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Improved European heat event simulation in eddy-resolving climate models

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Owing to the rapid increase of European heat event occurrences over the past decades, the understanding of their physical drivers has become increasingly important for the scientific community. Recently, it has been shown that cold North Atlantic sea surface temperatures are strongly linked to European heat events such as in summers of 2015 and 2018. Thereby, an accurate representation of this mechanism in climate models is crucial for a more realistic European heat event simulation. Here, we investigate the mechanism by employing seven global coupled climate models, of which six models are embedded in the High Resolution Model Intercomparison Project. Our results show that, compared to the models with low-resolution versions, high-resolution ones simulate a more realistic relationship between North Atlantic sea surface temperatures and European summer temperature extremes. This is attributable to a better reproduction of the North Atlantic trough and the downstream ridge anomalies over central Europe. Improvements in high-resolution ocean configurations reduce the North Atlantic surface biases and improves air-sea interactions, thus having implications for the prediction and projection of climate extremes in the North Atlantic-European region.

Most global coupled climate models within the current Coupled Model Intercomparison Project phase 6 (CMIP6)¹ misrepresent several features in the North Atlantic, such as a warm sea surface temperature (SST) bias off the North American coast², an incorrect path of the Gulf Stream, the North Atlantic Current and the strength of the associated mid-latitude SST front³. The North Atlantic Current simulated with a too zonal path causes a pronounced cold SST bias in the central subpolar North Atlantic e.g.,^{4–6}. The cold SST bias causes additional biases such as in the surface turbulent heat flux⁷, the development of atmospheric Rossby waves⁸ and weather regimes in the North Atlantic-European sector^{9,10}. A reduction of North Atlantic biases is related to a more realistic European climate and wintertime blocking frequency^{11,12}.

The North Atlantic influences the development of European summertime heat events, as shown in several case studies incorporating model experiments for European heat events in 2015^{13,14} and 2018^{15–17}. A general relation between North Atlantic SSTs and European heat events was established by using a composite analysis based on ERA5 reanalysis data which revealed that events of cold subpolar North Atlantic SSTs with an additional temperature decline on a timescale of a few days, hereafter referred to as “negative tendency”, are followed by a downstream

development of an atmospheric ridge and anomalously high temperatures over central Europe¹⁸. For instance, a specific event characterised by cold North Atlantic SSTs with a negative tendency as part of the composite happened on 25 June 2015, preceding the onset of the European heat event in the beginning of July 2015. The mechanism involves processes for the formation of blocking highs over Europe¹⁹, enhanced upward surface latent heat fluxes, ascending air movement and precipitation in the North Atlantic. An observational study further supports the role of cold subpolar SSTs in strengthening the mid-latitude SST gradient, enhancing low-level atmospheric baroclinicity and cyclonic conditions aloft, and ultimately contributing to anticyclonic conditions and warmer temperatures over Europe²⁰.

The aim of this study is to investigate this mechanism between cold North Atlantic SSTs with a negative tendency and European heat events in climate models participating in the High Resolution Model Intercomparison Project (HighResMIP). 100-year long experiments were run in pairs with one standard-resolution configuration and one high-resolution configuration to investigate the impacts of horizontal resolution in the atmosphere and ocean²¹. The atmospheric resolution is mostly increased from ~ 100km in standard-resolution to ~ 50km in high-resolution

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configurations. With respect to the ocean component, the standard-resolution configuration typically has a horizontal resolution ($\sim 100\text{km}$) unable to resolve baroclinic instability and thus mesoscale ocean eddies must be parameterised, hereafter referred to as *eddy-parameterised*. The high-resolution configurations often incorporate an *eddy-permitting* ($\sim 25\text{km}$) or *eddy-rich* ($\sim 10\text{km}$) ocean model^{7,22}.

In general, higher sample sizes are available relative to ERA5, owing to simulations covering 100 years. Together with a pre-industrial control experiment with the FOCI model²³, we assess the capability of climate models in HighResMIP (Table 1), to reproduce the mechanism between North Atlantic SSTs and European heat events¹⁸. We provide an estimate about how summertime surface biases over the North Atlantic influence this mechanism and the performance of the models with regard to the simulation of European heat events.

Results

North Atlantic surface biases

We examine surface latent heat flux (SLHF) biases in seven global coupled climate models (Table 1) including six models from HighResMIP and the FOCI model. The latter has an increased ocean horizontal resolution of the North Atlantic only, offering the advantage of assessing the effects of mesoscale ocean eddies confined to the North Atlantic domain.

There are currently no gridded data sets available providing long-term observational records of SLHF over the North Atlantic. Thus, we first compare two products as potential reference data sets for SLHF bias estimation, namely the ERA5 reanalysis product²⁴ and the Objective Analysis (OA) Flux data set. The latter is a blend of satellite observations and reanalysis with the COARE bulk formula applied²⁵. A general offset exists between both products, with OA Flux generally showing a stronger downward SLHF compared to ERA5. The difference over the North Atlantic region in summer is -9.75 W m^{-2} , which exceeds the uncertainty of the OA Flux SLHF data (-4.34 W m^{-2}) (Fig. S1). However, systematic

differences between the data sets are smaller in the extratropical North Atlantic compared to tropical regions, and are also reduced during summer relative to other seasons.

ERA5 has been shown to perform well in variables that influence SLHF, such as low-level winds over the ocean. Studies comparing ERA5 surface winds to direct measurements have demonstrated a substantial improvement in accuracy compared to its predecessor e.g., ERA-Interim²⁷. Specifically, North Atlantic air-sea heat fluxes of ERA5 have been quantitatively assessed and found to be temporally stable and reliable enough to serve as a reference for evaluating other products²⁸. Consequently, SLHF biases are calculated using ERA5 as the reference data set, also to ensure consistency with the composite analysis.

The summer climatology of SLHF is generally negative or upward in the subtropics and slightly positive (downward) in the subpolar regions (Fig. 1a). A downward SLHF bias of up to $50\text{--}60\text{ W m}^{-2}$ occurs along the Gulf Stream and extension region in all low-resolution models (Fig. 1b–h), consistent with a large cold SST bias (Fig. S2). The SLHF bias extends into the examined North Atlantic box in all low-resolution models except for CMCC-CM2, which has the highest ocean model resolution ($\sim 25\text{km}$) among the low-resolution configurations. The summertime biases presented here are similar to the wintertime biases¹¹.

