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Title	Contrasting Responses of Midlatitude Jets to the North Pacific and North Atlantic Warming
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Citation	Geophysical research letters, 46(7), 3973-3981 https://doi.org/10.1029/2019GL082550
Issue Date	2019-04-16
Doc URL	https://hdl.handle.net/2115/75780
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Type	journal article
File Information	Matsumura_et_al-2019-Geophysical_Research_Letters.pdf



Geophysical Research Letters

RESEARCH LETTER

10.1029/2019GL082550

Key Points:

- Different SST warming between the oceans induces a weakening of the North Pacific jet and a poleward shift of the North Atlantic jet
- The competing effects of midlatitude and tropical SST warming play a substantial role in the future jet
- An equatorward shift of the jet due to Arctic sea ice loss is suppressed by midlatitude SST warming

Supporting Information:

- Supporting Information S1

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Citation:

Matsumura, S., Ueki, S., & Horinouchi, T. (2019). Contrasting responses of midlatitude jets to the North Pacific and North Atlantic warming. *Geophysical Research Letters*, 46, 3973–3981. <https://doi.org/10.1029/2019GL082550>

Received 26 OCT 2018

Accepted 26 MAR 2019

Accepted article online 1 APR 2019

Published online 10 APR 2019

Contrasting Responses of Midlatitude Jets to the North Pacific and North Atlantic Warming

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Abstract Midlatitude atmospheric circulation is projected to shift poleward, yet the Northern Hemisphere jet shift is absent. Competing thermodynamic responses between tropical and Arctic warming have opposing influences on the jets and increase the uncertainties in future projections. This study shows, however, that sea surface temperature (SST) warming in the midlatitude is a major driver for the future midlatitude jet. Coupled Model Intercomparison Program phase 5 models indicate different SST warming between the midlatitude oceans, which induces a weakening of the North Pacific jet and a poleward shift of the North Atlantic jet. Our atmospheric model experiments enable to quantify the relative roles of Arctic, midlatitude, and tropical warming. The competing effects of midlatitude and tropical warming play a substantial role in the future midlatitude jet, hindering any poleward shift of the North Pacific jet, whereas for the North Atlantic jet, midlatitude SST warming is likely to win the competition.

Plain Language Summary Midlatitude weather and climate, including extreme events, are strongly influenced by changes in the jet stream and extratropical cyclones. The future midlatitude circulation in the Northern Hemisphere is considered to depend on the competing effects of tropical and Arctic warming, which have opposing influences on position and intensity of the midlatitude jet and, ultimately, increase the uncertainties in future projections. However, we find that ocean warming in the midlatitudes has a major influence on future midlatitude jet. In the North Pacific, sea surface temperature (SST) warming is the strongest in the north of the strong ocean currents, whereas the North Atlantic SST warming has a peak in the strong ocean currents. This different SST warming leads to the contrasting midlatitude jet responses between the oceans with jet cores. Despite a topic of much debate, the impact of Arctic sea ice loss on the jet is suppressed by midlatitude SST warming. We conclude that the competing effects of midlatitude and tropical SST warming will play a substantial role in the future midlatitude jet. The results here may help decrease the uncertainties in future projections and further our understanding of ongoing midlatitude climate change.

1. Introduction

The atmospheric circulation in the midlatitude is controlled mainly by the temperature difference between the tropics and poles and by the vertical temperature difference (e.g., Shaw et al., 2016). In the Northern Hemisphere (NH), the temperature difference between the tropics and pole has been small during recent decades, which is a result of the Arctic surface warming faster than in the tropics (e.g., Cohen et al., 2014). Although Arctic warming has weakened the surface temperature gradient, tropical warming has strengthened the upper tropospheric temperature gradient (Allen & Sherwood, 2008). The future position and intensity of midlatitude jet and storm tracks depend on processes that alter the equator-to-pole temperature gradients (Harvey et al., 2013; Shaw et al., 2016). Consequently, Arctic warming is suggested to shift the jet equatorward and decrease storm tracks, whereas tropical warming promotes a poleward shift of the jet and increase storm tracks (e.g., Barnes & Screen, 2015; Held, 1993). Indeed, future Arctic sea ice loss is considered a leading cause for the lack of a poleward shift in the NH jet (Deser et al., 2015). These opposing warming-related processes lead to competing thermodynamic influences on the future position and intensity of midlatitude jet and storm tracks (Barnes & Screen, 2015; Harvey et al., 2013; Held, 1993; Shaw et al., 2016).

