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Key Points:

- Projected Arctic sea-ice loss causes a robust equatorward shift of the North Atlantic jet across models, but no robust change in jet speed
- Changes in jet position and speed strongly shape the European winter surface climate response to projected Arctic sea-ice loss
- Constraining the jet response is important for reducing uncertainty in the European precipitation response to future Arctic sea-ice loss

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

K. Ye,
kunhui.ye@physics.ox.ac.uk

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European Winter Climate Response to Projected Arctic Sea-Ice Loss Strongly Shaped by Change in the North Atlantic Jet

Kunhui Ye[1], Tim Woollings[1], and James A. Screen[2]

[1]Atmospheric, Oceanic and Planetary Physics, University of Oxford, Oxford, UK, [2]Department of Mathematics and Statistics, University of Exeter, Exeter, UK

Abstract Previous studies have found inconsistent responses of the North Atlantic jet to Arctic sea-ice loss. The response of wintertime atmospheric circulation and surface climate over the North Atlantic-European region to future Arctic sea-ice loss under 2°C global warming is analyzed, using model output from the Polar Amplification Model Intercomparison Project. The models agree that the North Atlantic jet shifts slightly southward in response to sea-ice loss, but they disagree on the sign of the jet speed response. The jet response induces a dipole anomaly of precipitation and storm track activity over the North Atlantic-European region. The changes in jet latitude and speed induce distinct regional surface climate responses, and together they strongly shape the North Atlantic-European response to future Arctic sea-ice loss. Constraining the North Atlantic jet response is important for reducing uncertainty in the North Atlantic-European precipitation response to future Arctic sea-ice loss.

Plain Language Summary Variations in the North Atlantic jet affect temperature, precipitation, and storminess in Europe. It is not well understood how the jet and European climate will respond to future sea-ice loss in the Arctic under human-caused increases in global temperature. We study how atmospheric circulation and surface climate in winter over the North Atlantic-European region would respond to future Arctic sea-ice loss under 2°C global warming, using an unprecedented number of coordinated simulations from different climate models. In many models the North Atlantic jet stream in winter responds by shifting southward, but the response of its speed is less clear. These jet stream changes are found to strongly shape the responses in precipitation and storm track activity. More precise estimates of the jet stream response are key to reducing uncertainty in the North Atlantic-European precipitation response to future Arctic sea-ice loss.

1. Introduction

Arctic sea-ice cover has declined by approximately one-half over the 40 years of the satellite record (Stroeve & Notz, 2018). The rate of decline is unprecedented in at least the last 1,450 years (Kinnard et al., 2011). Many mechanisms have been proposed through which Arctic sea-ice loss could affect midlatitude weather and climate, including modulation of the North Arctic Oscillation (NAO; Alexander et al., 2004), jet waviness (Francis & Vavrus, 2015), changes in the storm tracks (Overland et al., 2011), modulation of planetary waves (Honda et al., 2009; Petoukhov & Semenov, 2010), and in turn, the stratospheric polar vortex (Kim et al., 2014). However, the magnitude and precise nature of the influence of Arctic sea-ice loss on midlatitudes remain uncertain (Barnes & Screen, 2015; Cohen et al., 2014, 2020; Masson-Delmotte et al., 2021). Strong internal atmospheric variability, incomplete mechanistic understanding, and competing processes all pose challenges to quantifying the remote effects of Arctic sea-ice loss.

In response to these challenges, the Polar Amplification Model Intercomparison Project (PAMIP; Smith et al., 2019) has conducted an unprecedented set of coordinated multi-model experiments to advance understanding of the causes and consequences of Arctic sea-ice loss. Using the PAMIP data, Smith et al. (2022) found a robust but weak winter circulation response to future Arctic sea-ice loss, characterized by a weakening and equatorward shift of the zonal-mean mid-latitude westerlies. However, it is not known to what extent the regional response to future Arctic sea-ice loss over the North Atlantic-European sector is consistent with this zonal-mean perspective.

The NAO and North Atlantic jet, which are closely related, are important drivers of climate variability over the North Atlantic-European region (Woollings et al., 2010). The observed/modeled statistical relationship between Arctic sea-ice and the NAO raised hope of further improving predictability of European weather and climate on subseasonal to decadal timescales (Strommen et al., 2022). However, this relationship is found to be nonstationary (Kolstad & Screen, 2019) and may be spurious, not causal, arising by chance (Siew et al., 2021). The North Atlantic jet response to future Arctic sea-ice loss is still highly uncertain (e.g., Barnes & Screen, 2015; Screen, 2021). Here, we analyze experiments from PAMIP with a focus on the North Atlantic jet response to future Arctic sea-ice loss and quantify its contribution to the surface climate response over the North Atlantic-European region.