The SLHF bias is reduced by $\sim 50\%$ with increased ocean horizontal resolution from an eddy-parameterised to an eddy-permitting ocean (Fig. 2), together with a decreased cold SST bias (Fig. S3). HadGEM3-GC3.1 configurations illustrate that the biases are most considerably diminished when moving from the eddy-parameterised HadGEM3-GC3.1-LL to the eddy-permitting HadGEM3-GC3.1-MM (Figs. 2a, S3a) compared to bias changes relative to the eddy-rich HadGEM3-GC3.1-HH version (Figs. 2b, S3b). This result demonstrates a significant reduction in SST bias as the model resolution increases from eddy-parameterised to eddy-permitting configurations in HadGEM3-GC3.1, which aligns with previous findings²⁹. Where the ocean horizontal resolution remains the same for low- and high-

Table 1 | List of HighResMIP and FOCI simulations with atmospheric resolution at 50°N¹¹ and ocean resolution approximated for a more straightforward classification

Model	Resolution Label	Atmos. resolution (km)	Ocean resolution (km)	SST/SLHF bias correlation	Composite size	Classification
HadGEM3-GC3.1	LL	135	100	0.87	37	Low-Res
	MM	60	25	0.63	41	High-Res
	HH	25	8	0.57	37	High-Res
CNRM-CM6	CM6-1	142	100	0.84	45	Low-Res
	CM6-1-HR	50	25	0.71	42	High-Res
EC-Earth3	3P	71	100	0.63	23	Low-Res
	3P-HR	36	25	0.69	43	High-Res
ECMWF-IFS	LR	50	100	0.79	25	Low-Res
	MR	50	25	0.73	40	High-Res
	HR	25	25	0.73	40	High-Res
CMCC-CM2	HR4	64	25	0.68	42	High-Res
	VHR4	18	25	0.75	47	High-Res
MPI-ESM1.2	HR-KPP	67	50	0.92	35	Low-Res
	XR-KPP	34	50	0.91	28	Low-Res
	HR-PP	67	50	0.93	42	Low-Res
	ER-PP	67	10	0.93	38	High-Res
FOCI1.10	Standard	200	50	0.93	31	Low-Res
	VIKING10	200	10	0.83	37	High-Res
ERA5 reanalysis	–	25	–	–	12	–

Pearson Correlation coefficient comparing spatial fields of SST and SLHF bias over time for grid points within the North Atlantic box (40–15°W, 45–60°N) returning a scalar correlation value; composite sizes and classification into Low-Res or High-Res; the ERA5 reanalysis is used for comparison, bold highlighted versions are used for Fig. S9.

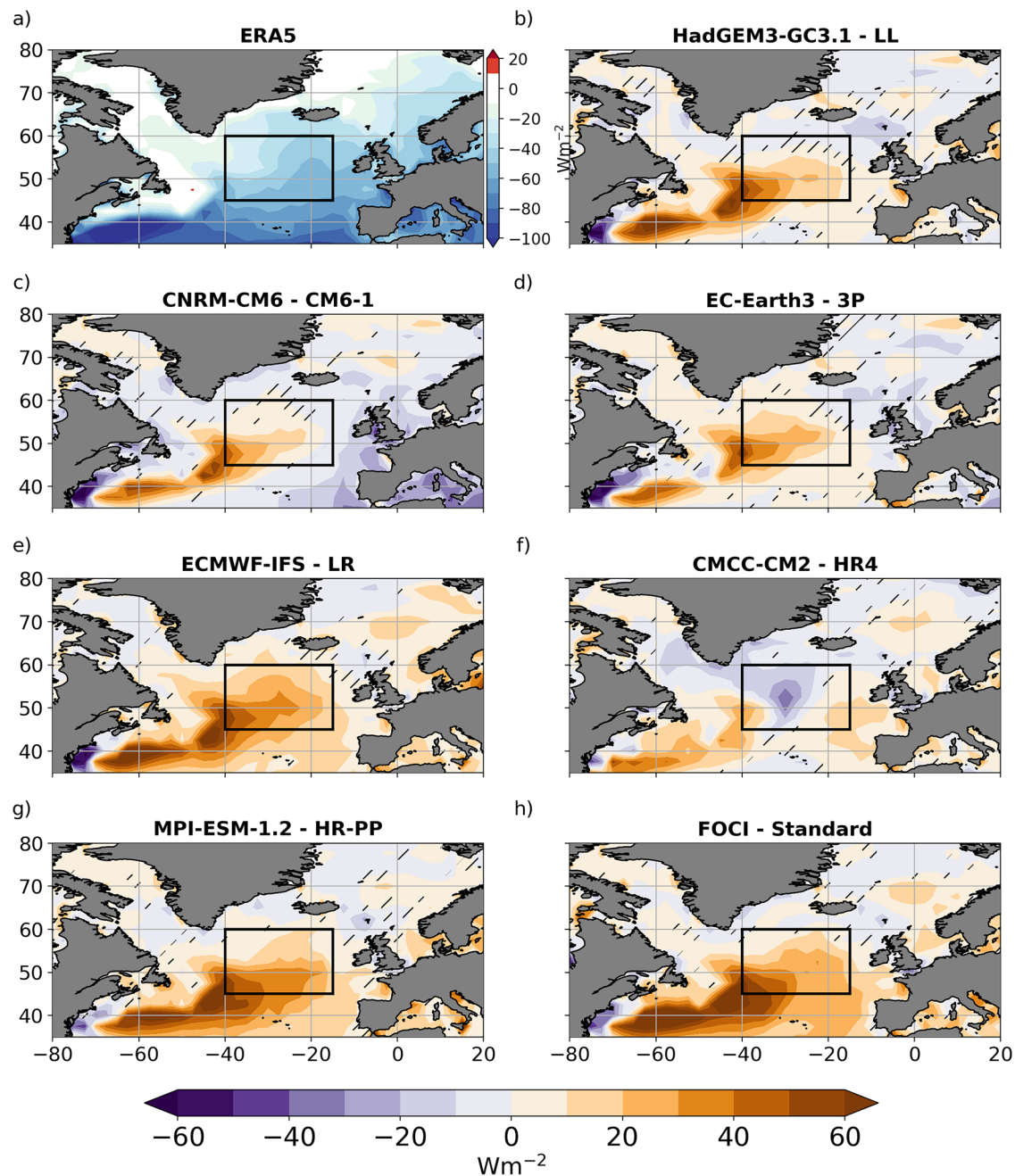


Fig. 1 | Surface latent heat flux bias during summertime. a Summer (JJA) surface latent heat flux (SLHF) climatology for the ERA5 reanalysis (downward positive); **b–h** SLHF bias for the low-resolution versions of each model. Hatching indicates

insignificant values according to a 95% confidence interval. The black box indicates the area (40–15°W, 45–60°N) used for the calculation of the Pearson correlation coefficient shown in Table 1.

