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Impact of Antarctic Meltwater Forcing on East Asian Climate Under Greenhouse Warming

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Key Points:
- Antarctic meltwater forcing induces an overall global cooling but regional warming in East Asia
- Antarctic meltwater forcing can shift the Intertropical Convergence Zone northward and suppress convection over the Western North Pacific
- Suppressed convection in the Western North Pacific is responsible for the regional warming of East Asia via atmospheric teleconnection

Supporting Information:
- Supporting Information S1

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Abstract In recent decades, Antarctic ice sheet/shelf melting has been accelerated, releasing freshwater into the Southern Ocean. It has been suggested that the meltwater flux could lead to cooling in the Southern Hemisphere, which would retard global warming and further induce a northward shift of the Intertropical Convergence Zone (ITCZ). In this study, we use experimental ensemble climate simulations to show that Antarctic meltwater forcing has distinct regional climate impacts over the globe, leading in particular to regional warming in East Asia, which offsets the global cooling effect by the meltwater forcing. It is suggested that Antarctic meltwater forcing leads to a negative precipitation anomaly in the Western North Pacific (WNP) via cooling in the tropics and the northward shift of the ITCZ. This suppressed convection in WNP induces an anticyclonic flow over the North Pacific, which leads to regional warming in East Asia. This hypothesis is supported by analyses of interensemble spread and long-term control simulations.

Plain Language Summary In recent decades, greenhouse warming has accelerated the melting of Antarctic glaciers, which discharges freshwater into the Southern Ocean and therefore reduces the surface density. Surface freshening in the Southern Ocean induces cooling and sea ice expansion on the surface, such that it could delay global warming and further lead to a northward shift of the Intertropical Convergence Zone (ITCZ). Here, we examine the distinct regional impacts of Antarctic meltwater forcing over the globe by analyzing experiments with and without meltwater forcing. For example, the Antarctic meltwater forcing induces a global cooling but leads to regional warming in East Asia. We find that Antarctic meltwater forcing leads to reduced convection in the Western North Pacific (WNP) due to the northward shift of the ITCZ and an overall cooling in the tropics. This circulation change in WNP induces regional warming in East Asia via atmospheric teleconnection.

1. Introduction

Observational evidence has revealed that Antarctic ice sheet/shelf melting has been accelerating in recent years and this has resulted in freshwater discharge into the Southern Ocean (Konrad et al., 2018; Paolo et al., 2015; Rignot et al., 2019; Shepherd et al., 2018; Wouters et al., 2015). In a future warmer world, freshwater release from the Antarctic continent may further accelerate (DeConto & Pollard, 2016; Fogwill et al., 2015; Hansen et al., 2016). Nevertheless, the effects of meltwater due to the mass loss from Antarctic ice have not been reflected in future climate projections (Collins et al., 2013; Kirtman et al., 2013) in the Coupled Model Intercomparison Project Phase 5 (CMIP5) and Phase 6 (CMIP6) (Eyring et al., 2016; Taylor et al., 2012).

In this context, many previous studies have investigated the impact of meltwater forcing on the climate system by applying an idealized freshwater forcing in climate simulations (Bintanja et al., 2013, 2015; Bronselaer et al., 2018; Fogwill et al., 2015; Park & Latif, 2019; Pauling et al., 2016; Stouffer et al., 2007). Meltwater forcing reduces the surface water density and the oceanic deep convection in the Southern Ocean, which hinders warm Circumpolar Deep Water (CDW) intrusion to the cold surface water; therefore, the intensified stratification in the Southern Ocean leads to anomalously cold surface and warm subsurface temperatures around Antarctica, which causes an expansion of the sea ice cover (Park & Latif, 2019; Pauling et al., 2016). This is accompanied by subsurface warming, leading to an acceleration in basal melting at the

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bases of the ice shelves (Obase et al., 2017; Rignot & Jacobs, 2002; Shepherd et al., 2004). An increase in the sea ice extent delays greenhouse warming in the Southern Ocean via a positive ice-albedo feedback. Moreover, the cooling discrepancy between the Southern Hemisphere and the Northern Hemisphere (Stocker, 1998) alters the atmospheric heat transport, resulting in a northward shift of the Intertropical Convergence Zone (ITCZ) (Bozbiyik et al., 2011; Cabré et al., 2017; Kang et al., 2008, 2009; Zhang & Delworth, 2005).