Climatologically, the equator-to-pole temperature gradient is largest in the midlatitudes, where jets and storm tracks develop due to strong baroclinicity. The climatological jet cores and storm tracks are located over the North Pacific (NP) and North Atlantic (NA) in the midlatitudes, where meridional sea surface

temperature (SST) gradients are also the largest and strong oceanic fronts develop in the Kuroshio and Oyashio Extension (KOE) and Gulf Stream regions, respectively. Changes in midlatitude SST gradients can impact the position and intensity of jet and storm tracks (Brayshaw et al., 2008; Kwon et al., 2010; Nakamura et al., 2008). In particular, the KOE SST frontal shift drives a jet shift by modifying the near-surface atmospheric baroclinicity (Nakamura & Miyama, 2014), even if tropical SST influences are removed (Frankignoul et al., 2011). Although midlatitude SST variability is considered an important driver of tropospheric circulation, it remains unclear how midlatitude SST warming influences the future jet and tropospheric circulation, compared with tropical and Arctic warming. To address this question, we investigated the difference between the projected NP and NA SST warming, based on Coupled Model Intercomparison Program phase 5 (CMIP5) models (Taylor et al., 2012), and examined the jet response to midlatitude SST warming using an atmospheric general circulation model (AGCM). A major advance in our study is to quantify the relative roles of Arctic, midlatitude, and tropical warming in the midlatitude jet.

2. Methods

2.1. Data and Analyses

We used 30 CMIP5 models (supporting information Table S1). Atmospheric data were horizontally interpolated onto a $2.5^\circ \times 2.5^\circ$ grid, and SST data were interpolated onto a $1^\circ \times 1^\circ$ grid. For the historical and Representative Concentration Pathway (RCP) 8.5 scenarios, the response to anthropogenic forcing is defined as the difference between the 2070–2099 period from the RCP8.5 run and the 1970–1999 period from the historical run. All data used in this study were averaged over the 30 CMIP5 models. To construct an annual mean, we averaged the 12 months from December through the following November. We also used the National Oceanic and Atmospheric Administration optimal interpolation SST (Reynolds et al., 2007). The significance test used in this study is a standard two-tailed *t* test.

2.2. Model and Experimental Design

We used the Dennou-Club Planetary Atmospheric Model (Takahashi & DCPAM Development Group 2018), which is reconstructed from Ishiwatari et al. (2007) for various planetary atmospheres. The governing equations for dynamical processes are the primitive equations, and simple parameterization schemes are adopted for physical processes. Here we set up various parameters for the Earth. The model configuration has 26 vertical layers with a spectral resolution of T85, roughly equivalent to $1.4^\circ \times 1.4^\circ$. For further details, the reader is directed to their website (<http://www.gfd-dennou.org/library/dcpam/index.htm.en>).

Four experiments were performed: forced with historical SST and sea ice distribution (HIST), SST and sea ice distribution in RCP8.5 scenario (RCP), Arctic sea ice loss (AICE), and RCP8.5 midlatitude SST (north of 35°N) and Arctic sea ice loss (MLSST + AICE). In the HIST experiment, the model is forced globally with historical SST and sea ice distribution, while the RCP experiment is forced globally with RCP8.5 SST and sea ice distribution. The AICE experiment is the same as HIST, except for RCP8.5 Arctic sea ice and SST distributions even in ice-free areas, following Deser et al. (2015) and Sun et al. (2015). The RCP and AICE responses are defined as the difference with the HIST experiment (see Figure S5). To obtain the atmospheric response due to midlatitudes and low latitudes SST warming, we performed MLSST + AICE experiment, which is forced with RCP8.5 midlatitude SST (north of 35°N : $15\text{--}35^\circ\text{N}$ with linear tapering zones, so that RCP8.5 midlatitude SST does not exceed the historical lower latitude SST) and Arctic sea ice distribution but with historical conditions elsewhere. The midlatitude SST warming (MLSST) response is estimated by subtracting AICE from the MLSST + AICE experiment. Similarly, the difference between the RCP and MLSST + AICE experiments provides the atmospheric response due to the low latitude (including the Southern Hemisphere) SST warming (LLSST response). The thermodynamic responses in these experiments reflect global warming, Arctic sea ice loss, and midlatitude and tropical SST warming (see Figure S7). We used the same SST and sea-ice boundary conditions obtained by averaging over the 30 CMIP5 models (i.e., climatology for the periods 1970–1999 and 2070–2099). The experiments were integrated for 30-year after 1-year spinup. In all of the experiments, radiative forcing is fixed at the 2,000 level, following previous studies (Peings & Magnusdottir, 2014; Sun et al., 2015).