resolution configurations, the SLHF bias hardly changes (Fig. 2f). Still, the reduction of the SLHF bias varies among ECMWF-IFS and EC-Earth versions, although both models use the same ocean model (NEMO) and have identical ocean resolutions across their two configurations (25 and 100km), which in turn emphasises the sensitivity to, and the dependence on, the choice of the atmosphere model for the SLHF bias (Fig. 2d, e). In this context, an accurate simulation of near-surface winds has been generally found to be important for controlling the modelled SST state³⁰.

The cold bias emerges through insufficient horizontal resolution in the ocean model component e.g.,⁷. Low-resolution ocean models have a higher viscosity, parameterised eddies and simulate a diffuse and too-zonal North Atlantic Current³¹. Subtropical warm water masses do not flow as far north and cold subpolar water masses extend further south compared to observations. The SLHF bias has a strong positive correlation (Pearson

correlation coefficient) with the SST bias within the North Atlantic box throughout all model versions (Table 1). The SLHF is governed by the difference ($q_s - q$) of saturation specific humidity q_s and the specific humidity q ³². With a cold SST bias, q_s gets smaller and in turn the difference $q_s - q$ is reduced, equal to an underestimation of evaporation and SLHF³³. Thereby, the SLHF bias is expected to strongly result from the cold SST bias and the ocean model component, although near-surface atmospheric stratification and wind can contribute to the SLHF bias as well.

Composites of cold North Atlantic SSTs

In this section, we examine composites of events of cold North Atlantic SSTs with a negative tendency according to the methodology presented in a previous study¹⁸. A cold North Atlantic SST event with a negative tendency is identified when the North Atlantic SST remains below the 0.1 quantile

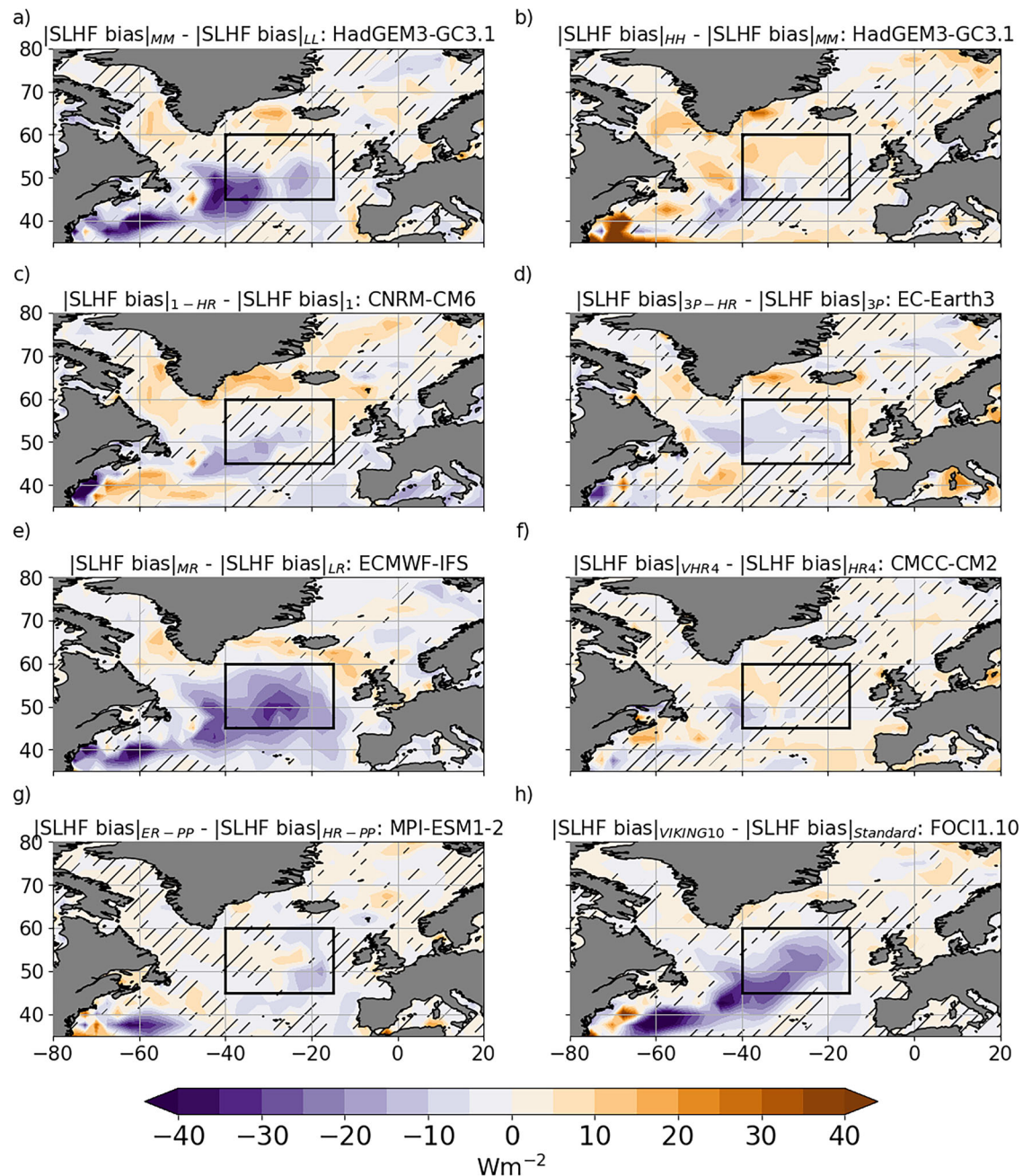


Fig. 2 | Difference of surface latent heat flux bias between high- and low-resolution versions. a–h Differences of absolute values of the JJA surface latent heat flux (SLHF) bias between high- and low-resolution configurations for each model.