2. Data and Methodology

2.1. PAMIP Data

The two experiments considered are named pdSST-pdSIC and pdSST-futArcSIC. These are multi-member atmosphere-only experiments prescribed with ocean surface boundary conditions. Both were run with present-day sea surface temperatures (SSTs) and Antarctic sea-ice concentrations, but different Arctic sea-ice concentrations, and Arctic SSTs if sea-ice loss is over 10%. The first was run with present-day Arctic sea-ice and the second was run with future Arctic sea-ice projected under 2°C global warming above preindustrial levels. The present-day SST and sea-ice concentrations are based on the 1979–2008 climatology from the Hadley Center Sea Ice and SST data set (Rayner et al., 2003). The future sea-ice concentrations were derived using a multi-model ensemble of projections, sampled at the 2°C global warming level (specifically, CMIP5 RCP8.5). The same set of SST/sea-ice concentrations were prescribed in all the models. Each experiment was initialized on 1 April 2000 and was run for 14 months with the first 2 months discarded as spin-up. More details about these experiments can be found in Smith et al. (2019, 2022).

Monthly zonal wind at both 850 hPa (u850) and 250 hPa (u250), surface air temperature, precipitation and pressure at sea-level (PSL; daily data also used) from 12 models were obtained for the analysis from the Earth System Grid. These models are ECHAM6.3, CanESM5, CESM1-WACCM-SC, CESM2, CNRM-CM6-1, EC-Earth3, FGOALS-f3-L, HadGEM3-GC31-MM, IPSL-CM6A-LR, MIROC6, NorESM2-LM, and TaiESM1. A total of 100, 300, 299, 200, 500, 173, 100, 290, 200, 100, 200, and 100 ensemble members, as counted for u850 in pdSST-pdSIC, were obtained for these models, respectively. Note that due to lack of data, the response of precipitation and storm track activity to future Arctic sea-ice loss was not computed for CESM1-WACCM-SC and ECHAM6.3, respectively. The original model output was re-gridded to a common grid with 2.5° horizontal resolution.

The response to future Arctic sea-ice loss was taken as the difference between pdSST-futArcSIC and pdSST-pdSIC. Unless stated, the term "response" or "total response" refers to the constructed ensemble-mean difference between this pair of experiments. The significance of the response was assessed using a two-tailed Student's *t*-test against the 5% significance level. For the jet response in Figure 1, 95% confidence level is shown. We focus on winter averages, defined as the months of December, January, and February. The multi-model-mean (MMM) was constructed as an unweighted average over all the ensemble means of the models.

2.2. Jet Stream Indices and Storm Track Activity

Two North Atlantic jet indices—latitude and speed—were calculated using monthly u850 following the procedures in Woollings et al. (2010). First, the zonal average of zonal wind at 850 hPa over a longitudinal sector (0°–60°W) is computed. Jet speed is defined as the maximum wind speed found between 15° and 75°N and the latitude for this maximum wind speed is set as the jet latitude. Note we use monthly data instead of filtered daily data as used in Woollings et al. (2010). The use of monthly data increases the number of available models and results are mostly qualitatively similar to those using daily data that were only available for a subset of the PAMIP models. Storm track activity is measured by the root-mean-square of 2.5–6-day band-pass filtered PSL. The root-mean-square was computed for each winter after seasonal-mean was removed from the band-pass filtered data.

2.3. Jet Stream Contribution to Response to Future Arctic Sea-Ice Loss

The component of the response to future Arctic sea-ice loss that can be explained by the North Atlantic jet was calculated using pair-wise difference fields between the two experiments across-ensemble members as follows. First, multiple linear regression was performed to obtain regression coefficients at each grid point of a

