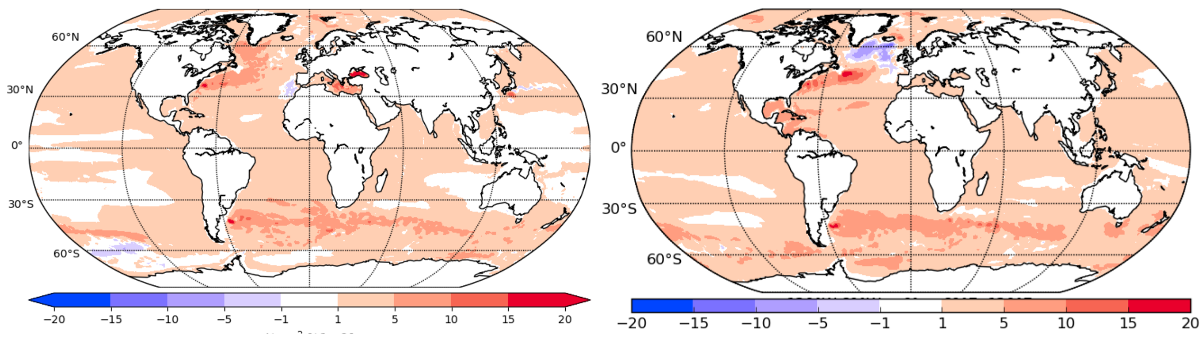

Figure 5: Ocean heat content anomaly (J*m^{-2}*1.e9) in the simulation with 1% CO_2 increase per year in the 20 years centered around doubling CO_2 (years 61-80) compared to the pre-industrial control simulation. Left: AWI-CM, right: MPI-ESM.

3.1.3 Impact of Nordic Seas overflows on the AMOC

Since AMOC can have an effect on the surface temperature distribution (see section 3.1.1), we investigate the contributions of various deep water formation sources to the AMOC variability, namely Labrador Sea and Nordic Seas overflow. In particular, we evaluate the effect of resolution on these sources and their impact on AMOC variability.

Based on the PRIMAVERA stream1 (WP6) and frontier (WP4) 1950 control simulations, we have assessed the impact of subpolar deep water formation and Nordic Seas overflows on AMOC variability across different model resolutions. At the current state, only simulations with our own model (MPI-ESM) applying three different ocean grid configurations (1 degree, 0.4 degree, 0.1 degree resolution) have been used, but the study shall be extended across all PRIMAVERA models.

As outlined in deliverable D2.5, the dominant impact of deep water formation in the Labrador Sea vanishes in the frontier resolution (0.1 degree), in line with Li et al. (2019). Regarding the Nordic Seas overflows, the frontier resolution is the only resolution, where a clear impact of the Faroe-Shetland-Channel overflow on AMOC variability is found (in contrast to the Denmark Strait overflow). For the coarser resolutions, no significant correlations are seen, when the AMOC is lagging the Faroe-Shetland-Channel overflow (Fig. 6).

The latter result is likely related to a better representation of the flow path of Iceland Scotland Overflow Water (ISOW). In the real world, the ISOW crosses the Mid-Atlantic-Ridge through relatively narrow fracture zones to eventually join the lower branch of the AMOC, manifested mainly in the deep western boundary current. The fracture zones are not resolved in the topography of the coarser-resolution model versions, and thus no clear flow of the ISOW across the Mid-Atlantic-Ridge is found. The topography in the frontier model version, however, exhibits fracture zones in the Mid-Atlantic-Ridge, through which the ISOW is flowing to the western basin (Fig. 7).

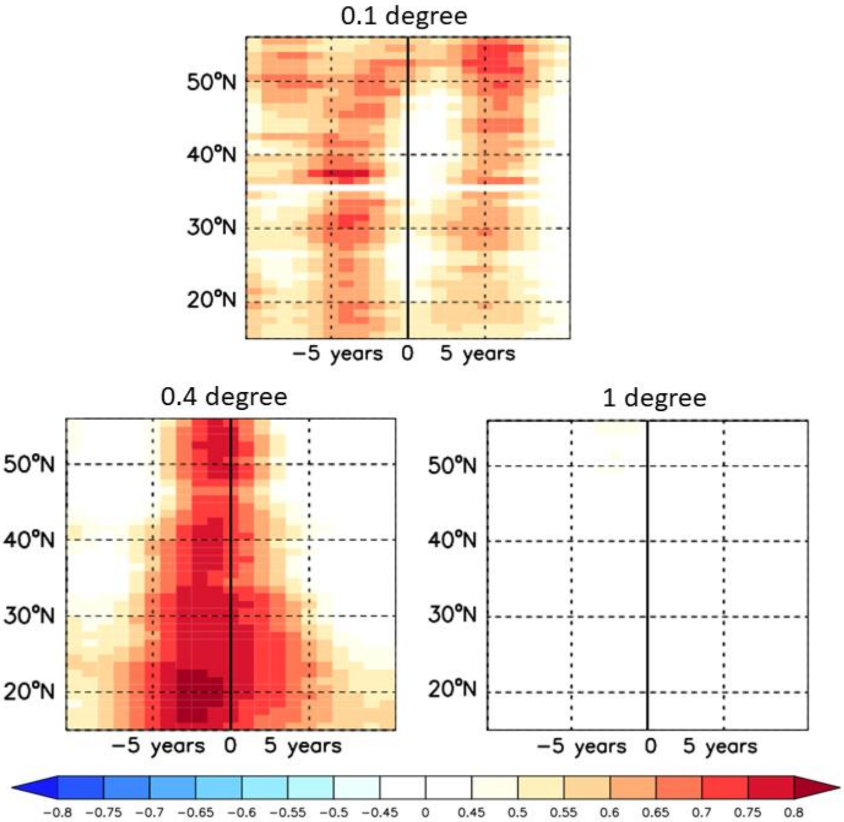

Figure 6: Lag correlation analysis between the maximum AMOC strength at different latitudes and the overflow transport through Faroe-Shetland-Channel for the different ocean grid configurations. Positive (negative) lags indicate that AMOC is lagging (leading).