Hatching indicates insignificant values according to a 95% confidence interval. The black box indicates the area (40–15°W, 45–60°N) used for the calculation of the Pearson correlation coefficient shown in Table 1.

threshold of the distribution of daily summer SSTs for at least three consecutive days and two events have to be at least 30 days apart from each other.

Composites based upon ERA5 show that cold North Atlantic SSTs with a negative tendency are followed by positive central European surface temperatures of +1.5 °C in the composite mean around five days later (Fig. 3a, S4a,c). A trough over the eastern North Atlantic with anomalies of more than -60gpm induces the negative tendency of already cold SSTs and upward SLHF anomalies of -25Wm⁻² (Figs. 3g, S4a,b). Positive anomalies in the 775hPa maximum Eady Growth Rate (EGR), reaching up to +0.16 day⁻¹, occur as a result of an enhanced meridional SST gradient, in agreement with previous studies^{11,20}. In turn, strengthened low-level baroclinicity between 45 and 50°N contributes to both the intensification and anchoring of the trough over the eastern North Atlantic (Fig. 3j).

Subsequently, a ridge and positive surface temperature anomalies develop downstream over central Europe (Fig. 3a,d, S4c,d).

In the following, we assess the capability of climate models classified into low- and high-resolution models (Low-Res and High-Res) to reproduce this observed time-lagged mechanism by creating composites of events of cold North Atlantic SSTs with a negative tendency for each model configuration. Upward SLHF anomalies are quite weak with values in the range of -5 to -10Wm⁻² in the Low-Res multi-model mean, indicating an underestimation of evaporation and low-level moisture anomalies compared to ERA5 (Fig. 3h). Consequently, insufficient moisture supply and baroclinicity with EGR anomalies of only +0.08 day⁻¹ in the lower troposphere prevent the reinforcement and anchoring of the trough over the eastern North Atlantic (Fig. 3k). Thus, the upper-tropospheric trough-ridge pattern is considerably weaker than in ERA5 (Fig. 3e), also resulting in European

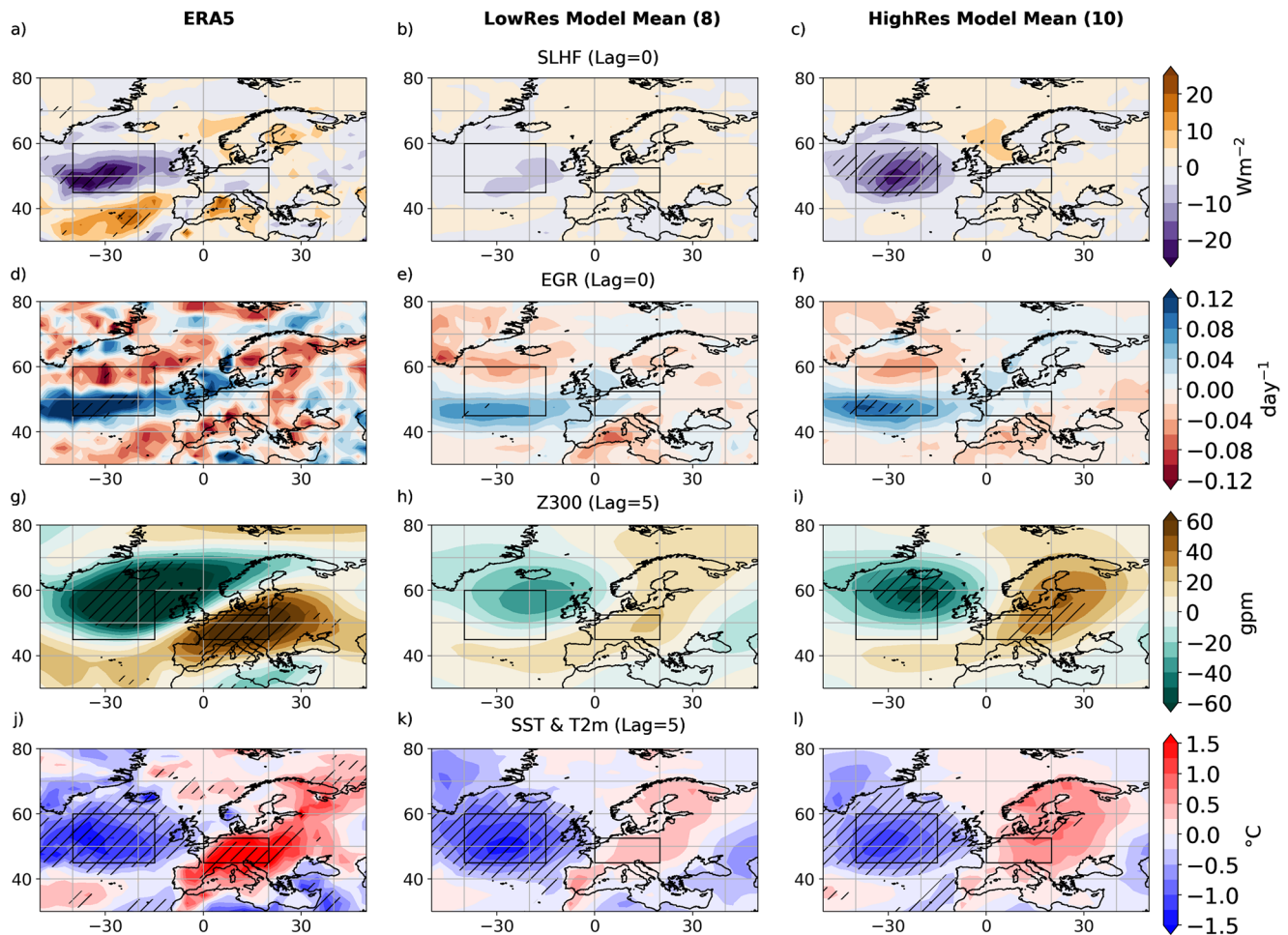


Fig. 3 | Mechanism as identified in ERA5 and its representation in low- and high-resolution multi-model means. Composite mean of events of cold North Atlantic SSTs with a negative tendency for ERA5 reanalysis data **a, d, g, j**, the mean of 8 low-resolution configurations **b, e, h, k** and the mean of 10 high-resolution configurations **c, f, i, l** with corresponding anomalies of SST and T2m at lag = 5 **a–c**, 300hPa geopotential height (Z300) at lag = 5 **d–f**, surface latent heat flux (SLHF) at lag = 0 **g–i**,

775hPa Maximum Eady Growth Rate (EGR) at lag = 0 **j–l**. The lags are chosen based on strongest anomalies in ERA5. A 5-day mean centred around the respective lag is applied to account for persistence. Hatching indicates significant values according to a 95% confidence interval. Black boxes indicate the North Atlantic area (40–15°W, 45–60°N) and European area (0–20°E, 45–52.5°N) used for spatial averaging in Fig. 4.