3. Results

3.1. Future Changes in Midlatitude Jet and SST

The NH midlatitude eddy-driven jet is projected to shift marginally poleward in the late 21st century, but the jet response is vastly different between the NP and NA (Barnes & Polvani, 2013; Grise & Polvani, 2014; Simpson et al., 2014). The annual mean NA jet shows a significant zonal wind response, with positive values poleward and negative values at lower latitudes, indicative of a poleward jet shift (Figure 1a). However, no significant jet shift is evident over the NP. The NA jet shifts poleward in all seasons except winter, while the NP jet weakens in summer and only shifts poleward in autumn (Figure S1), confirming previous studies (Barnes & Polvani, 2015; Grise & Polvani, 2014; Simpson et al., 2014). More than 80% of the individual models simulate a poleward shift of the NA jet over the lower to midtroposphere and an intensification of the upper tropospheric jet (Figure 1c). Conversely, there is little model consensus on the jet response in the NP, except in the upper troposphere (Figure 1b). Overall, despite the fact that climatologically, the NP jet is stronger than the NA jet, the zonal wind response is weaker.

Projected SST warming also shows different responses in the NP and NA, where SST warming is projected to exceed 4 °C in the northern NP and Gulf Stream regions, respectively, comparable with Arctic Ocean warming (Figure 1d). The NP SST warming is the strongest in the north of 40°N, which causes the KOE SST front (i.e., a peak in the poleward SST gradient) to be weaker but not shift poleward (Figure 1e). Such warming in the northwest NP Ocean has also been observed over the past few decades (Nakanowatari et al., 2007). This situation is reminiscent of a recent temperature difference between tropical and Arctic warming. The KOE SST frontal weakening is most pronounced in summer and autumn (Figure S2), when weakening of the SST gradient is also robust across models (Figure 1g). In summer especially, there is a significant linear relationship across the models ($r = -0.41$; $p < -0.05$) between the NP jet weakening and weakening of the KOE SST gradient (Figure S3).

In contrast to the NP, the NA SST warming, with a peak in the Gulf Stream region, is reduced in the northern NA (Figure 1d) where a weakening of the Atlantic Meridional Overturning Circulation (AMOC) is expected to offset the local SST warming (Woollings et al., 2012). The northern NA is the only region where the SST warming is not robust across the models, indicative of the uncertainty in the AMOC reduction. Despite a weakening of the SST front, the north-south SST warming difference results in a poleward shift of the SST front (Figure 1f). This poleward shift is independent of season (Figure S2), and intensification of the SST gradient is robust across the models during all seasons (Figure 1h). The individual models also exhibit a poleward shift in both the SST front and NA jet in autumn ($r = 0.42$; $p < -0.05$), although there is some uncertainty on the SST frontal shift among the models (Figure S3). These results indicate that although the projected SST warming is robust in both oceans, the contrasting SST frontal changes correspond to the contrasting midlatitude jet changes.

The atmospheric impact on midlatitude SST warming is highlighted in the NP. The recent SST warming observed in the NP is most pronounced in the KOE region, especially during summer and autumn (Figure S4). The KOE SST warming drives a poleward SST frontal shift that enhances a poleward jet shift together with the intensification of the western Pacific subtropical high (Matsumura et al., 2015; Matsumura & Horinouchi, 2016). In the projected NP SST warming, however, there is no significant SST frontal shift among the models (Figure S3), as the KOE SST front weakens, which corresponds with the upper tropospheric jet weakening in summer (He et al., 2015) and even autumn (Figure S4), consistent with a projected storm track decrease (Chang et al., 2012). Observed NA SST warming is in contrast to the projected NA SST warming due to the AMOC reduction (Figure S4).