In fact, satellite observations have recorded a slight expansion in Antarctic sea ice during the satellite era (Cavalieri & Parkinson, 2008; Comiso & Nishio, 2008) consistent with the cooling trend in the Southern Ocean during recent decades (Turner et al., 2009; Zwally et al., 2002). Conversely, abyssal warming in the Southern Ocean was observed during that same period (Fahrbach et al., 2011; Purkey & Johnson, 2010, 2012; Robertson et al., 2002), possibly due to an enhanced salinity stratification (De Lavergne et al., 2014).

Several mechanisms have been suggested to explain the recent observational trends in the Southern Hemisphere. One is the intensification of the Southern Annular Mode (SAM) (Thompson & Wallace, 2000) due to stratospheric ozone depletion, leading to enhanced evaporation from the sea surface in the Southern Ocean (Thompson & Solomon, 2002; Turner et al., 2009). Another candidate is related to surface freshening in response to anthropogenic greenhouse warming, which possibly contributes to the amplification of the global hydrological cycle (de Lavergne et al., 2014) and Antarctic ice shelf melting (Bintanja et al., 2013). In addition, long-term internal variability associated with deep convection in the Southern Ocean has been proposed as one of the drivers of the recently observed trend (Latif et al., 2013; Zhang et al., 2019).

Meanwhile, previous studies investigating the impacts of meltwater have primarily focused on effects in the Southern Hemisphere and do not cover impacts on other areas on the globe, for example, the Northern Hemisphere and related teleconnection mechanism. Regarding atmospheric teleconnections, tropics are known to play an active role and can regionally affect the extratropical climate in the Northern Hemisphere by modulating tropical convective activities (Hoskins & Karoly, 1981; Lau & Nath, 1994). Many previous studies also have suggested impacts of changes in tropical convection on the East Asian climate via the tropical-extratropical teleconnection (Gong et al., 2015; Kim & Kug, 2018; Son et al., 2014). Here, we examine the impact of Antarctic meltwater forcing, in particular on East Asia, and suggest a possible mechanism linking Antarctic changes to East Asian climate as a bridging role of the tropics.

2. Data and Methods

To examine the impacts of Antarctic meltwater forcing on global climate, idealized ensemble simulations of the Kiel Climate Model (KCM; Park et al., 2009) were analyzed. The KCM is composed of the European Centre for Medium-Range Weather Forecasts (ECMWF) Hamburg atmospheric general circulation model (GCM) version 5 (ECHAM5) coupled with the Nucleus for European Modeling of the Ocean (NEMO) ocean/sea ice GCM. The experimental design of the present study was the same as that of Park and Latif (2019); however, we included additional 12 ensemble members (for a total of 22 ensemble members) to obtain more robust responses to the Antarctic meltwater forcing.

The following three different simulations were used in our study to investigate the sensitivity of the climate system to a freshwater forcing from the Antarctica. The first is a preindustrial control simulation over 2,300 years (CTRL) applying a constant carbon dioxide (CO_2) concentration of 286.2 parts per million (ppm). The other two are global warming simulations with and without Antarctic meltwater forcing. Both simulations were integrated over 200 years with 22 ensemble members. The initial conditions of the individual realizations were taken from CTRL every 100 years and were different for each realization. The first global warming ensemble employed an increasing atmospheric CO_2 concentration at a rate of 1% $year^{-1}$ until CO_2-quadrupling ($4 \times CO_2$, 1,144.8 ppm); this simulation is termed GW. In the other global warming simulation, the increased CO_2 concentration was applied as in GW but with the addition of a freshwater flux to only the Southern Ocean; this simulation is termed GWMW. The total amount of meltwater forcing was 0.1 Sv and not changed in time. The forcing was exerted proportionally at all of the coastal points of Antarctica describing runoff into the Southern Ocean in the CTRL simulation. Meltwater forcing in GWMW is assumed to be the result of ice sheet/shelf melting with iceberg calving. 0.1 Sv is consistent