2m-air temperature (T2m) anomalies being vastly underestimated with anomalies of only up to +0.5°C (Fig. 3b).

The High-Res multi-model mean reveals considerably enhanced North Atlantic SLHF anomalies with a peak magnitude comparable to ERA5 (Fig. 3i). As a result, a statistically significant signal of positive low-level baroclinicity contributes to fuelling and a spatio-temporal locking of the North Atlantic trough, with an amplitude approximately twice as the Low-Res mean (Fig. 3f,l). A stronger downstream European ridge and increased T2m anomalies with values of +0.75°C over Europe (Figs. 3c,f, S4c,d) indicate that High-Res models still underestimate the anomalies found in ERA5. However, they simulate considerably more realistic surface and upper-tropospheric anomalies than the Low-Res counterparts, and additionally show significant signals of both the European ridge and the positive T2m anomalies over Eastern Europe.

The European T2m maximum can vary both locally and temporally among the models, i.e. the timing of the peak anomaly is not happening at lag = +5 throughout all of the models (Fig. S4). Even though all models peak at positive lags, meaning the decline of the North Atlantic SST precedes the European T2m maximum, some models show an earlier and other ones a later peak of the positive T2m anomalies, implying that the mechanism that connects the North Atlantic SST and the European T2m has a model-dependent speed. Beside averaging over larger sample sizes in the models relative to ERA5 (Table 1), this model dependency leads to a smoothing of

the multi-model mean maps (Fig. 3; averages over 8 Low-Res and 10 High-Res model versions, respectively). Considering the temporal evolution of the models individually reveals that three High-Res model versions reach a peak of above +1°C and another one is close to +1.0°C and thus comparable to the magnitude of ERA5, whereas Low-Res model versions hardly reach anomalies of above +0.5°C around lag = +5 (Fig. S4). Beside, the magnitude, the duration of positive T2m anomalies is also crucial for the occurrence of a heat event. While a single Low-Res configuration exhibits a positive T2m anomaly of more than +0.5°C for about 6 days, four High-Res configurations remain above +0.5°C for about 12–15 days. Consequently, T2m anomalies indicate a stronger persistence in High-Res models and are closer to ERA5 compared to Low-Res. Thus, inspecting the duration and magnitude of significantly positive T2m anomalies over central Europe in the models individually, confirms a substantial improvement of High-Res against Low-Res models in the simulation of this mechanism leading to European heat events.

Despite the general displacement of the European anomalies towards Eastern Europe in the models, each model has a slightly different displacement of the ridge relative to ERA5, which affects the significance of the positive T2m anomaly maximum, as it is collocated with each modelled ridge (Fig. 3h,i, k,l). Still, the vast majority of the High-Res models simulates a stronger European ridge compared to the Low-Res counterparts (Fig. S5), aligning with an enhanced surface warming (Fig. S6). Computing area

averages of the highest anomalies in the models, i.e. spanning a box over Eastern Europe, and comparing them to the ERA5 anomalies over central Europe, the model's T2m anomaly would align more closely with the +1.5°C anomaly observed in ERA5.

ECMWF-IFS, MPI-ESM1.2-PP and FOCI show enhanced upward SLHF (Fig. S7) and an intensified trough when increasing only the ocean resolution (Fig. S8). Such consistent changes are missing when increasing the atmospheric resolution only (MPI-ESM1.2-KPP and CMCC-CM2), supporting the importance of the ocean model. This also emerges using an equally-weighted model contribution to the multi-model mean (Fig. S9), i.e., when the multi-model mean is restricted to two versions for each model and only to those models where the ocean resolution is increased (highlighted versions in Table 1).

Relating North Atlantic surface biases to European heat event simulation

Now we compare the performance of all studied models individually, and relate North Atlantic surface biases to key variables of the composites by averaging within the boxes indicated in Fig. 3. All Low-Res versions have both a downward SLHF bias and a cold SST bias in the North Atlantic, except for CMCC-CM2 (Fig. 4a). Both biases are strongly reduced in model configurations where the ocean model resolution is increased. Particularly, the SLHF bias of more than +20Wm⁻² and the SST bias of more than -4°C present in ECMWF-IFS-LR and FOCI-Standard are more than halved in ECMWF-IFS-MR and FOCI-VIKING10. The relationship between SST and SLHF bias is approximately the same, i.e., a SST bias reduction of 3°C corresponds to a SLHF bias reduction of 10Wm⁻². This corroborates that the SLHF bias is almost entirely driven by SST biases and near-surface stratification has little impact. Increasing the atmospheric resolution alone (as in MPI-ESM-KPP, CMCC-CM2 or ECMWF-IFS-MR, HR) results in small bias reductions, if any.

Enhanced SLHF biases in Low-Res versions are associated with reduced upward SLHF anomalies during events of cold SSTs with a negative tendency, whereas High-Res versions exhibit a lower SLHF bias and more pronounced upward SLHF anomalies (Fig. 4b). This difference is consistent throughout all models where the ocean resolution is increased. HadGEM3-GC3.1 configurations indicate that most discernible changes are found when moving from an eddy-parameterised (LL) to an eddy-permitting (MM) version, while only smaller changes are found between eddy-permitting and eddy-rich (HH) versions.

Associated with the presence of negative Z300 anomalies, all model versions reveal positive total precipitation anomalies, except for EC-Earth3 (Fig. 4c). Enhanced precipitation anomalies in the eddying versions of HadGEM3-GC3.1, ECMWF-IFS and MPI-ESM-PP compared to their Low-Res versions might be caused by enhanced evaporation (and thus SLHF) promoting stronger ascent and low-level baroclinicity (Fig. S10). However, no consistent increase of precipitation anomalies towards a higher ocean or atmospheric resolution is identified. Insignificant area averages emerge as the location of the precipitation patterns differs among model configurations (Fig. S11).