3.2. Impact of Midlatitude SST Warming on Simulated Jet

Our results suggest that the future position and intensity of the jets is related to the projected midlatitude SST warming. However, it is difficult to determine causality with coupled climate models alone due to feedbacks between the atmosphere and ocean. To better understand the causality, four experiments were performed using an AGCM. We quantified the atmospheric response derived from (1) global SST warming (RCP), (2) Arctic sea-ice loss (AICE), (3) midlatitude SST warming (MLSST), and (4) tropical SST warming (LLSST; Figure S5). It is notable that, for the atmospheric response to greenhouse gas forcing, the indirect SST-mediated component is substantially larger in magnitude than the direct radiative component and

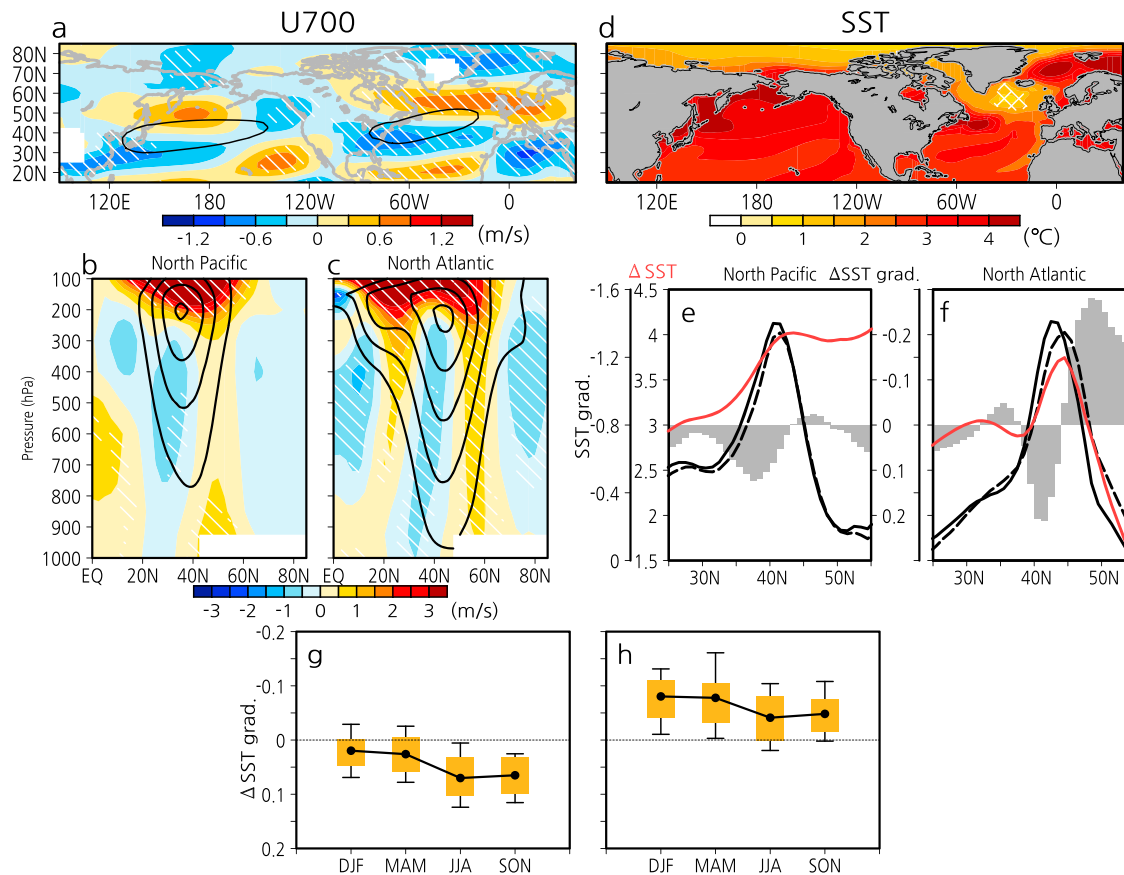


Figure 1. (a) Response of annual mean 700-hPa zonal wind from 30 Coupled Model Intercomparison Program phase 5 models, defined as the difference between the means over 2070–2099 and 1970–1999. Vertical sections of the zonal wind response over the (b) NP (120°E–180°) and (c) NA (20–80°W). Black contours denote the historical jet climatology (contour interval in (a) and (b) is 10 and 5 m/s in (c) with the zero contours omitted). Hatching indicates $\geq 80\%$ model agreement on the sign of the response. (d) As in (a) but for SST response, and hatching indicates $< 90\%$ model agreement on the sign of the response. Latitudinal sections of the (e) NP (150°E–180°) and (f) NA (25–55°W) SST response (red line) and poleward SST gradient ($^{\circ}\text{C}$ per latitude) in historical (solid line) and Representative Concentration Pathway 8.5 (dashed line) runs and their difference (shaded). Seasonal response of poleward SST gradient showing the 25th–75th (boxes) and 10th–90th (bars) percentile range and multimodel mean (black circles) in the (g) NP (150°E–180°, 30–50°N) and (h) NA (25–55°W, 35–55°N). SST = sea surface temperature; NP = North Pacific; NA = North Atlantic.

dominates the total response to greenhouse gas forcing, particularly in the NH (Deser & Phillips, 2009; Grise & Polvani, 2014).