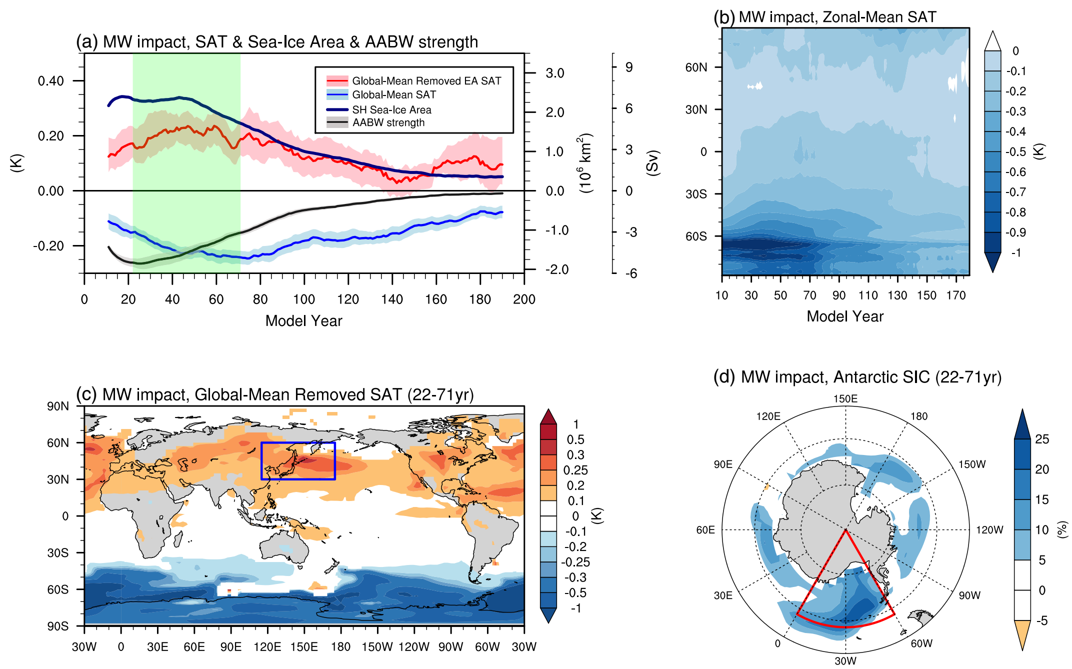

Figure 1. (a) Time series of global-mean removed SAT in East Asia (blue box in panel c) (red), global-mean SAT (blue), sea ice area in the Southern Hemisphere (navy blue), and AABW strength (black) in the ensemble-mean difference (GWMW-GW) smoothed by the 21-year running mean. The AABW strength is defined each year as the absolute value of the minimum in the global overturning stream function in south of 60°S. Shading shows the 99% uncertainty in the mean. The green box, which indicates the model year period from 22 to 71, indicates the maximum temperature in East Asia. (b) Time series of the zonal-mean SAT in the ensemble mean, smoothed in the same way as in panel (a). Ensemble-mean difference of the (c) SAT (global-mean removed) and (d) SIC, both averaged over the 22- to 71-year period (green box in panel a). The regions denoted by colors indicate where the responses are significant at the 99% confidence level by using bootstrap method.

with DeConto and Pollard (2016), which estimated that historical and representative concentration pathways (RCPs) 8.5-projected Antarctic meltwater reaches 0.1 Sv around the year 2035. However, it should be noted that this estimate can be potentially high because they considered a critical ice sheet/cliff instability. Detailed descriptions of experimental design can be obtained in Park and Latif (2019).

Because all the other conditions of the two global warming simulations are identical except for the meltwater forcing, the differences between GW and GWMW imply impact of the meltwater forcing. To test a statistical significance, the bootstrap method and student's *t* test were used.