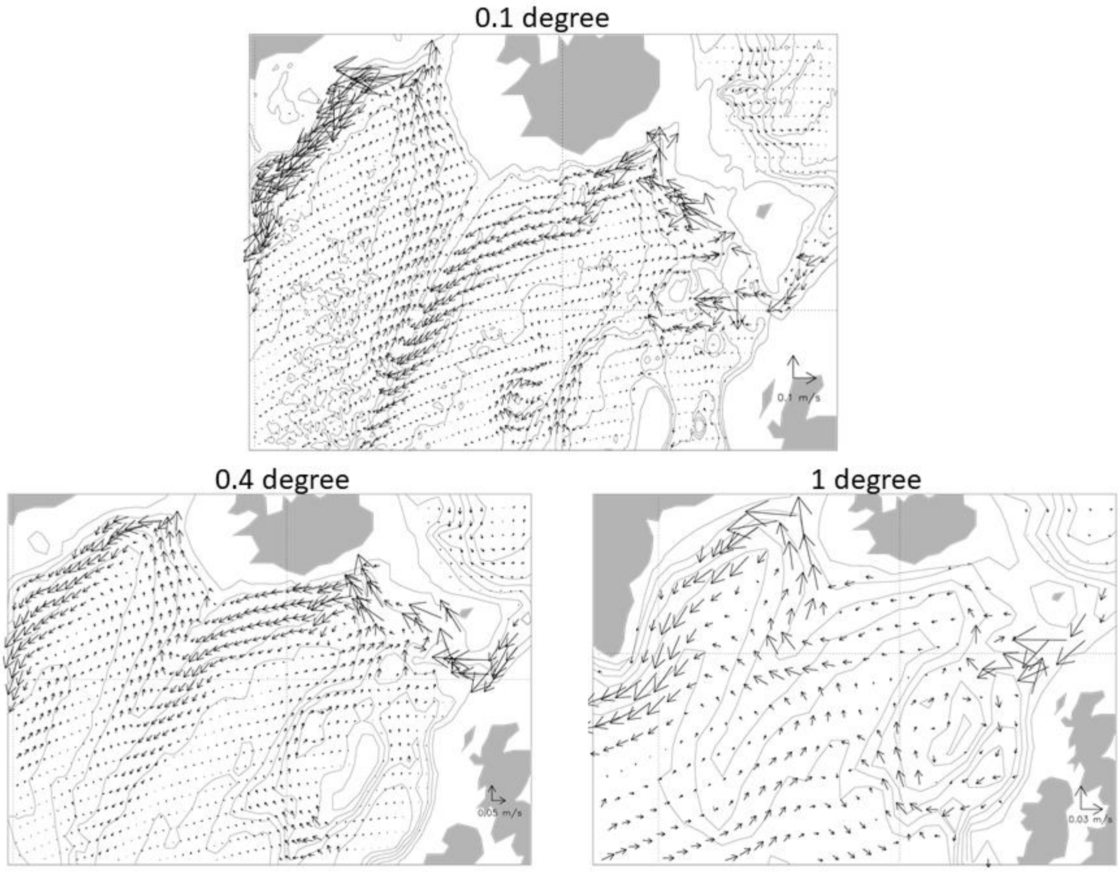

Figure 7: Model topography and current vectors (vertically averaged between the sill depth of the Iceland-Scotland-Ridge and 2000 m) for the different ocean grid configurations.

3.2 North Atlantic Oscillation (NAO) and weather regimes

3.2.1 Changes in relationship between NAO and Euro-Asia near-surface temperatures under severe global warming

Moving from the ocean perspective to the atmosphere, we investigate the impact of ocean resolution on a climate mode and its influence on regional climate variability. The North Atlantic Oscillation (NAO) has substantial influence on climate variability over Europe, Africa and North America (Hurrell and Deser, 2009). However, under global warming scenarios, it is unclear how the influence of NAO on northern hemispheric near-surface temperatures might change. It is even less clear how model resolution can affect those changes. We therefore seek to address the following questions:

1) How might the regional influence of NAO on wintertime near-surface temperatures over Euro-Asia and other parts of the world change under global warming? (Putrasahan and von Storch, 2020)
2) How does resolution affect the response to NAO- near-surface temperature relation to global warming?
3) Is the NAO- near-surface temperature relationship sensitive to the resolution independent of warming?

To address the first question, we employ the Max Planck Institute - Grand Ensemble (MPI-GE), which comprises 100 realisations of historical (1850-2014) and scenario cases (2015-2099), as well as 1%-CO_2 case (150 years from 1850). MPI-GE uses the MPI-Earth System Model (MPI-ESM1.2) at 1.5º ocean and 2º atmosphere resolution, to which we consider low resolution. We use the first 20-years of the 1%-CO_2 case to denote the baseline, i.e. 0K global mean surface temperature (GMST) anomaly, and the last 20-years of the 1%-CO_2 to signify a warmer climate state at 4K GMST anomaly. The upper panel of Fig. 8 shows the 20-years averaged ensemble covariability between NAO and 2m temperatures around the world based on MPI-GE. Over eastern Canada, western Greenland and the Sahel region, there is an anti-phase relation (blue negative values), while over Europe, Siberian Asia, Arctic and eastern US reveals a positive relation (red) between NAO and near-surface temperatures. Under severe warming, there is a stark decline in the magnitude of the covariability, especially over eastern Canada/western Greenland, and over Euro-Asia. Loss of sea ice greatly reduces surface temperature variability, which contributes to major decrease in NAO- near-surface temperature covariability for areas in the vicinity of sea-ice. Decrease in covariability further inland of Euro-Asia may be affected by the changes in mean atmospheric circulation of a warmer world. In contrast to the decline in covariability in higher northern latitudes, we detect a slight increase in the magnitude of covariability over the Sahel region, which may be attributed to the expansion of the Hadley cell that allows for more tropical disturbances to enter the subtropics and increase temperature variability.

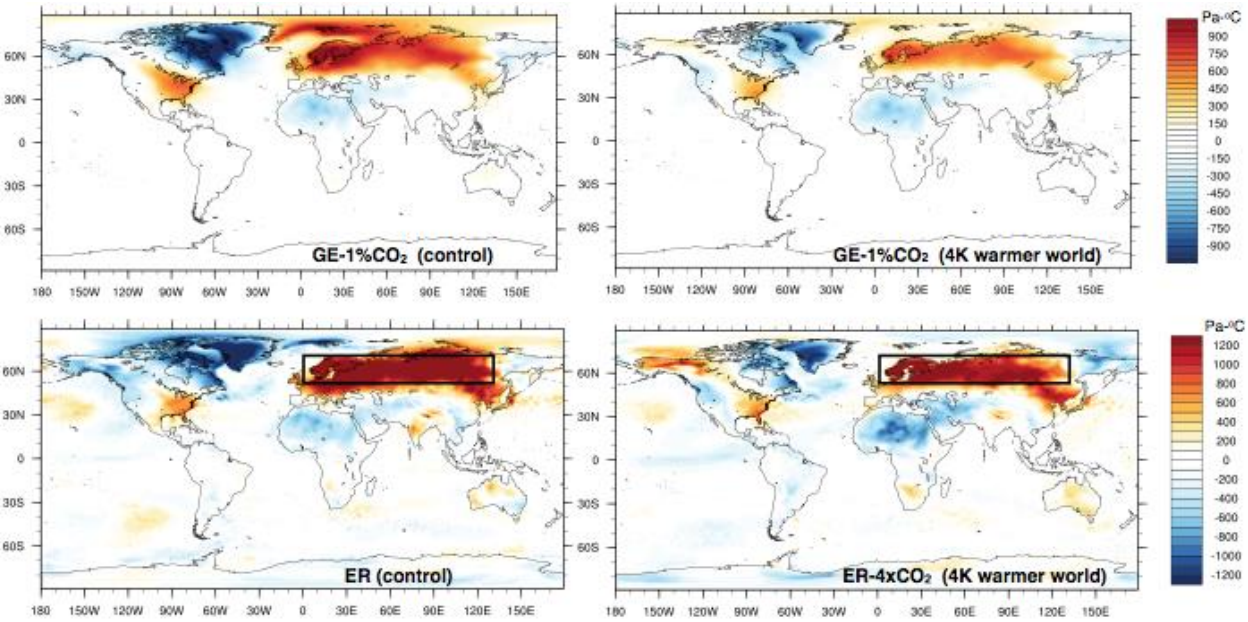

Figure 8: 20-years averaged ensemble covariability of NAO and surface temperatures based on: a) MPI-GE for the baseline 0K GMST anomaly; b) MPI-GE for a warmer climate state (4K GMST anomaly); c) ER control simulation for the baseline 0K GMST anomaly; d) abrupt 4xCO_2 ER simulation for a warmer climate state (4K GMST anomaly).