Differences in the jet between the simulated RCP and projected CMIP5 model responses are produced by the direct radiative component that drives a weak poleward jet shift (Grise & Polvani, 2014; Shaw & Voigt, 2015) and by ocean-atmosphere coupling (Deser et al., 2015; Woollings et al., 2012). Nevertheless, the RCP response reproduces well the projected NA jet shift (Figure 2a), whereas the NP jet weakens with no poleward shift. In agreement with previous studies (Deser et al., 2010; Peings & Magnusdottir, 2014; Sun et al., 2015), the AICE response weakens the westerly winds along the poleward flank of the jet, shifting the jet equatorward over the NP (Figure 2b), whereas a NA jet shift is almost absent, occurring only in winter (Figure S6; Barnes & Polvani, 2015). Interestingly, the MLSST response reproduces the NA jet shift (Figure 2c). This indicates that the projected NA jet shift is caused by midlatitude SST warming. In contrast, the NP jet is markedly weakened in MLSST, accounting for the projected NP jet weakening in summer (Figure S6). Over the northern NP, the westerly wind is enhanced as a result of intensification in the surface temperature gradient between the northern NP SST warming and Arctic (Figure S7). However, AICE appears to offset the enhanced westerly, which is indeed suppressed in the MLSST + AICE experiment (Figure S6).