3. Results

To examine the impact of the Antarctic meltwater forcing, we first analyzed the ensemble-mean difference between the GW and GWMW simulations, as shown in Figures 1 and 2. Figure 1a shows the evolution of the Southern Hemisphere sea ice area, global-mean SAT, and Antarctic Bottom Water (AABW) strength. As pointed out by previous studies, Antarctic meltwater forcing weakens the AABW cell (i.e., isolates the warm CDW from the surface; Figure S1 in the supporting information), resulting in subsurface warming and surface cooling (Figure S2). This induces an increase in the sea ice concentration (SIC) in the Southern Ocean. In the presence of a strong positive albedo feedback, the air temperature, and sea ice responses are enhanced. Interestingly, the sea ice response gradually weakens even though the meltwater forcing is constant. In a linear framework, this is possibly due to ocean adjustments caused by subsurface warming related to the limitation of the deep heat reservoir; a similar mechanism has been suggested in previous studies (Martin et al., 2013; Zhang et al., 2017; Zhang & Delworth, 2016). SAT around the Antarctica significantly decreases due to the negative downward sensible heat flux and the ice-albedo feedback as a consequence of both cold sea surface temperature (SST) and additional sea ice formation. Subsequently, the cooling in the Antarctic area plays a role in decreasing the global temperature, even in the Arctic (Figure 1b).