How would resolution affect such changes in covariability? We use a suite of ocean eddy-resolving MPI-ESM1.2-ER simulations (hereon denoted as ER for brevity sake) performed under WP4 of PRIMAVERA, and compared results to those obtained from the MPI-GE. ER configuration uses a 0.1º ocean and 1º atmosphere resolution, which we consider as high resolution. Due to the computational cost of running ER configuration, we were only able to produce 3 ensemble members of ER 4xCO2 simulations, each 100 years long and branched off on different neutral ENSO years from a 200-years ER control simulation. The spatial patterns of in-phase and out-of-phase covariability of NAO and near-surface temperature in ER (bottom panels of Fig. 8) are very similar to those found in MPI-GE, especially over land, albeit much higher. Over ocean, ER shows regions of covariability that are almost non-existent in MPI-GE. These differences may be attributed to increased temperature variability induced by increased resolution. In ER and under severe warming, a marked decline in magnitude of covariability is also seen over higher northern latitudes, and a more obvious increase in magnitude of covariability is observed over the Sahel region compared to MPI-GE.

The statistics for ER are based on 3 ensemble members, so the question arises if the results we see for ER are robust. We can actually test this by using the MPI-GE that has 100 members, subsample and create a probability density function (PDF) of 3-member ensemble covariances. For ease of visualisation and distillation of results, we focus on the relationship between NAO and near-surface temperature averaged over Euro-Asia (boxed region in Fig. 8), and evaluate if the reduction in covariance between NAO and Euro-Asia near-surface temperature is robust. Not only does the mean of the ensemble covariance (dashed lines) and the PDF in general decrease under severe warming, the PDF also narrows (Fig. 9). We see that the ensemble covariance in ER also decreases (solid dots). Indeed, the decrease in covariance seen in ER is robust.

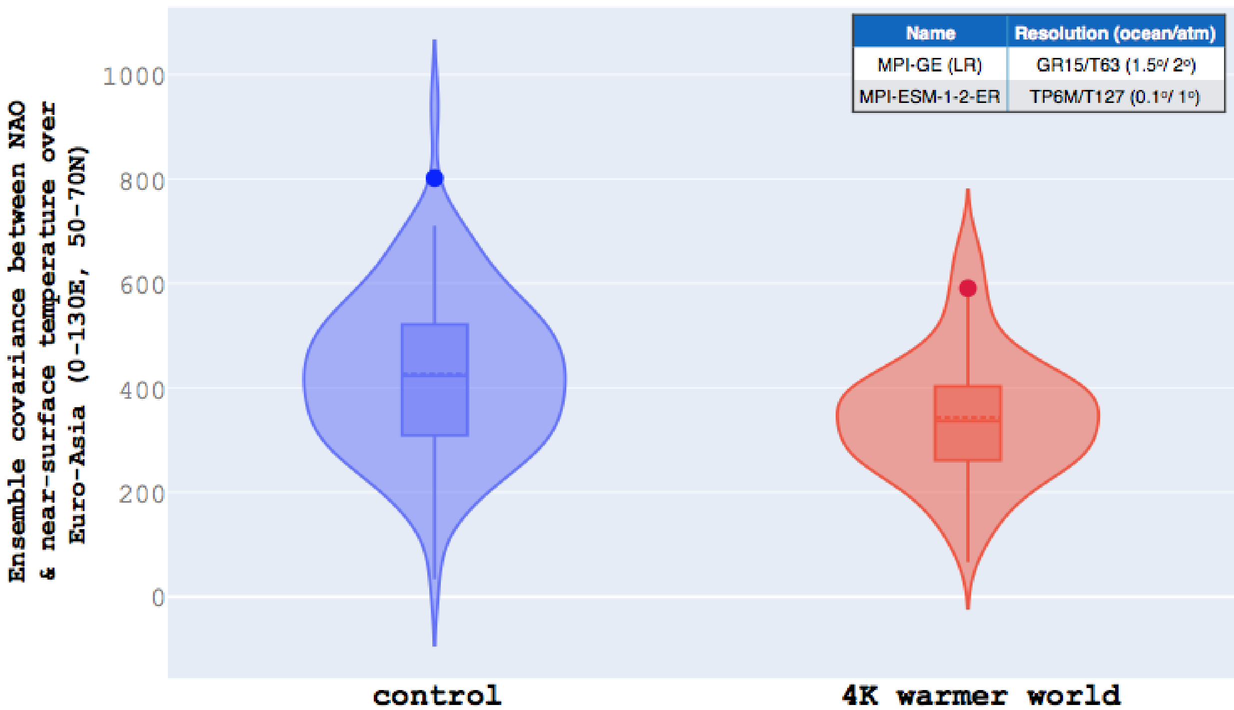

Figure 9: Probability density functions (PDFs) of 3-member ensemble covariance between NAO and near-surface temperature averaged over Euro-Asia for control baseline (0K GMST anomaly; blue) and 4K warmer climate (red). The PDFs were constructed by resampling from MPI-GE. Whisker plots inside PDFs indicate 2.5%, 25%, 50%, 75% and 97.5% percentiles of the PDFs. Dashed lines indicate ensemble mean. Solid dots are corresponding ensemble covariance from ER.

Even though ER and MPI-GE behave similarly in terms of the reduction in covariance under severe warming, it is striking that the covariance in ER is in the upper end of the PDF formed by the low resolution MPI-GE (Fig. 9). This suggests that higher resolution may have a different PDF than the low resolution, or in other words, the NAO-2m temperature relation could be sensitive to resolution, regardless of warming. We investigate this by looking at control runs from various PRIMAVERA models with differing ocean resolution, namely MPI-ESM, AWI-CM, HadGEM, CNRM and EC-Earth. Here we show PDFs of ensemble correlations between NAO and area-averaged near-surface temperature over Euro-Asia with blue PDFs representing those derived from eddy-resolving simulations, green are from eddy-permitting runs and yellow are the low resolution, non-eddy resolving runs (Fig. 10). The results are inconclusive for the effect of resolution on NAO-2m temperature relation when comparing eddy-permitting (green PDFs) to non-eddy resolving (yellow PDFs) runs. However, we can say that PRIMAVERA control runs show that eddy-resolving simulations (blue PDFs) generally have a higher correlation than their low-resolution counterparts (green and yellow PDFs).