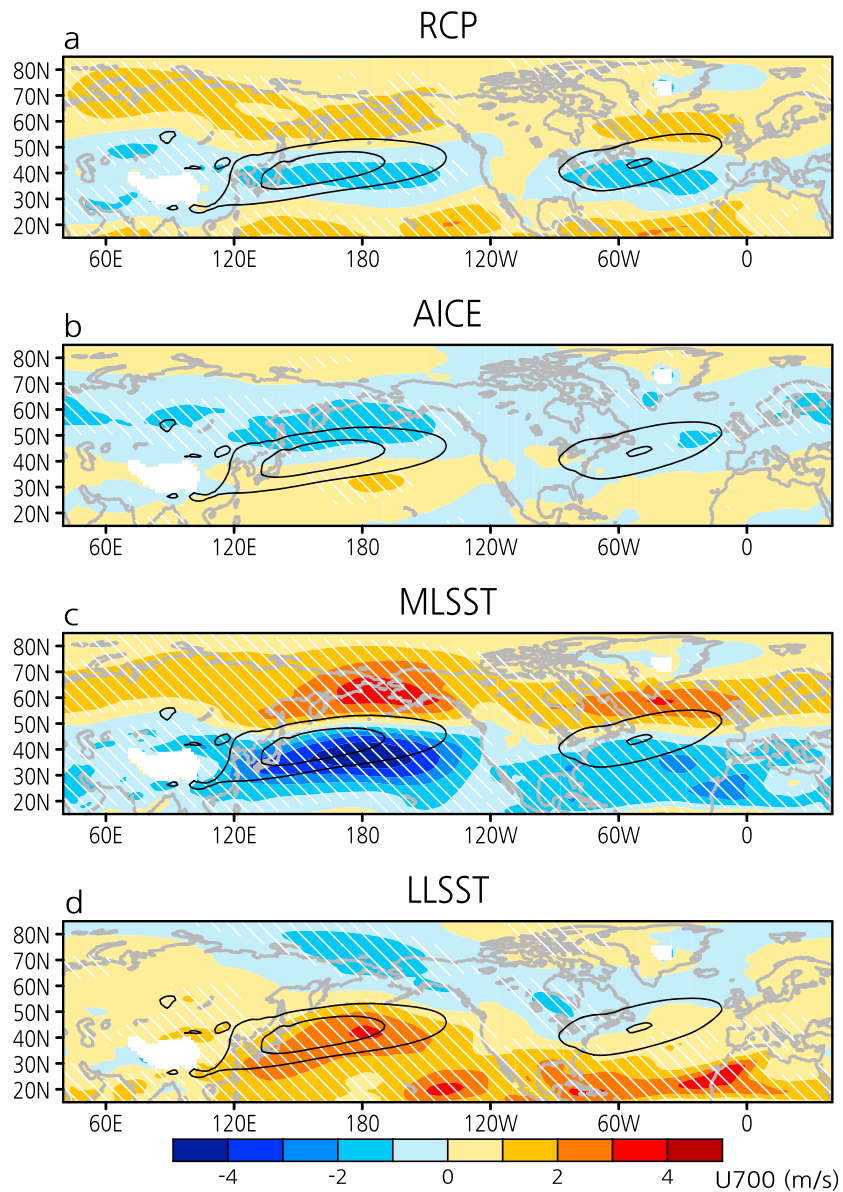


Figure 2. Response of annual mean 700-hPa zonal wind in (a) RCP, (b) AICE, (c) MLSST, and (d) LLSST. Black contours denote the climatological jet in the HIST experiment (contours for 10 and 15 m/s). Hatching indicates statistical significance at the 99% level. RCP = global warming; AICE = Arctic sea ice loss; MLSST = midlatitude SST warming; LLSST = low latitude SST warming.

To further examine the physical linkage, we show storm tracks in Figure 3. Over the NA, the RCP response shows a particular strengthening and northeastward extension of the storm track toward Europe, consistent with the eddy-driven NA jet shift (Figure 2a). The MLSST response increases the storm track over the north side of the main storm-track region and decreases over its south side, indicative of a poleward shift of the storm track, which is consistent with the NA jet shift (Figure 2c) as stronger SST gradients on the poleward side of the subtropical jet (Figure 1f) lead to stronger storm track and eddy-driven jet (e.g., Brayshaw et al., 2008). The storm-track weakening over the south side is expected to offset the LLSST-intensified storm track, indicating that intensified storm track in RCP is caused by MLSST. Although the LLSST response also increases the storm track over the Labrador Sea, AICE appears to offset it over the northeast Atlantic sector. These results are consistent with a storm track increase due to the AMOC reduction (Woollings et al., 2012). In contrast, over the NP, the RCP response is significant in the downstream of the main storm-track region