The European Z300 anomaly peaks five days after the events of cold SSTs with a negative tendency in almost all model versions (Fig. 4d). Apart from HadGEM3-GC3.1 and MPI-ESM1.2-PP, anomalies grow in amplitude with increasing horizontal resolution in all models. For instance, from FOCI-Standard to FOCI-VIKING10, the European Z300 anomaly has substantially increased from almost 0 to +45 gpm, however, the anomaly is still underestimated compared to ERA5 with a magnitude of +60gpm. Thus, increasing the ocean resolution and reducing the cold SST bias triggers an improved representation not only of the SLHF anomaly but also of the European ridge, even though MPI-ESM1.2-PP versions act as an outlier (Fig. 4e). European Z300 anomalies coincide with the European T2m anomalies, suggesting an improved heat event simulation by reducing the cold North Atlantic SST bias (Fig. 4f).

The sequence of processes involved in the mechanism linking the cold North Atlantic SSTs with European heat events is better reproduced in

models using an eddy-permitting or eddy-rich ocean component and can be summarised as follows:

- Resolving the mesoscale ocean eddies leads to a more realistic SST mean state and gradient along the Gulf Stream stream and extension region and thus reduces the North Atlantic cold SST bias as well as the strongly correlated downward SLHF bias (Figs. 1, 2, S2, S3).
- During the presence of cold North Atlantic SSTs, the reduced SLHF bias enables a more accurate representation of the observed upward SLHF and enhanced surface evaporation (Figs. 3, S7). Low-level baroclinicity, sensitive to the location and intensity of the SST and SLHF gradient, is also represented closer to observations (Fig. S10).
- The improved representation of the lower-tropospheric state combined with enhanced upward motion present during these events further helps High-Res models to produce a North Atlantic trough with a state closer to the observed high intensity and strong persistence (Figs. 3, S4, S8).
- The models reproduce the positive precipitation anomalies present during these events, however, they deviate in their location and intensity across the models as they are stronger influenced by the atmospheric model component (Figs. 4, S11).
- Similarly, the propagation of signals downstream towards Europe is largely sensitive to the atmospheric model component and physics, which results in spatial inhomogeneity of the simulated European ridge across models. Even though the location of the European ridge deviates from observations in some models, it consistently aligns with the positive T2m anomalies, with the vast majority of High-Res models reproducing the duration and magnitude of the positive European T2m anomalies more accurately than their Low-Res counterparts (Figs. S4, S5, S6).

Since Low-Res, eddy-parameterised models already lack in reproducing the mechanism starting at the North Atlantic surface as indicated by the absent upward SLHF anomaly (Fig. 3), the improvement of High-Res models in simulating the European T2m anomaly can be attributed to the improved surface state of the North Atlantic ocean. Thereby, our study emphasises the need of eddy-permitting or eddy-rich ocean models.

Discussion and Conclusion

Using ERA5 reanalysis data, it has been demonstrated that events of cold North Atlantic SSTs with a negative tendency are followed by a sequence of atmospheric processes leading to European heat events¹⁸. In this study, the same composite analysis is applied to investigate this mechanism between North Atlantic SSTs and European heat events across seven global coupled climate models, including control-1950 experiments from six HighResMIP models and a pre-industrial control run from the FOCI model. Experiments with a low-resolution, eddy-parameterised ocean (~100km) from typical state-of-the-art CMIP models reveal cold SST and downward SLHF biases in the subpolar North Atlantic. Previous studies indicate an influence of these biases on the simulated atmospheric variability e.g.,^{4,34}. The downward SLHF bias likely causes a low specific humidity bias, increased static stability and inhibited vertical motion¹¹. In turn, low precipitation and reduced mid-tropospheric heating lead to an underestimation of the wintertime European blocking frequency¹².

Our findings indicate a similar bias propagation in summer: Misrepresented North Atlantic SSTs result in reduced upward SLHF and evaporation, which weakens atmospheric variables such as low-level baroclinicity (as indicated by EGR anomalies), upward motion, precipitation and the upper-tropospheric trough. As a result, mid-tropospheric diabatic heating over the North Atlantic is reduced, which leads to an underestimation of the modelled downstream European ridge and associated positive T2m anomalies identified five to seven days after the negative tendency of cold North Atlantic SST events in the composites of low-resolution versions.

High-resolution model versions show an improved representation of North Atlantic surface variables, such as SST and SLHF.