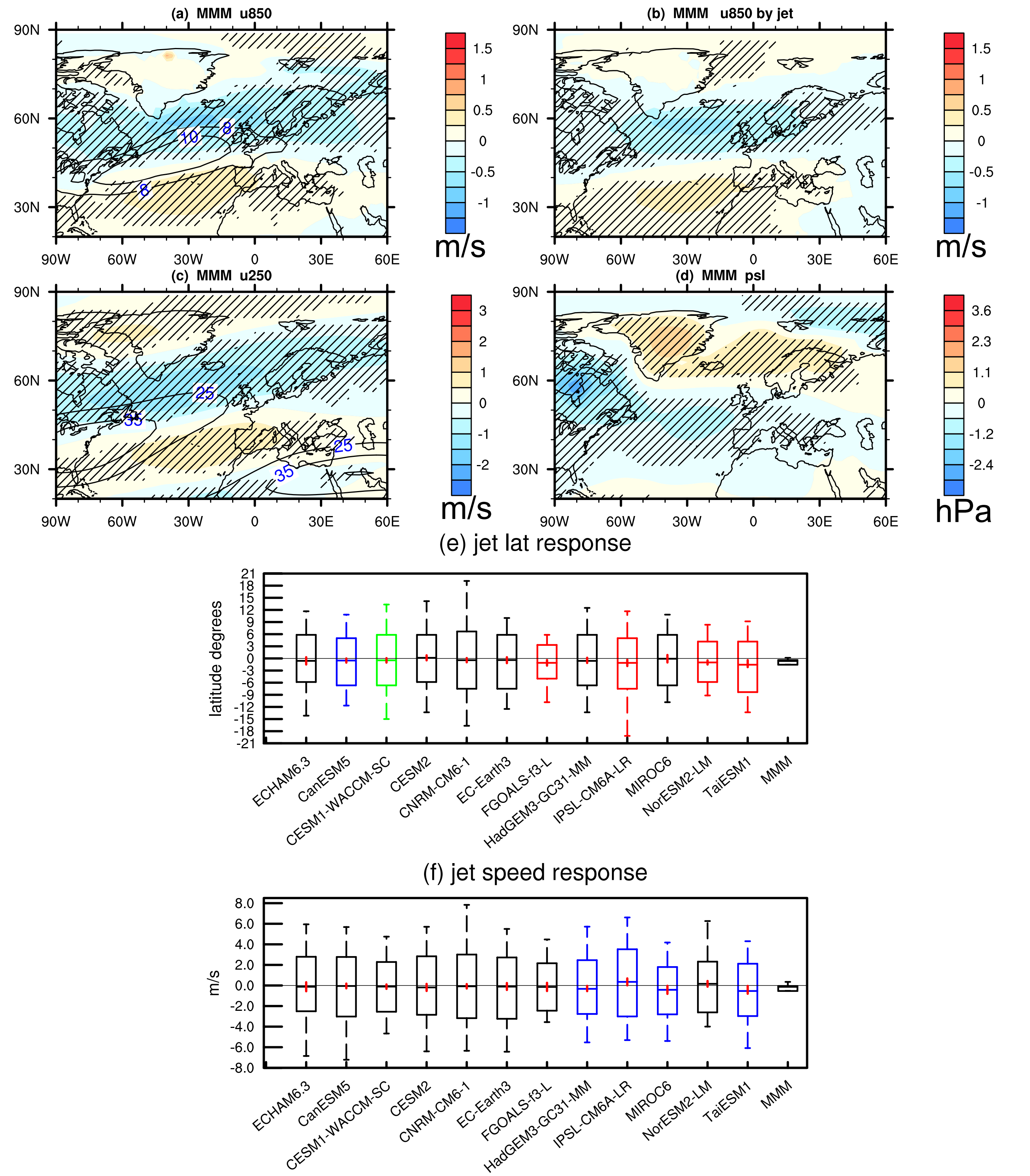

Figure 1. Response of (a) u850, (c) u250, (d) pressure at sea-level (PSL), and (e and f) jet indices to future Arctic sea-ice loss. Multi-model-mean is indicated as "MMM." Specific contours for MMM results of u850 and u250 are shown for pdSST-pdSIC experiment. (b) MMM u850 response explained by the jet. The box plots show maximum, upper 90th percentile, mean, lower 10th percentile and minimum of the ensembles. The vertical red lines in the box plots indicate the 95% confidence level. Hatching indicates 80% of the models agree on the sign of the response. Units: m/s for u850/u250/jet speed, hPa for PSL and degrees in latitude for jet latitude. Ensemble-mean response in panels (e and f) significant at 1%, 5%, and 10% is denoted by red, blue, and green bars, respectively.

particular field (e.g., SAT difference) versus the two jet indices. These regression coefficients represent changes in a particular field (e.g., SAT difference) corresponding to a unit change in the pair-wise jet index difference. Second, these regression coefficients were multiplied by the jet index response, where the coefficients were significant at the 5% significance level, to estimate the response explained by each jet index. Responses of the two jet indices are weakly correlated with the strongest correlation being 0.25 (EC-Earth3). This is an important reason for considering the two jet indices separately. As a note of caution, it is beyond the scope of this work to consider possible nonlinear interaction between jet speed and latitude (Woollings et al., 2018). The quantification method is similar to that in Deser et al. (2004), who studied direct and indirect components of the response to North Atlantic SST and sea-ice anomalies. The residual response is defined as the difference between the total response and jet-explained response.

We also quantify the impacts of jet changes on inter-model spread, which is quantified by standard deviation. First, the difference in inter-model spread between the total response and the residual response is obtained. This difference is then divided by the inter-model spread in the total response and this ratio is interpreted as the fraction of inter-model spread explained by the jet.