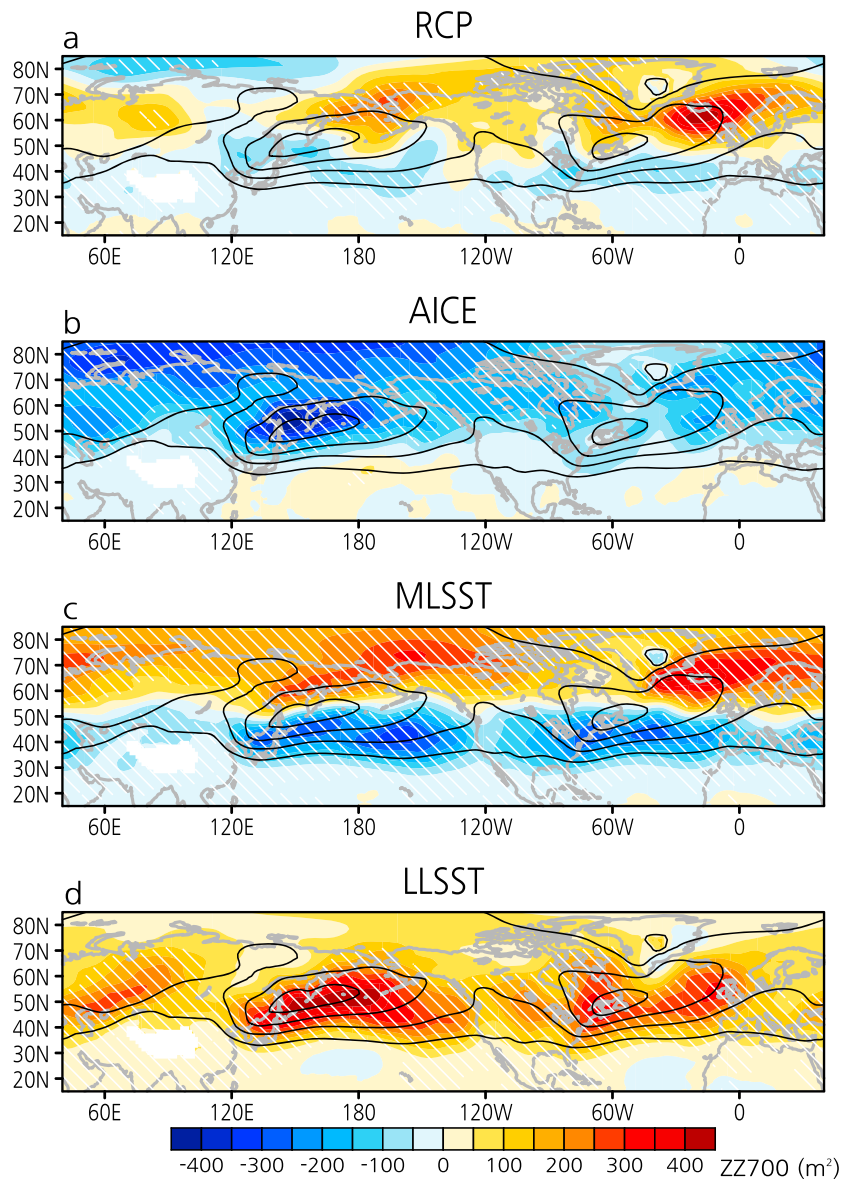


Figure 3. As in Figure 2 but for variance of 2–6-day-filtered 700-hPa geopotential height. Black contours denote the climatological storm track in the HIST experiment (contours interval is 500 m²).

while in its upstream is not. The AICE response decreases roughly over the north side of the main storm-track region and the MLSST decreases over its south side, which appear to offset the LLSST response, suggesting that the dominating forcing is weaker than the NA.

Difference in the jets between the two oceans and impact of tropical warming on the jets are more evident in the vertical structures (Figure 4). The RCP response reproduces well the projected upper tropospheric jets over both oceans (Figures 1b and 1c) and also the NA jet shift over the lower to midtroposphere (Figure 1c). The NP jet weakening over the lower to midtroposphere is forced by MLSST, and Arctic sea ice loss contributes negatively, suppressing the MLSST-enhanced westerly over the northern NP. In both oceans, the LLSST response intensifies the jet on the southward flank of the jet axis, with the strongest changes in the upper troposphere, indicative of the tropically driven component of the subtropical jet, which is comparable in magnitude with the eddy-driven jet component induced by MLSST. The competing effects between tropical and midlatitude warming primarily result in the total jet (RCP) response. Naturally, these changes in the jets correspond to thermodynamic responses that alter equator-to-pole temperature gradients