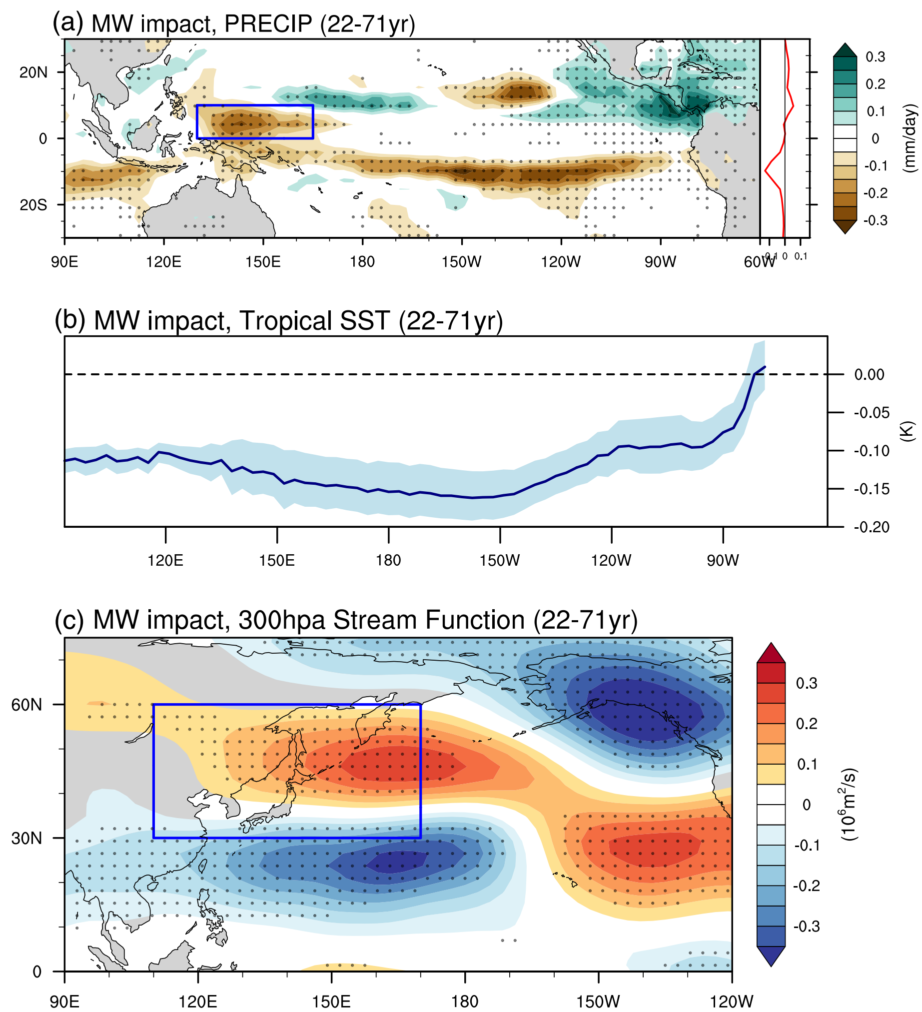

Figure 2. Ensemble-mean difference of the (a) precipitation, (b) SST (5°S to 5°N), and (c) stream function at 300 hPa (zonal-mean removed) averaged over the 22- to 71-year period (green box in Figure 1a). The regions denoted by black dots indicate where the responses are significant at the 99% confidence level by using bootstrap method, and the light-blue shading indicates the 99% uncertainty in the mean. The rightmost red line in panel (a) shows the zonal-mean within 60°E to 60°W.

The surface cooling is weaker in the Northern Hemisphere than that in the Southern Hemisphere. To examine the regional dependency of the SAT changes, Figure 1c shows the temperature responses to Antarctic meltwater forcing after the global-mean SAT is removed. An interhemispheric contrast is clear, showing cooling in the Southern Hemisphere and relative warming (actually weak cooling) in the Northern Hemisphere. However, there is absolute but weak warming in East Asia, which is most prominent among the Northern Hemisphere (Figure 1c). This suggests that the temperature response in East Asia to the Antarctic meltwater forcing is determined by a competition between the global cooling effect and a regional warming effect, respectively. In this study, we focus on how Antarctic meltwater forcing leads to the regional warming in East Asia. Here, we will use the term of the "regional warming," which is defined as the meltwater-induced SAT anomalies after the global-mean SAT (global cooling effect) is removed.

The regional warming over East Asia gradually increases from the starting point of the meltwater forcing and has a maximum value at the model years 22–71 (Figure 1a, green box), suggesting that the regional warming response in East Asia has an approximately 21-year delay. Also, the SIC increase and weakening of AABW cell in the Southern Ocean have a peak 6 years after the initial start of the forcing, indicating the 6-year-delayed ocean responses to the meltwater forcing. From these results, the 21-year delay for the regional warming in East Asia is divided into the following two processes: 6-year delay for sufficient ocean stratification and 15-year delay for regional warming in East Asia (from Southern Ocean responses to East Asia).

To understand how Antarctic meltwater forcing leads to regional warming in East Asia, Figure 2 shows the precipitation, equatorial SST, and stream function at 300 hPa anomalies for the same period as in Figure 1c. It is evident that precipitation tends to decrease in the southern tropics and increase in the northern tropics, suggesting a northward shift of ITCZ (Figure 2a). Due to the overall cooling tendency in the tropics, the response in the southern tropics is more distinctive than that in the northern tropics. The Antarctic meltwater forcing leads to more negative temperature anomalies in the Southern Hemisphere compared to those in the Northern Hemisphere, which implies an interhemispheric temperature contrast (Stocker, 1998). In this case, the anomalous interhemispheric atmospheric heat transport is toward the Southern Hemisphere, which possibly induces the northward shift of the ITCZ (Kang et al., 2008, 2009).

In addition to the northward shift of ITCZ, it is also clear that the precipitation is significantly reduced over the Western North Pacific (WNP) (Figure 2a). The decrease in the WNP precipitation might be due to the northward shift of ITCZ because the climatological ITCZ is located in WNP. Moreover, the decreased WNP precipitation might be connected to the zonally asymmetric cooling in the tropical Pacific. As shown in Figure 2b, this cooling is more pronounced in the western Pacific than in the eastern Pacific, which indicates a weakened zonal temperature gradient in the equatorial Pacific. Such SST variations can induce suppressed atmospheric convection in WNP and activate convection in the eastern Pacific.