3. Results

3.1. Response of North Atlantic Jet, Storm Track Activity and Surface Climate Over North Atlantic-Europe

The MMM response of u850 is characterized by an anomaly dipole over the North Atlantic-European region (Figure 1). In most regions of the North Atlantic and Europe, at least 80% of the models agree on the sign of the u850 response. Only three models (CESM1-WACCM-SC, CESM2, and MIROC6 in Figure S1 in Supporting Information S1) deviate substantially, where the responses are weak and non-significant. The MMM response of zonal wind is equivalently barotropic (cf., Figures 1a and 1c) and dominated by the jet (Figure 1b). The zonal wind response suggests a southward shift of the jet and the associated SLP anomaly suggests a negative NAO response (Figure 1d). There is a southward jet shift in most of the models with the remaining being nearly zero, but the magnitude varies across models (Figure 1e). The response to future sea-ice loss is small compared to the interannual variability (ensemble member spread). However, half of the models (blue, green and red bars) show a consistent and significant southward jet shift, which is unlikely due to sampling of internal variability. In contrast, the response of jet speed is not consistent across the models (Figure 1f). A significantly stronger jet is seen for IPSL-CM6A-LR while a significantly weaker jet is seen for HadGEM3-GC31-MM, MIROC6, and TaiESM1; the jet response is extremely weak or unchanged in other models.

The MMM values of the jet indices (Figures 1e and 1f) suggest a southward shift of the jet of about 0.61° latitude and a reduced jet speed of about −0.12 m/s for winter. Overall, the response of both jet latitude and speed is relatively small compared to interannual (inter-member) variability, consistent with the zonal-mean results of Smith et al. (2022). The models agree on a southward shift of the jet but there is less agreement on jet speed, with only a few models showing significant responses yet these are of either sign.

The responses of SAT, precipitation, and storm track activity to future Arctic sea-ice loss are displayed in Figure 2 for the MMM. The responses of SAT and precipitation and the jet-related precipitation response for individual models are displayed in Figures S2–S4 in Supporting Information S1. In terms of SAT, the MMM results show strongest warming over the regions of sea-ice loss and with weaker warming spreading to surrounding regions (Figure 2a). The response over North Africa and eastern part of the Mediterranean is weak and consistent across models. The individual models show diverse responses at mid-low latitudes and those with cooling responses are generally not statistically significant (Figure S2 in Supporting Information S1). For example, there is a widespread cooling response over southern Europe and the Mediterranean in MIROC6, although internal variability may contribute to this given the lack of significance.

Enhanced precipitation is tied closely to local sea-ice loss (Figure 2b), as expected from enhanced evaporation. Interestingly, there is a dipole in the MMM precipitation response over the North Atlantic, with drying around 60°N and wetting around 40°N, and in the individual models but of differing magnitudes (Figure S3 in Supporting Information S1). There are widespread decreases in storm track activity in high latitudes, with broad agreement between models, and increases in storm track activity in midlatitudes, albeit much weaker and less consistent across the models (Figure 2c).

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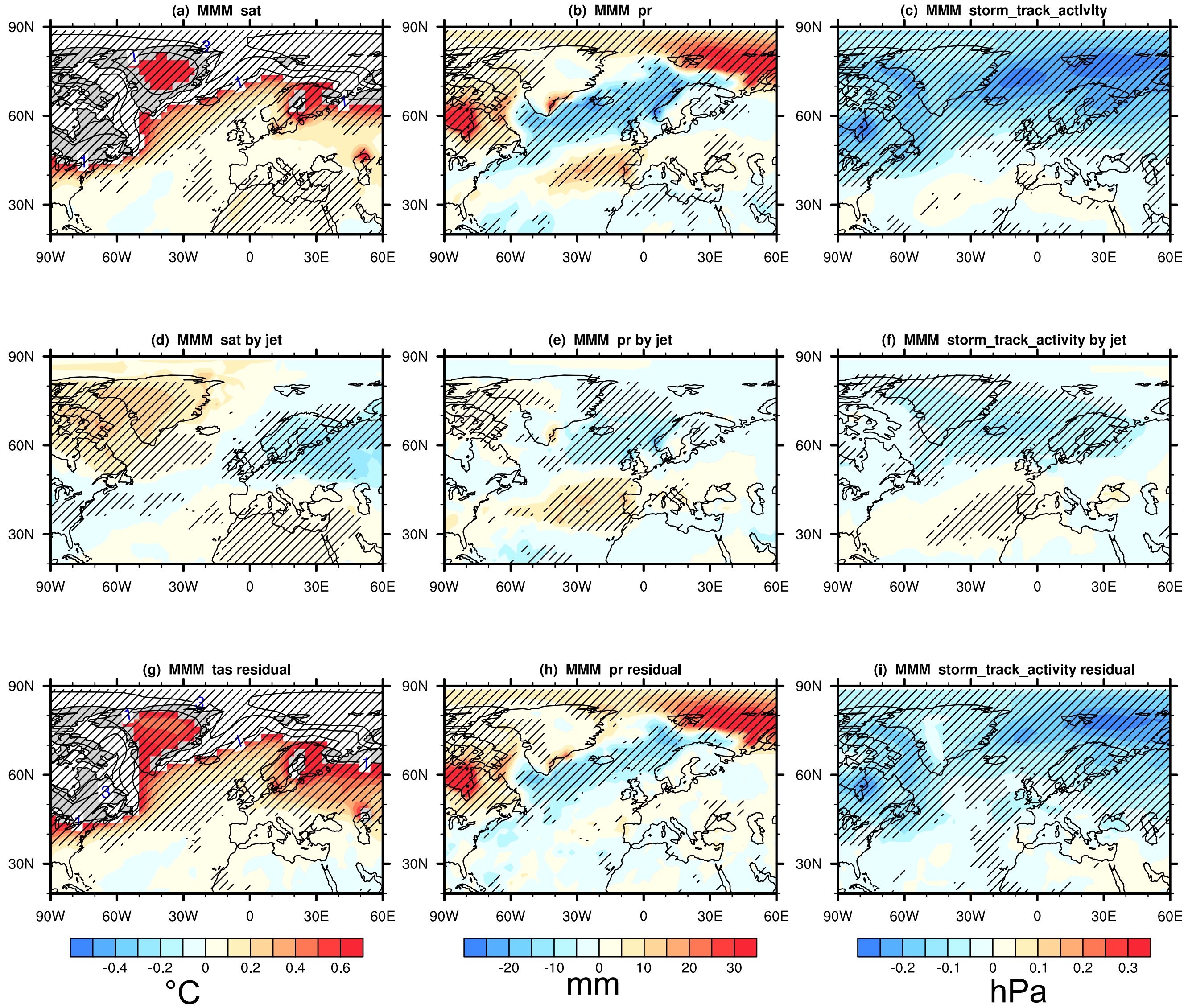