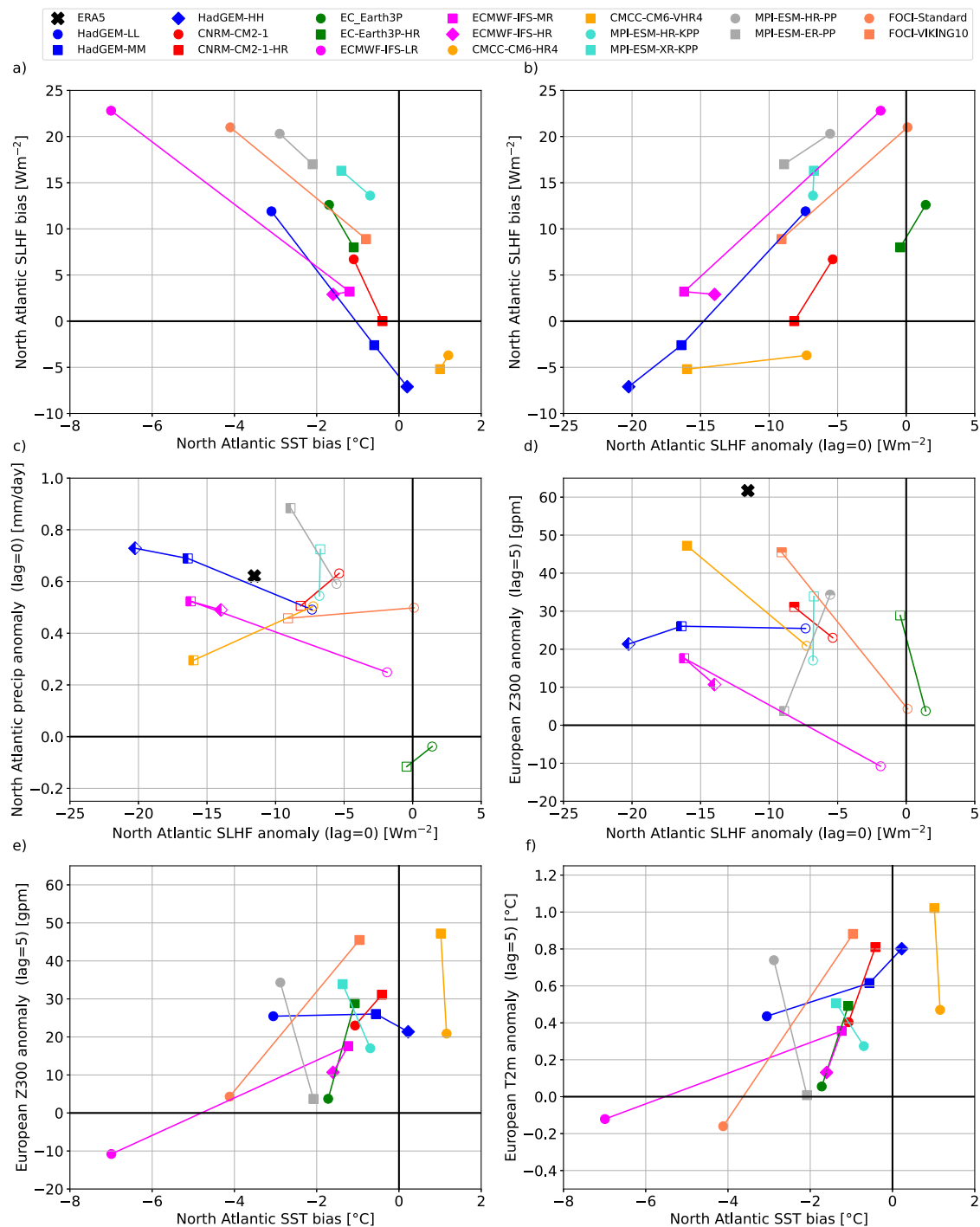


Fig. 4 | Relationship of North Atlantic surface biases and European anomalies. Scatter plots of **a** biases only, **c** and **d** composite mean anomalies only and **b**, **e** and **f** biases related to composite mean anomalies; area averages are calculated over the North Atlantic (40–15°W, 45–60°N) or over Europe (0–20°E, 45–52.5°N) at different lags for low- and high-resolution configurations; circles and squares refer to low- and high-resolution versions, respectively; diamonds indicate highest resolution, where three versions are available (HadGEM3-GC3.1, ECMWF-IFS); MPI-ESM1.2 is

separated into versions with either the Pacanowski and Philander (PP) or the K-Profile-Parameterisation (KPP) ocean mixing scheme; **c** and **d** indicates significance for the anomalies according to the bootstrap method (95% confidence interval) with non-filled markers (not significant in both anomalies); left-filled markers (significant in terms of x-axis anomaly only); top-filled (significant in terms of y-axis anomaly only); filled (significant in both anomalies).

Improvements mostly stem from refining the ocean model from eddy-parameterised to eddy-permitting resolution. Further refinement to eddy-rich configurations yields only marginal improvement, consistent with previous findings²⁹. In particular, the increase of the ocean resolution confined to the North Atlantic as indicated by FOCI, enables the resolution of oceanic mesoscale processes and reduces North Atlantic

surface biases by ~ 50%. Further studies illustrate that an improved performance of air-sea interaction processes and certain atmospheric dynamics in high-resolution HighResMIP models can be attributed to a refined ocean model e.g.,³⁵. High-resolution versions are identified with an improved stationary component of Rossby wave activity⁸, explaining the stronger persistence of the North Atlantic trough and the European

ridge, and thereby an improved simulation of European heat events in high-resolution versions.

While the duration and intensity of European heat events is improved in high-resolution models, there remains potential for improvement regarding the simulated location of European heat events. The disagreement of the location of the European T2m anomalies in the models compared to ERA5 results from differences in the climatological summer mean pattern (Fig. S12). Generally, climate models exhibit this pattern found to be shifted compared to ERA5 reanalysis such that the European ridge appears displaced towards Eastern Europe during periods of cold subpolar North Atlantic SSTs¹⁶, which is in agreement with the displacement found in our study. Such a shift also leaves the imprint towards a biased simulation of the summer East Atlantic pattern³⁶, which has been found to be predominantly in its positive phase during events of cold North Atlantic SSTs¹⁸. Reducing the climatological summer mean bias would likely improve the location of the centre of the simulated anomalies closer to central Europe.

Building on this, the representation of European blocking offers another perspective on model performance. High-resolution models show improvements through reduced SST biases³⁷ and more realistic remote diabatic heating³⁸. Nevertheless, European blocking remains underestimated, leading to an inadequate representation of heat events and their future trends^{39–41}. Examining the mechanism between North Atlantic SSTs and European heat events using historical rather than control experiments from the HighResMIP model ensemble may provide deeper insights into how this mechanism changes under climate change conditions and its relation to future trends of European blocking and heat events.

A more realistic simulation of atmospheric dynamics leading to European blocking and heat events is presumably possible by increasing the atmosphere model resolution, even though resolving convective processes in (multi-)centennial global coupled climate simulations is limited by current computational resources⁴². Enhancing the atmospheric resolution beyond 25km, thereby reducing the atmosphere-ocean grid resolution difference, allows the atmosphere to more effectively interact with ocean mesoscale processes. As a result, improved signals propagate into the atmosphere, leading to a more realistic North Atlantic storm track⁴³ and contributing to further improvements in simulating downstream European heat events.

The composite analysis based on ERA5 data shows a distribution of cold North Atlantic SST events¹⁸, that seems to be modulated by the Atlantic multidecadal variability (AMV)⁴⁴. The multi-model ensemble from High-ResMIP can potentially shed more light on the relationship between the AMV and the temporal distribution of cold North Atlantic SST events therein. Also, multi-centennial simulations could be performed by FOCI-VIKING10 as it uses regional grid refinement⁴⁵, which reduces computational cost.

In summary, high-resolution models and in particular those with an eddy-permitting or eddy-rich ocean model component better represent the observed mechanism between North Atlantic SSTs and European heat events, compared to their low resolution counterparts. This study motivates to continue efforts in high-resolution modelling and developing improved model physics and better parameterisations of ocean eddies and mesoscale air-sea interaction in the North Atlantic. Thereby, our findings indicate potential for further enhancing the prediction and projection skill of European summer climate extremes.