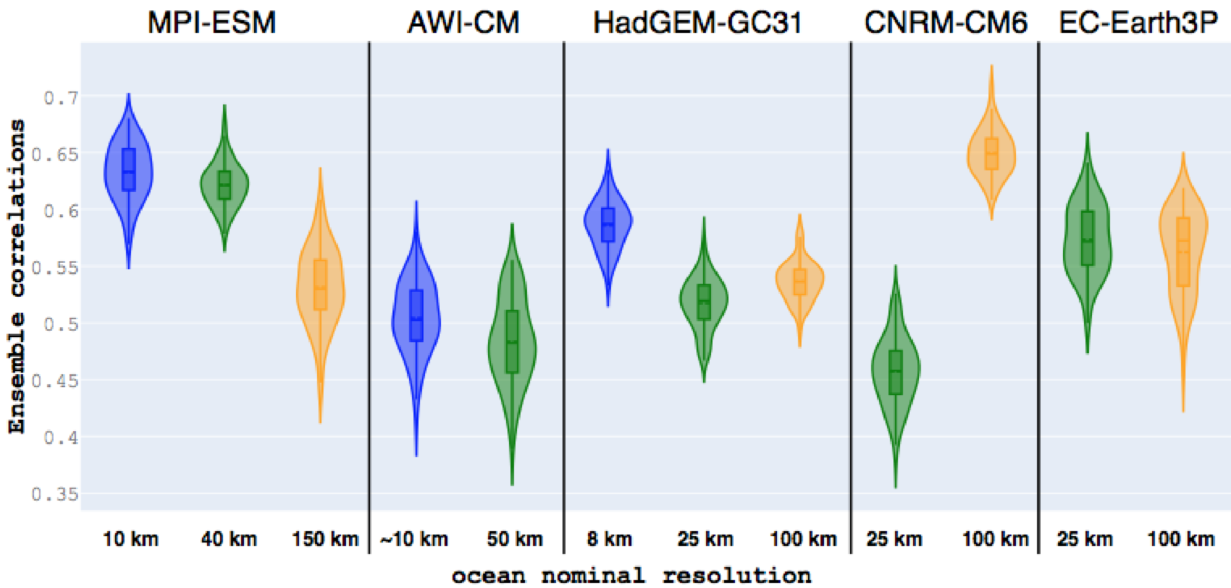

Figure 10: PDFs of 30-member ensemble correlation between NAO and near-surface temperature averaged over Euro-Asia for 5 different PRIMAVERA models. Each PDF is obtained by resampling control runs of ~100 years.

3.2.2 Future change in wintertime Euro-Atlantic weather regimes and related climate impacts over Europe

Weather Regimes (WRs) are persistent dynamical configurations that can last from a few days up to two or three weeks (Dawson et al., 2012; Hannachi et al., 2017). Here we focus on the Euro-Atlantic sector during winter (DJF) and look at the impacts of each WR in terms of temperature and precipitation anomalies over Europe.

For each simulation, we consider the daily geopotential height at 500 hPa over the Euro-Atlantic region and perform a K-means clustering analysis in a reduced phase space. The WR calculation is done through the Python package WRtool, following the procedure in Fabiano et al. (2020).

We analyze here the PRIMAVERA highresSST-present (1979-2014) and highresSST-future (2015-2050) simulations. The work is still ongoing, so some results are preliminary and only performed on a subset of all available simulations. In particular, the future projections (Figures 4 and 5) are only analyzed on EC-Earth, HadGEM and MPI-ESM.

First, we assess how the PRIMAVERA highresSST-present simulations reproduce the observed WR patterns. The results are shown in the Taylor plot in Fig. 11. The figure has four panels, one for each WR: NAO+, Scandinavian Blocking (SBL), NAO-, Atlantic Ridge (AR). The future simulations also show similar results in terms of pattern correlation (not shown), hinting that the change in the regime patterns is not significant with respect to the multi-model variability.

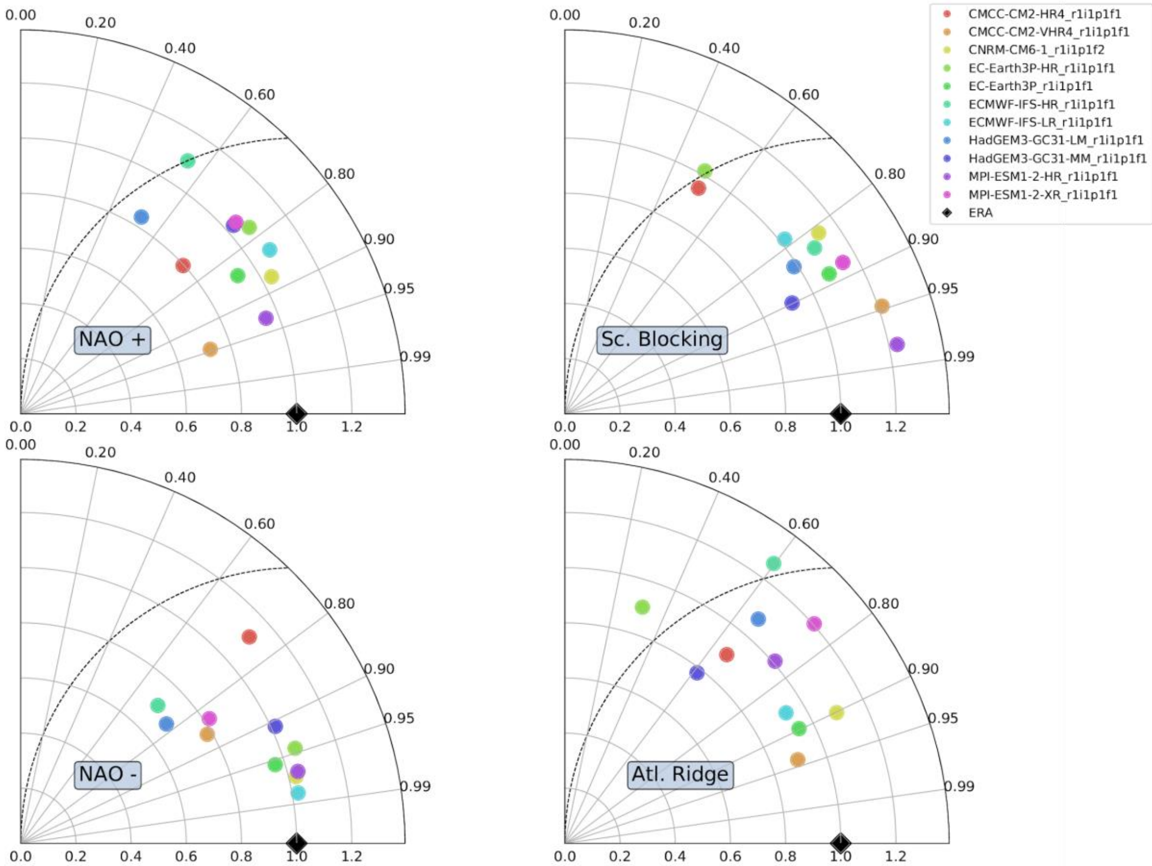

Figure 11: Taylor plot to evaluate the simulated regime patterns in highresSST-present simulations. The 4 panels correspond to the 4 regimes. The radial axis indicates the pattern standard deviation (normalized to the observed one) and the angular axis indicates pattern correlation with ERA. The linear distance between ERA and the models represents the RMS distance (without bias), so the closer the points the more similar are the patterns.