Figure 2. (a–c) The multi-model-mean (MMM) for the total responses of SAT, precipitation and storm track activity. Panels (d–f) similar to panels (a–c), but for response explained by jet. Panels (g–i) similar to panels (a–c), but for residual response. The meaning of hatching is as in Figure 1. Contours instead of shading are shown for large values (≥1°C) in panels (a and g). Units: °C for SAT, mm for precipitation and hPa for storm track activity.

3.2. Contributions of North Atlantic Jet to the Response of Storm Track Activity and Surface Climate Over North Atlantic-Europe

Several of the individual model responses are similar to the known responses of temperature, precipitation, and storm activity to North Atlantic jet changes, most commonly the southward shift of precipitation and weakening of storm activity (e.g., Woollings et al., 2015). In other examples, jet speed decreases reduce heat transport and storm activity and this may explain the cooling response over Europe for MIROC6 (Figure S2j in Supporting Information S1) and TaiESM1 (Figure S2l in Supporting Information S1).

Although the climate response is weak compared to internal variability over North Atlantic-Europe, the contributions of sea-ice induced changes in jet latitude and speed warrant further quantification given that models may underestimate the dynamical response to sea-ice loss (Mori et al., 2019; Smith et al., 2022).

The jet change is a robust feature in the circulation response over the North Atlantic (cf., Figures 1a and 1b). We next examine the explained response of SAT by the jet for the MMM results (Figure 2d). The total jet-explained response features a triple pattern, resembling the response to a negative NAO and consistent in most of the