Methods

Model simulations, classification and reanalysis

This study uses six global coupled climate models with different configurations following the HighResMIP protocol²¹, mainly comprising a standard and a higher resolution version. ECMWF-IFS and HadGEM3-GC3.1 contribute with a third intermediate version. In addition to the CMIP-embedded versions of MPI-ESM1.2 with the K-Profile-Parameterisation (KPP) ocean vertical mixing scheme, where only the atmospheric resolution is changed, we also include the MPI-ESM1.2 versions with the Pacanowski and Philander (PP) scheme⁴⁶, in order to assess changes with respect to

different ocean resolutions. 100-year simulations for variables of SST, Z300, SLHF, total precipitation, EGR as well as T2m are retrieved based on the “control-1950” experiment, where solar forcing, greenhouse-gas concentration, and aerosol concentrations are fixed at year-1950 levels. Detailed information about the design of each individual model and their contributions to HighResMIP are found in the respective reference papers: HadGEM3-GC3.1²⁹, CNRM-CM6⁴⁷, EC-Earth3⁴⁸, ECMWF-IFS⁴⁹, CMCC-CM2⁵⁰, MPI-ESM1.2⁵¹.

In addition, pre-industrial control simulations from the global coupled climate model FOCI (Flexible Ocean Climate Infrastructure) is used²³, where the solar forcing, greenhouse gas concentrations and aerosol concentrations are kept fixed at year-1850 levels. Thus, one would expect FOCI to simulate a slightly colder mean climate than the HighResMIP control-1950 simulations. The standard version of FOCI with an eddy-parameterised ocean at ~ 50km horizontal resolution is used as a low-resolution configuration. A version where an eddy-rich nest at ~ 8km resolution is embedded in the North Atlantic from 30°N to 85°N (VIKING10) is used as a high-resolution configuration²³. Both FOCI-Standard and FOCI-VIKING10 consist of 100-year length (1950–2050) sliced from 300-year long simulations labelled with the run IDs “FOCI1.10 TM020” and “FOCI1.10 TM026”⁵².

Model simulations with an ocean resolution of above ~ 50km are classified into “Low-Res” and below ~ 50km into “High-Res”. This threshold is chosen as model simulations with an ocean resolution of below ~ 50km have considerably reduced biases in the North Atlantic¹¹. Low-Res consists of eight and High-Res of ten members. Note that the atmospheric resolution also differs in some cases between Low-Res and High-Res, which inhibits to attribute changes to the ocean model component in this multi-model classification. While HadGEM3-GC3.1, EC-Earth3 and CNRM-CM6 increase the resolution of both the ocean and atmosphere model component, MPI-ESM1.2-KPP and CMCC-CM2 increase the resolution of the atmosphere model only. Even though both CMCC-CM2 versions have the same ocean resolution of ~ 25km, we include them to enhance robustness and thus increase the reliability of the results of the ensemble of high-resolution models, in which both CMCC-CM2 versions are classified in. ECMWF-IFS and its three configurations separately increase the atmosphere and ocean resolution. FOCI1.10 with the VIKING10 nest is characterised by an increase of the ocean model resolution only locally in the North Atlantic.

The ERA5 reanalysis product provided by ECMWF serves for bias calculation by subtracting the JJA climatology of the ERA5 reanalysis from the JJA climatology of the model versions, respectively. Further, it is used as reference for the composite analysis²⁴. All data of model simulations and the ERA5 reanalysis are remapped to a 2.5° x 2.5° longitude/latitude grid using bilinear interpolation due to computational reasons.

Composite analysis

For the composite analysis, the same composite criteria are applied, i.e., a cold North Atlantic SST event with a negative tendency is identified when North Atlantic SSTs averaged over a box south of Greenland (40–15°W, 45–60°N) are below the 0.1 quantile of the June–August (JJA) SST distribution in the North Atlantic box for three consecutive days and two identified events have to be at least 30 days apart from each other¹⁸. This analysis is performed for each model configuration and the ERA5 reanalysis separately and the numbers of identified events are listed in Table 1. There are 266 events available from 8 Low-Res simulations and 407 events from 10 High-Res simulations. The composite dates are applied on anomalies of SST, T2m, SLHF, Z300, EGR and total precipitation. The EGR is computed at the 775hPa in agreement with previous studies^{11,18}. Lag = 0 for EGR, SLHF and total precipitation anomalies and lag = 5 for SST, T2m and Z300 anomalies, respectively (Figs. 3, 4), are chosen for the models as strongest signals mostly occur at these time steps¹⁸. Variables are smoothed by applying a 5-day running mean. A linear trend is removed in order to cancel out a potential model drift. Also, the daily climatology is removed from the 100-year model

simulations as well as from ERA5 reanalysis data sets used in the period of 1979 to 2019.

Significance

Significance for SST and SLHF biases and bias differences shown in Figs. 1, 2, S2, S3 is computed by performing a two-sided T-test for the null hypothesis that the expected value of the distribution of biases or bias differences for each year (100 values) is equal to 0 using a 95% confidence interval.

Significance for the maps (Figs. 3, S5, S6, S7, S8, S9, S10, S11) and of North Atlantic box (40–15°W, 45–60°N) and European box (0–20°E, 45–52.5°N) averaged results (Fig. 4c, d) is tested using the bootstrap method for each model configuration separately. 1000 samples with a sample size that equals the number of events within the respective composite are drawn from the JJA values of the 100-year long simulations (Table 1). For instance, results of HadGEM3-GC3.1-LL are tested against a distribution of 1000 bootstrap samples with a size of 37 events of each sample. If the composite mean value is within one of the 2.5% tails of the distribution of 1000 bootstrap sample means (95% confidence interval), the results are considered significant.

Data availability

The HighResMIP data is retrieved from and publicly accessible through <https://esgf-node.ipsl.upmc.fr/search/cmip6-ipsl/>. The ERA5 Reanalysis data is retrieved from and publicly accessible through <https://cds.climate.copernicus.eu/datasets>. The OA Flux data is retrieved from and publicly accessible through <https://climatedataguide.ucar.edu/climate-data/>.

Code availability

The analysis and production of all figures is performed using Python code as shown by Jupyter Notebooks, which are freely accessible on Github https://github.com/julian28295/HighResMIP_NA_SST_Euro_heat.

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Author contributions

J. Krüger designed the analysis, produced the figures and wrote the manuscript. J. Kjellsson designed the analysis and contributed with helpful comments to the manuscript. K.L. provided data for the analysis and contributed together with D.M. and R.P.K. with helpful comments to the manuscript.

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