In a Gill-type response to the suppressed convection in WNP, there is a local anticyclonic flow in the lower troposphere and a cyclonic flow in the upper troposphere, as shown in Figure 2c (Gill, 1980; Rui & Wang, 1990). The upper-level cyclonic flow and accompanying convergence lead to Rossby wave energy propagation to the extratropical region (Hoskins & Karoly, 1981), which is responsible for a distinctive anticyclonic circulation over the western side of the North Pacific. This circulation pattern is very similar to the so-called Kuroshio anticyclone, which is a response to the suppressed convection in the WNP during the El Niño phase (Kim & Kug, 2018; Son et al., 2014). The Kuroshio anticyclone has a barotropic structure; therefore, there is still anticyclonic circulation in the lower troposphere. Eventually, this anomalous anticyclonic flow accompanies the warm advection in East Asia, which might be responsible for the regional warming in East Asia in response to the Antarctic meltwater forcing.

However, a time within-year might be sufficient for atmospheric teleconnection from tropics to East Asia, so that the 15-year delay for regional warming in East Asia might be mostly related to bridging AABW weakening and tropical changes. How the Southern Ocean signals are conveyed to the tropics with such long-term time delay is unclear in our analysis, but a slow oceanic advection process might be a possible way as the previous studies suggested that the isopycnal oceanic advection can contribute to the decadal to multidecadal tropical SST anomalies (Luo et al., 2003; Luo & Yamagata, 2001; Tatebe et al., 2013).

So far, from the ensemble-mean results, we hypothesize that the Antarctic freshwater discharge induces suppressed convection in WNP, which leads to regional warming in East Asia. To check this hypothesis, we examined these processes in the interensemble spread. If the hypothesis is correct, it should work not only in the ensemble-mean but also in the interensemble spread. The precipitation anomaly in WNP has a strong positive correlation ($r = 0.8$) with SAT in the equatorial Pacific (Figure 3a). This suggests that, at the given meltwater forcing, the strength of the suppressed convection in WNP depends on how fast the equatorial Pacific cools down. Further, it is apparent that ensemble members with more suppressed convection in WNP are prone to simulating stronger warming in East Asia with a correlation coefficient of -0.57 (Figure 3b).

To further support this argument, the regression with respect to the East Asian SAT index was computed from the interensemble spread. It is interesting that the precipitation pattern (Figure 3c) associated with the regional East Asian warming in the ensemble spread space is in good agreement with the ensemble-mean responses (Figure 2a). For example, the decreased precipitation in WNP and the increased precipitation in the off-equatorial Pacific of the Northern Hemisphere are significant. This similarity indicates that this precipitation pattern is a key for explaining the regional warming in East Asia. As discussed earlier, the precipitation decrease in WNP leads to Rossby wave energy propagation, which is also well captured in the regression pattern in the Figure 3d. It is also seen that the East Asian warming is related to