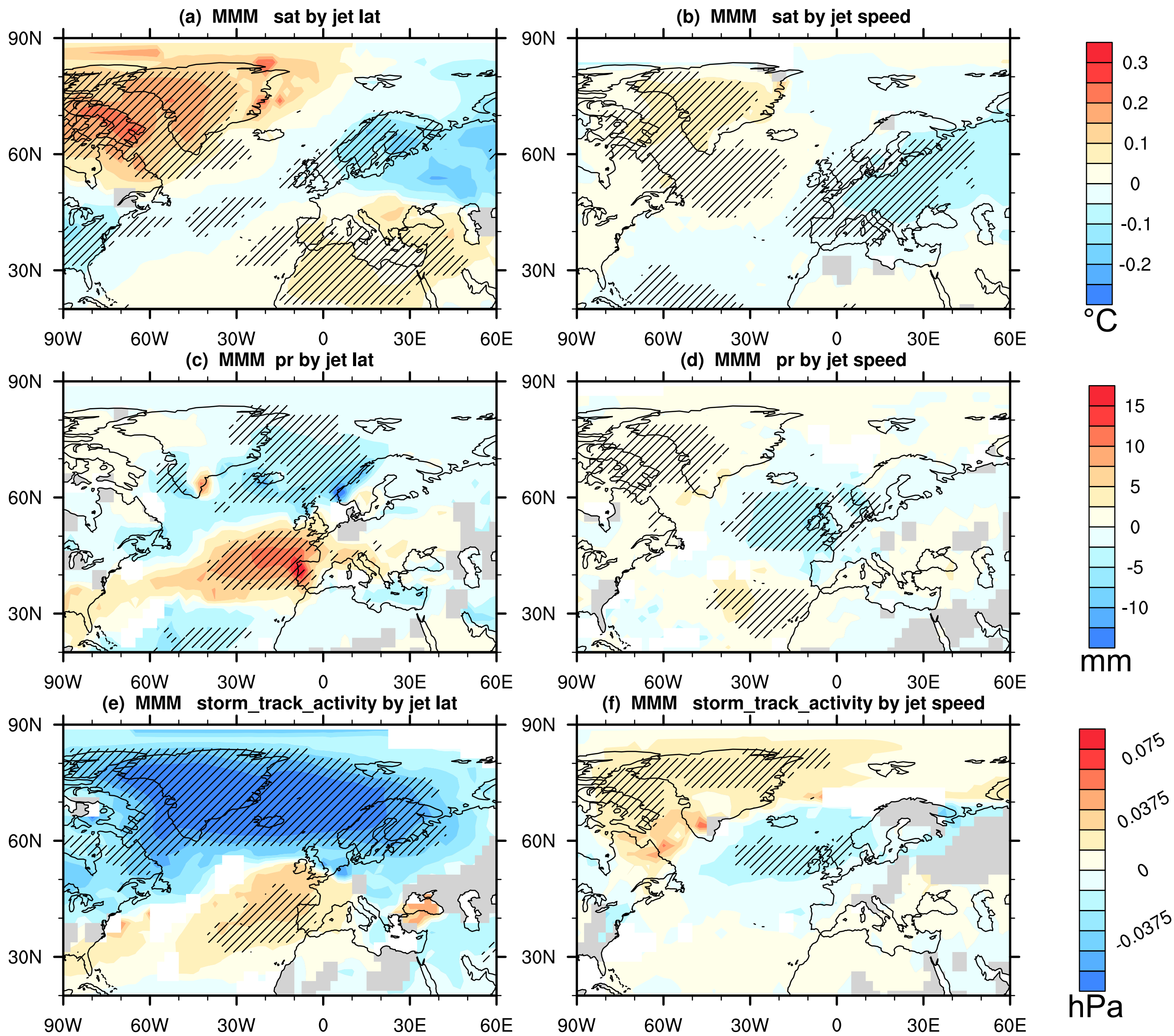

Figure 3. The multi-model-mean (MMM) for the total responses of (a and b) SAT, (c and d) precipitation, and (e and f) storm track activity explained by (left panels) jet latitude and (right panels) speed. The meaning of hatching is as in Figure 1. Units: °C for SAT, mm for precipitation and hPa for storm track activity.

models. The jet explains most of the response of SAT over parts of southern Europe, North Africa and the Mediterranean region, and a large portion of the response over Greenland (Figure 2d). The contribution by jet latitude dominates over that by jet speed for the MMM in Northern and the Mediterranean (cf., Figures 2d, 3a and 3b).

The jet changes also explain a large fraction of the precipitation and storm track responses to future sea-ice loss over Iberia and parts of Scandinavia (Figures 2e and 2f). The dipole anomaly of precipitation (Figure 2e) and storm track activity (Figure 2f) related to the jet shift is clearly visible. The contribution of jet latitude is larger than that of jet speed also for the precipitation (Figures 3c and 3d) and storm track responses (Figures 3e and 3f), for the MMM. The anomaly dipole of storm track activity explained by jet latitude, features reduced storm activity and precipitation over the subpolar North Atlantic and enhanced storm activity and precipitation over the midlatitude North Atlantic (Figures 3c and 3e). However, the jet speed contribution is not negligible. For temperature, the jet speed contributes to a dipole anomaly over the mid-high latitudes (Figure 3b). It induces a weaker and more southward dipole of precipitation anomaly (Figure 3d), and an opposite dipole of storm track activity anomaly (Figure 3f) than those due to the jet latitude.

We now consider the residual (non-jet-related) response, which is obtained by subtracting the jet-related response from the total response (bottom panels, Figure 2). The MMM residual response for SAT is dominated by high latitude warming, which can be interpreted as the first-order thermodynamical response to sea-ice loss. Comparing the total response (Figure 2a) to the residual response (Figure 2g), robust warming extends further south in the residual response. This suggests that over northern Europe, the warming due to sea-ice loss is moderately offset by a local cooling associated with the jet response (Figure 2d). For precipitation, the residual response is mainly located over the regions of sea-ice loss (Figure 2h); again likely a thermodynamical response. Over the central North Atlantic, the residual response of precipitation is small, relative to the total response, which underscores that most of the precipitation response is related to jet changes. For storm track activity, the residual component is dominated by reductions over the high latitudes, particularly over sea-ice loss areas (Figure 2i). These reductions are further north than those related to the jet response, and tend to align with meridional gradients in the temperature response (cf., Figures 2g and i). This is possibly a direct consequence of the reduction in baroclinicity in these regions in response to sea-ice loss.