The models generally tend to produce less NAO+ states than the observations (not shown) and to overestimate the occurrence of AR. This behavior is also seen for the hist-1950 simulations (Fabiano et al., 2020).
The different regimes drive specific temperature and precipitation anomaly patterns over Europe. Daily composites of temperature and pressure for each regime are shown in Fig. 12. The models reproduce generally quite well the observed temperature and precipitation anomaly pattern, though with a large variability in the response and reduced amplitude. The ensemble mean of the HR models composites during the same period 1979-2014, shown in Fig. 13, systematically underestimates the amplitude of the observed anomalies. The LR ensemble produces qualitatively similar results (not shown), and no clear improvement is seen with increased resolution.

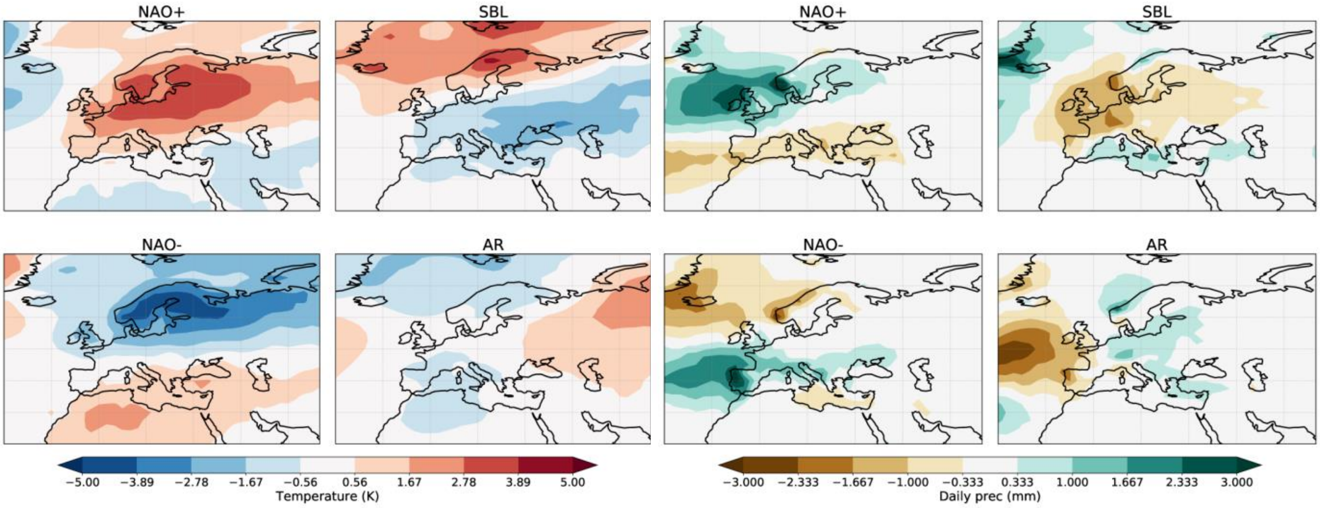

Figure 12: Composites of temperature (left) and precipitation (right) anomalies for each of the 4 regimes, from ERA-Interim 1979-2014.

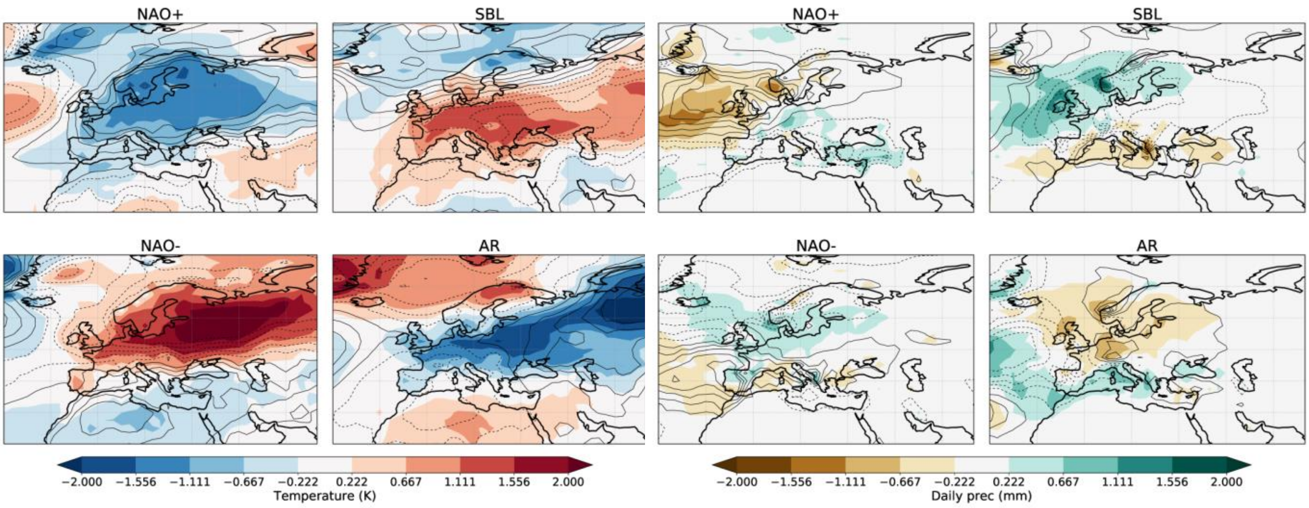

Figure 13: Difference between the multi-model mean of the HR models composites and the observed composites (shading), in years 1979-2014. Observed composites are shown by contours for reference (solid = positive, dashed = negative).

To understand how future changes in the large-scale circulation influence the temperature and precipitation variability over Europe, we observed how the temp/prec composites change in the highresSST-future runs. The predicted change in the HR models is shown in Fig. 14. The response shows a tendency for intensification in both the temperature and precipitation anomaly patterns with respect to present, with the only exception of the AR regime which shows a reduction in the temperature anomaly. Also, a southward shift in the maximum response is apparent in the NAO+ and NAO- regimes.