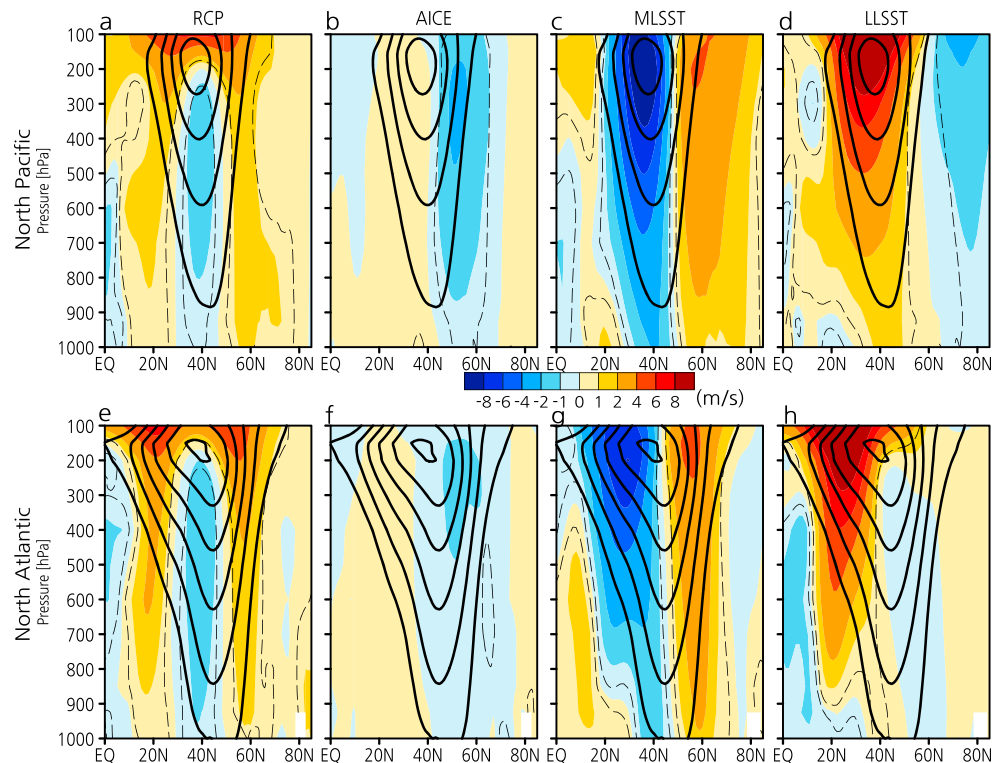


Figure 4. As in Figure 2 but for vertical sections of the zonal wind over the (a–d) North Pacific (120°E–180°) and (e–h) North Atlantic (20–80°W). Solid contours denote the climatological jet in the HIST experiment (contour interval is 10 m/s in the North Pacific and 5 m/s in the North Atlantic, with the zero contour omitted). Dashed contours indicate statistical significance at the 99% level.

(Figure S7). These experiments provide evidence that although tropical warming intensifies the upper tropospheric jet, the lower to midtropospheric jet depends on midlatitude SST warming, which produces the jet differences between the NP and NA.

4. Discussion and Conclusions

We conclude that the competing effects of tropical and midlatitude warming will play a more substantial role in the future midlatitude jet than the competing influences of tropical and Arctic warming. Although the simulated NP jet weakening is suppressed by the direct radiative component that drives a weak poleward jet shift (Grise & Polvani, 2014; Shaw & Voigt, 2015), midlatitude SST warming accounts for the projected NP jet weakening in summer, whereas in winter, tropical warming may win the competition. Tropical Pacific warming induces anomalous stationary eddies that propagate into the extratropics and disturbs the jet and storm tracks (Shaw et al., 2016). Indeed, changes in stationary eddies cause a poleward jet shift in the western Pacific and an equatorward shift in the eastern Pacific, particularly in winter (Grise & Polvani, 2014; Simpson et al., 2014; Figure S1). Given the lower model consensus on the projected NP jet (Figures 1a and 1b), the dominating forcing is likely to be dependent on season and model, similar to the radiative response of clouds that is linked to the midlatitude circulation uncertainty (Voigt & Shaw, 2015). In contrast to the NP jet, the NA jet shift is robust in both the CMIP5 models and AGCM experiments. As a result, midlatitude SST warming is likely to win the competition with tropical warming. Additionally, current climate models might underestimate the AMOC reduction (Liu et al., 2017).

The objective of our simulation is to evaluate the relative role of Arctic, tropical and midlatitude warming. First of all, the RCP response needed to reproduce the atmospheric circulation anomalies identified in the CMIP5 model analysis. Indeed, the RCP response reproduces well the projected NA jet shift, although the NP jet may be dependent on model. However, the midlatitude jets can be affected by internal variability,

such as the feedback between Arctic sea ice loss and midlatitude SST warming by ocean-atmosphere coupling (Deser et al., 2015; Deser et al., 2016). Although our results indicate that an equatorward shift of the jet due to Arctic sea ice loss is suppressed by midlatitude SST warming, the jet response to Arctic sea ice loss is amplified by the ocean-atmosphere coupling, which might produce the jet difference between the CMIP5 models and our RCP simulation over the NP. Further research is needed to understand how internal variability affects the jet response. The impact of Arctic sea ice loss on midlatitude circulation has been debated extensively (Barnes & Screen, 2015; Cohen et al., 2014); however, minimal research has focused on the role of midlatitude oceans. Our results provide important information for the improvement of projections on future midlatitude circulation, which may also further our understanding of ongoing midlatitude climate change.

Acknowledgments

We acknowledge the WCRP's Working Group on Coupled Modeling and thank the climate modeling groups (Table S1) for producing and making available their model output. The CMIP5 data sets can be downloaded from the Earth System Grid Federation website (<https://pcmdi9.llnl.gov/projects/cmip5/>). The model data were processed by the Environment Research and Technology Development Project of the Ministry of the Environment and provided by the Data Integration and Analysis System for National Key Technology from MEXT, Japan. DCPAM5 is available online (<http://www.gfd-dennou.org/library/dcpam/index.htm.en>). We also wish to thank H. Endo for providing additional model data and appreciate the comments from the reviewers and the Editor. This study was supported by the Environment Research and Technology Development Fund (2–1503) of the Ministry of the Environment, Japan and the Japan Society for the Promotion of Science (JSPS) grant 16K05550 and was conducted using the Fujitsu PRIMERGY CX600M1/CX1640M1 (Oakforest-PACS) in the Information Technology Center, The University of Tokyo.

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