The inter-model spread in jet changes also impacts inter-model spread in surface climate changes (Figure 4; see Section 2.3 for method). The diversity in the jet responses leads to a considerable increase (albeit with regional variation) in inter-model spread in the temperature (Figure 4b) and precipitation (Figure 4d) responses in parts of Europe. A similar change in the model uncertainty in the storm track response over high latitude is related to differing jet responses. The strongest impacts on the model spread are in different regions for different variables. For temperature, the strongest impact is over part of southern/eastern Europe and the Mediterranean with the jet explaining up to 60% of the total spread in regions where the total model spread is still relatively large (Figure 4a). For precipitation, the strongest impact is over Eastern Atlantic, parts of Western Europe and Greenland, with largest contributions of around 60%. Again, these regions show relatively large total model spread. For storm track activity, the strongest impact is over east Greenland and the seas to the east, with largest contributions of around 50%. Considering that the jet-related SAT response is generally overwhelmed by the residual response, these results suggest that constraining the jet response may only significantly reduce model uncertainty in precipitation and storm track activity response to projected Arctic sea-ice loss over these regions.

We illustrate the impacts of jet changes on inter-model spread by examining the precipitation response in individual models. The dipole in the precipitation response over the North Atlantic in multiple models (Figure S3 in Supporting Information S1) bears a close resemblance to that related to differing jet responses (Figure S4 in Supporting Information S1). For example, the jet-related precipitation response in FGOALS-f3-L is greater and the south node is shifted westward compared to that in CanESM5 (cf., Figures S4b and S4f in Supporting Information S1), which is reflected in the different precipitation responses over the North Atlantic-European region between these two models (cf., Figures S3b and S3f in Supporting Information S1). The jet latitude is generally dominant over jet speed in contributing to this dipole precipitation pattern for the first three models (not shown). However, the jet speed seems to be at least as important as the jet latitude for HadGEM3-GC31-MM and IPSL-CM6A-LR, and seems to dominate over the jet latitude for MIROC6. The jet speed response shifts the dipole pattern further south for MIROC6 and HadGEM3-GC31-MM compared to CanESM5 and IPSL-CM6A-LR. This suggests that the jet speed response is not trivial in contributing to the precipitation response over the North Atlantic-European region for some models. This along with a relatively weak residual precipitation response over midlatitudes has led to the jet-explained intermodel spread (Figure 4d) being different from the jet-explained MMM response (Figure 2e).

4. Discussion and Conclusions

We found a robust equatorward shift in the North Atlantic jet in response to projected Arctic sea-ice loss. The jet speed response is less clear, with the models not in agreement, which shows that the dynamical response is more complicated than might be expected from simple arguments based on thermal wind balance and a weakened temperature gradient. Consistent with Smith et al. (2022), the response of the jet is small compared to internal variability, and not significant in some individual models. Despite being weak, the sea-ice-induced North Atlantic jet change strongly shapes the surface climate response in parts of the North Atlantic-European region. The jet response is also an important source of model uncertainty in the surface climate response in some specific areas in the North Atlantic-European region. Similar results are seen for mean winter precipitation projection for the role of NAO (McKenna & Maycock, 2022). Constraining the uncertainty in the jet response (particularly the