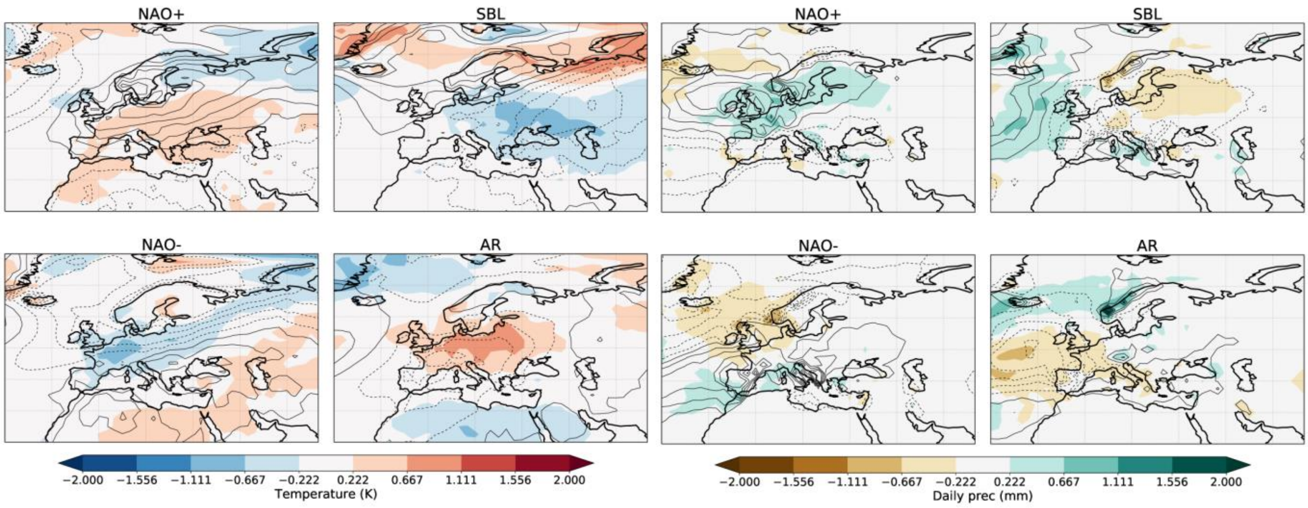

Figure 14: Change in the temperature (left) and precipitation (right) composites in the HR future simulations (2015-2050) with respect to the present ones (1979-2014). The present HR composites are shown in contours.

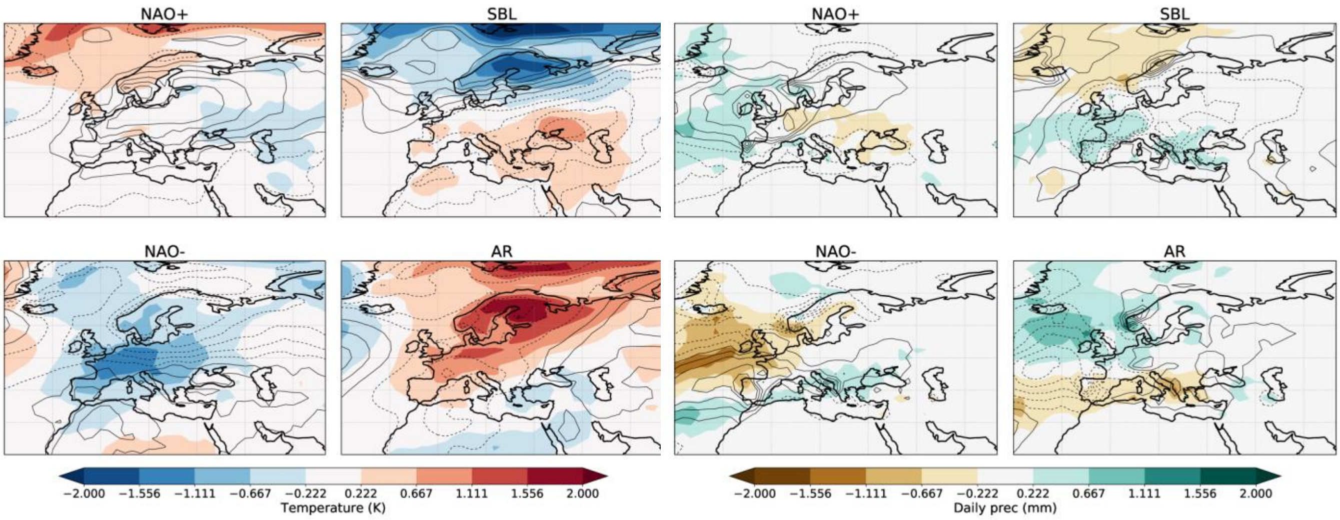

Figure 15: Same as Figure 4, but for the LR models.

The predicted change in the LR models shows some differences with respect to the HR ones (Fig. 15). Large differences in temperature are seen at the high latitudes for most regimes. Apart from that, the response of the NAO- and AR regimes are quite consistent with the HR ones. The NAO+ and SBL show a reversed response in temperature and SBL also shows large differences in precipitation, with a reduction of the present anomalies.

To better assess differences in the model projections, further analysis is needed and more models/ensemble members will be taken into account.

3.3 Comparative Analysis

3.3.1 Future changes in wintertime precipitation over Europe and the North Atlantic

IPCC models project a *likely* increase in winter precipitation over northern Europe under a high-emission scenario [IPCC, 2013]. However, the magnitude of the change in North Atlantic extratropical cyclone activity is less certain and, therefore, its impact on that precipitation increase [IPCC, 2013]. This is partly related to the sensitivity to model resolution of key processes driving precipitation and atmospheric circulation changes at local and hemispheric scales [e.g., IPCC, 2013; Willison et al., 2015; Shaw et al., 2016]. To evaluate this sensitivity, most of previous studies have relied on atmosphere-only regional and global models, which only provide a limited view of the climate system [e.g., Willison et al., 2015; Baker et al., 2019].

In collaboration with Met Office, we have assessed the sensitivity of future precipitation changes over Europe in winter (December–February; DJF) in ensembles of historical and scenario simulations generated with the coupled climate model HadGEM3-GC3.1 at five different resolutions, LL, MM, HM, MH, and HH (for L, low; M, medium; and H, high resolution; where the first and second letters indicate the resolutions of the atmosphere and ocean models respectively).

Although winter precipitation increases over parts of the North Atlantic and Europe by mid-century at all resolutions, the largest increase over NW Europe is projected in HH (at the highest atmosphere and ocean resolutions available; Fig. 16). Increased resolution in both the atmosphere and ocean is crucial for this increase, which suggests that models at lower resolutions, including the traditional ~100-km resolution, might considerably underestimate the projected winter precipitation increase over Europe.

The first element to explain the exceptional increase in precipitation in HH is an upper-ocean warming in the Gulf Stream (Fig. 17). The warming is only simulated in eddy-rich ocean models (MH and HH), related to a northward shift in the Gulf Stream. No such Gulf Stream warming and northward shift are projected at lower resolutions. The Gulf Stream warming, however, appears not sufficient to explain the changes in HH alone, since MH shows no large precipitation changes over NW Europe for a similar warming. Differences in the response of the atmosphere to the warming explain this.

HH shows enhanced extratropical cyclone activity in the North Atlantic compared to MH (Fig. 18a) or lower resolutions (not shown). This is characterized by the maximum eddy growth rate (computed with ESMValTool; Eyring et al., 2019), which is a measure of baroclinic instability and the development rate of extratropical cyclones. Increased eddy growth rate in HH implies more active extratropical cyclones compared to lower resolutions, which are responsible for the precipitation increase over NW Europe in winter.