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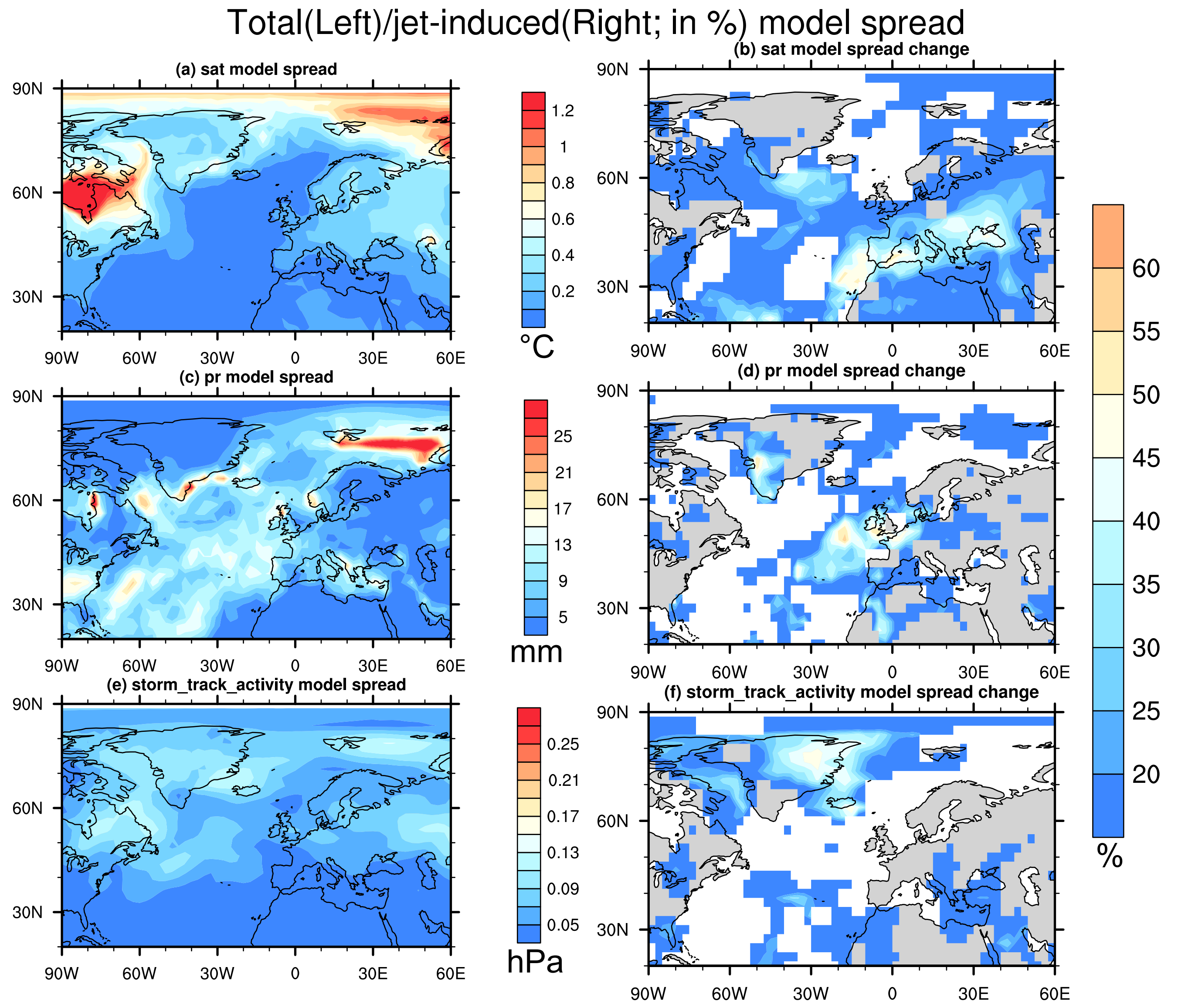

Figure 4. Inter-model spread for (a) SAT, (c) precipitation, and (e) storm track activity. Units: °C for SAT, mm for precipitation and hPa for storm track activity. The change in inter-model spread after removing the jet contributions (inter-model spread in total response minus that in residual response) divided by the inter-model spread in total response for (b) SAT, (d) precipitation, and (f) storm track activity. Negative and zero values are omitted.

magnitude and sign of it) is important for reducing model uncertainty in the European precipitation response to future Arctic sea-ice loss (see Text S1 and Figure S5 in Supporting Information S1 for more details). However, we note that our results represent the upper bound of reducible model uncertainties by constraining the jet response. As similarly discussed in Peings et al. (2021) and Screen et al. (2022), internal jet variability may still explain a considerable fraction of the jet response, particularly for models with a weak jet response. Although this issue is out of scope in our study, further quantification of internal jet variability versus truly forced jet response is important for quantifying the reducible model uncertainties in response to future Arctic sea-ice loss.

This paper has focused on understanding the response to sea-ice loss in isolation to elucidate some of the mechanisms acting in the response; but sea-ice loss is only one aspect of the climate response to anthropogenic forcing. As expected, the mid- and low-latitude temperature response to future Arctic sea-ice loss is weak compared to that induced by direct radiative forcing as well as lower-latitude SST warming (Deser et al., 2010; Hay et al., 2022; Masson-Delmotte et al., 2021; Overland et al., 2021). In terms of atmospheric circulation, the impacts are more comparable—future Arctic sea-ice loss tends to offset the effects of SST warming/direct greenhouse gases radiative forcing, leading to weak jet responses to future global warming (Oudar et al., 2017; Screen et al., 2022). Even compared to the response to 2°C global warming (cf., Figure 1 in our study, Figure 9 in Zappa et al., 2013), the atmospheric circulation response to future Arctic sea-ice loss is still considerable. Hence, the response to future Arctic sea-ice loss plays an important part in future climate change over mid-high latitudes.

Data Availability Statement

All the data used can be freely downloaded from https://esgf-node.llnl.gov/search/cmip6/ by selecting "PAMIP" activity.

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