Increased activity in extratropical cyclones in HH is driven by enhanced atmospheric diabatic heating in the North Atlantic (Fig. 18b). Diabatic heating accounts for latent heat release within an extratropical cyclone formation and normally works to sustain and amplify its development. Increased diabatic heating therefore leads to further storm development, contributing to the increase in the eddy growth rate in HH. Increased diabatic heating is directly related to the Gulf Stream warming, which provides an additional (latent) heat source to the atmosphere (not shown). However, only at a high atmosphere resolution (H) and not at a medium one (M), the increase in air–sea heat flux translates into enhanced diabatic heating, likely associated with better resolved mesoscale structures [e.g., Willison et al., 2015].

In tandem with increased diabatic heating, enhanced activity in extratropical cyclones is also driven by a much stronger acceleration of the jet in HH compared to lower resolution (Fig. 18c). This is because of enhanced eddy–mean flow interactions at higher (H) atmospheric resolution, in contrast to lower ones (M and L; not shown). A strengthened jet decreases atmospheric stability and, thereby, contributes to further storm development. The proposed changes explain the large increase in eddy activity and, by extension, in precipitation in HH.

Our analysis suggests that traditional coarse resolution global circulation models might be missing key processes implicated in future climate change. In particular, the North Atlantic and NW Europe climate appears more sensitive to greenhouse gas forcing at a much higher (25 km atmosphere, 1/12° ocean) resolution than at lower ones, including a traditional 100-km one.

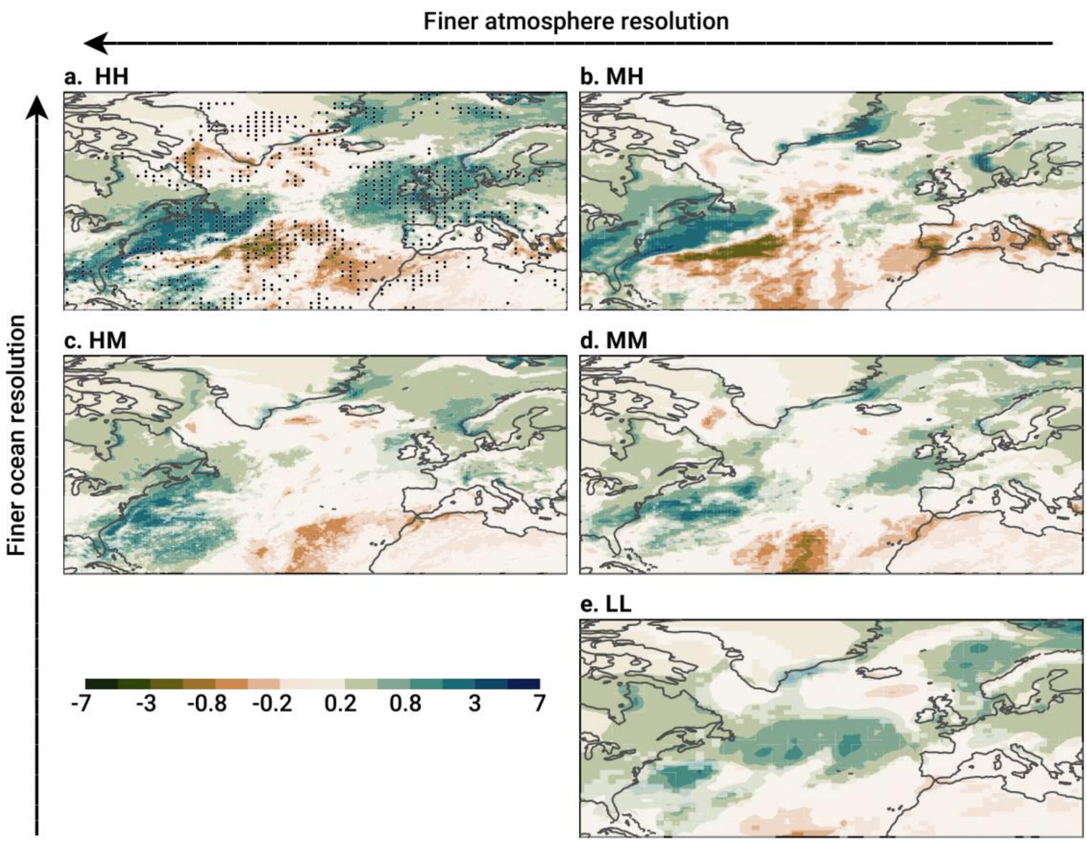

Figure 16: Change in DJF precipitation (in mm/day) between 2030–2050 and 1960–1980 in

(a) HH, (b) MH, (c) HM, (d) MM, and (e) LL. Ensemble means are shown for HM, MM, and LL. White shading masks non-significant anomalies at the 5% level. Stippling in (a) indicates anomalies in HH falling outside a distribution including anomalies from all the other resolutions.

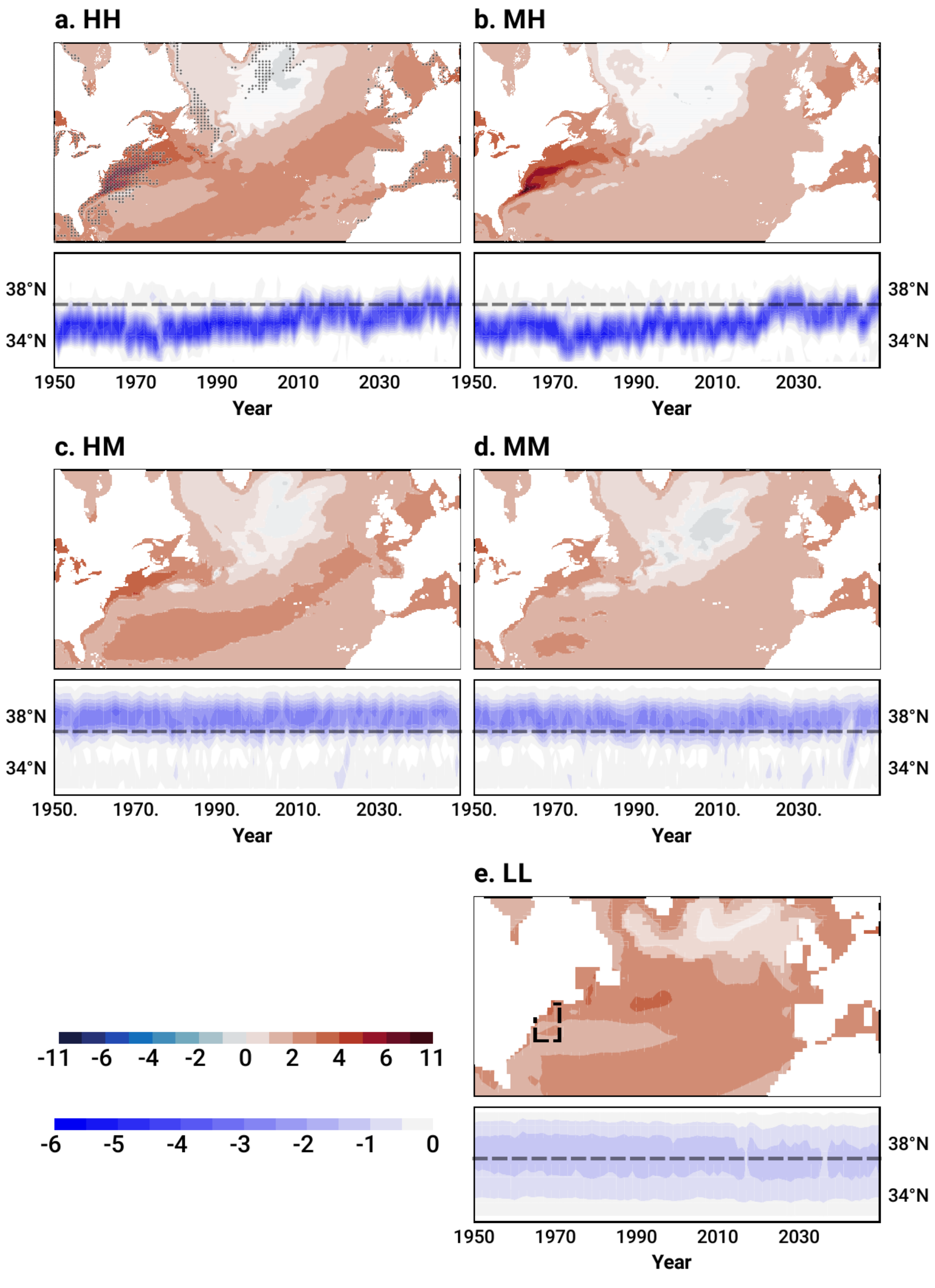

Figure 17: *Top panels*: As in Fig. 16, but for the yearly sea-surface temperature (in K). *Bottom panels*: Change in the latitudinal position of the Gulf Stream, illustrated through the time evolution of the maximum gradient in the yearly sea-surface height, averaged between 70°W and 74°W (units in 10^6 m/m; area shown in e, top panel). The dashed line indicates the mean position in the AVISO satellite observations for the period 1993–2018.

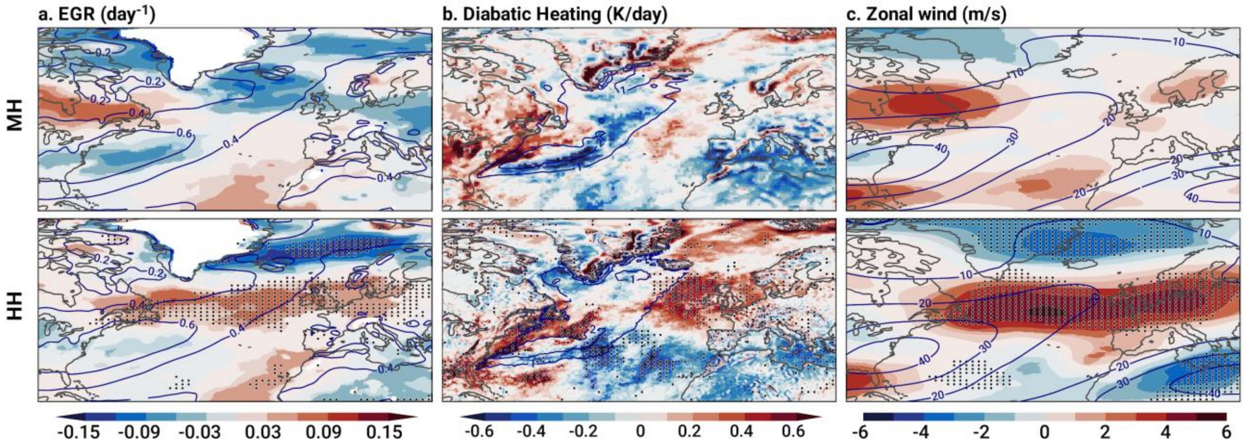

Figure 18: As in Fig. 16, but for the (a) DJF maximum eddy growth rate (EGR) at 700 hPa (in day^{-1}; Methods), (b) DJF atmospheric diabatic heating, averaged between 850 hPa and 250 hPa (in K/day), and (c) zonal wind at 250 hPa (in m/s), in MH (*top*) and HH (*bottom*). Contours are the 1960–1980 mean.

3.3.2 Enhancement of east Atlantic storminess in future projection

A manuscript entitled "Future evolution of an eddy rich ocean leads to enhanced east Atlantic storminess in a coupled model projection" by Grist et al. is being prepared for a journal article. Changes in North Atlantic winter surface ocean conditions and storminess associated with moving from an eddy-permitting (1/4º) to an eddy-resolving (1/12º) ocean in the 25 km atmosphere version of HadGEM3-GC31 have been examined. In the eddy-resolving control simulation, unlike the eddy-permitting version, the Gulf Stream correctly separates from the east coast of the USA at Cape Hatteras. This change leaves an imprint on the North Atlantic SSTs and surface fluxes. With regard to the future projections, the higher ocean resolution reveals a pronounced increase in storminess near the westernmost parts of Europe. This increase is associated with the distinctive long-term evolution of both the North Atlantic warming hole and the Gulf Stream separation in the eddy-resolving model.

This analysis illustrates that increased ocean resolution can reduce important model biases, such as the location of the Gulf Stream separation. The removal of such biases could potentially (and does in this example) allow processes to operate that more clearly reveal future climate risks such as mid-latitude storm changes. However, an ensemble of simulations may be required for a fuller understanding of the impact of eddy-rich oceans on future projections of European climate, which is currently challenging due to their high cost.

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4 Lessons Learnt

One of the biggest challenges in WP4 work has been the length of time and cost of setting up and running the eddy-rich ocean simulations, which is why there are only three such models available for analysis. Given the apparently typical behaviour of the Gulf Stream separation moving north under warming (also found in previous studies), and the implications for European climate, we could have placed more emphasis and resource on producing such simulations with other models. However, this would have meant compromising other simulations (such as the additional ensemble members in Stream 2 used in many other WPs), which have also been important in both assessing variability, and have really contributed to the end-user work in WPs 10,11.

Future work may well focus on this eddy-rich regime, since it is clear that despite 10-20 years of development, the lower resolution ocean models are not able to produce a better separation of the Gulf Stream from the US coast.

5 Links Built

As indicated in much of this work, there are very strong links between these analysis and work in WP2 using the simulations from WP6. We also used various tools, such as for AMOC analysis, as used in WP1,2.

Producing eddy-rich simulations and presenting work at conferences helped to make links with the iHESP project (collaboration between NCAR, Texas A&M and Qingdao in China) who have been running long eddy-rich simulations with CESM1.3. We have shared results and data, with contributions to several peer-reviewed papers and the likelihood of many others in the future The MPI-ESM eddy-resolving configuration that we set up in PRIMAVERA has now been adopted for use in other projects such as FAFMIP and German BMBF-project HIPRED RACE, and is likely to be used in future projects too.