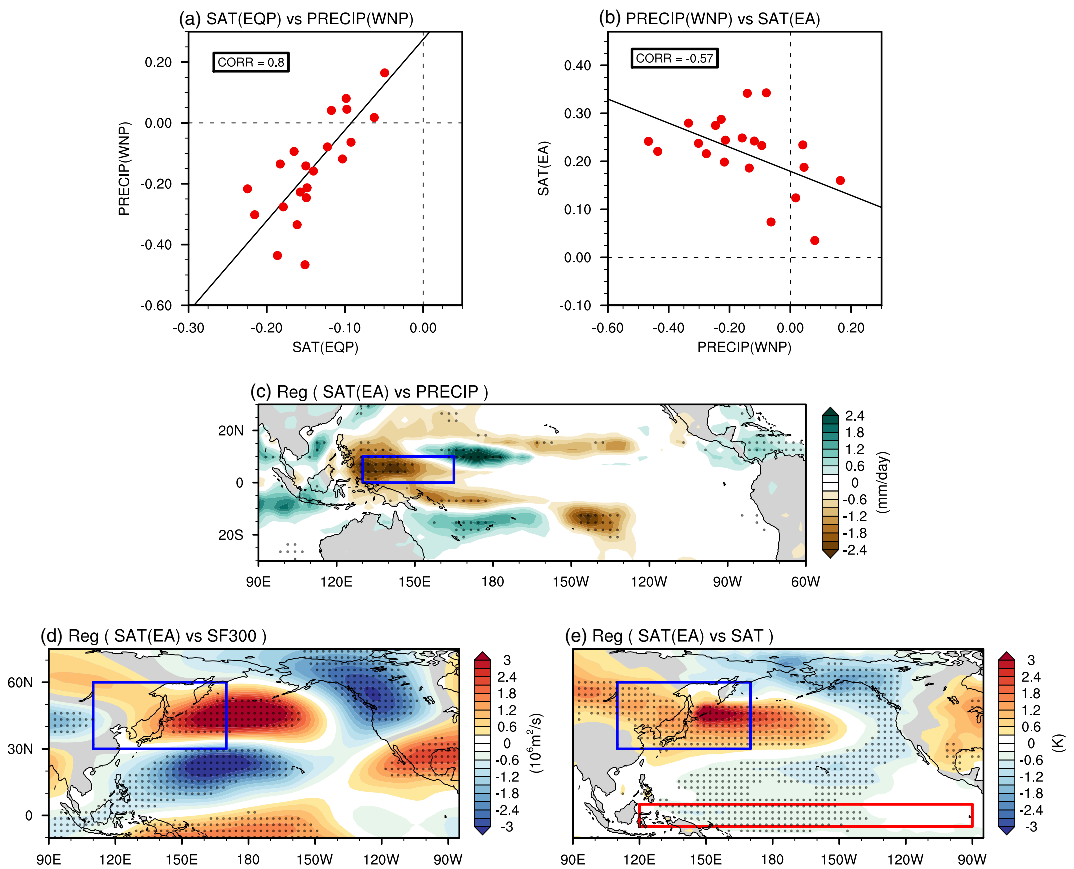

Figure 3. (a) Scatter diagram of SAT in the Equatorial Pacific (red box in panel e) versus the precipitation in WNP (blue box in panel c) calculated in the interensemble spread for the same period as in Figure 2. (b) The same as panel (a) but for the precipitation in WNP versus SAT (global-mean removed) in East Asia (blue box in panel d). Regression maps of the (c) precipitation, (d) stream function at 300 hPa, and (e) SAT onto SAT (global-mean removed) in East Asia. The regions denoted by black dots indicate where the responses are significant at the 99% confidence level by using student's *t* test.

cooling in the equatorial Pacific (Figure 3e), which might be responsible for the WNP convective response. As in the ensemble mean, the cooling is more dominant in the western Pacific than in the eastern Pacific. These results in the interensemble spread strongly support our hypothesis concerning how Antarctic meltwater forcing induces regional warming in East Asia.

In addition to the interensemble spread, we also analyzed the 2,300-year long-term control integration to further support our hypothesis. To link the East Asian warming to the variability in the Southern Ocean, the sea ice in the Southern Ocean was regressed with respect to the East Asian SAT index. For consistency, the East Asian SAT index was calculated after the global-mean temperature was removed after applying a 50-year moving average. Figure 4a shows the 15-year leading regression pattern of sea ice versus the East Asian SAT index. It is evident that regional warming in East Asia is related to the SIC increase in the Weddell Sea, which is consistent with the result in Figure 1d. Moreover, the regression coefficient of the global-mean removed SAT in East Asia onto the SIC in the Weddell Sea has a maximum value when the SIC leads the SAT by 15 years (Figure 4b). This is consistent with the meltwater-induced result that the regional warming in East Asia has a maximum value 15 years after the peak of Antarctic SIC and AABW strength response.

In the control simulation, the spatial patterns of the precipitation, tropical temperature, and stream function at 300 hPa against the East Asian SAT index are also similar to those in Figure 2. That is, the suppressed convection in WNP and the anticyclonic flow at midlatitudes are distinctive. It seems that the WNP precipitation is sensitive to the sea ice variability in the Weddell Sea. In the case of the nonconvective phase in the Weddell

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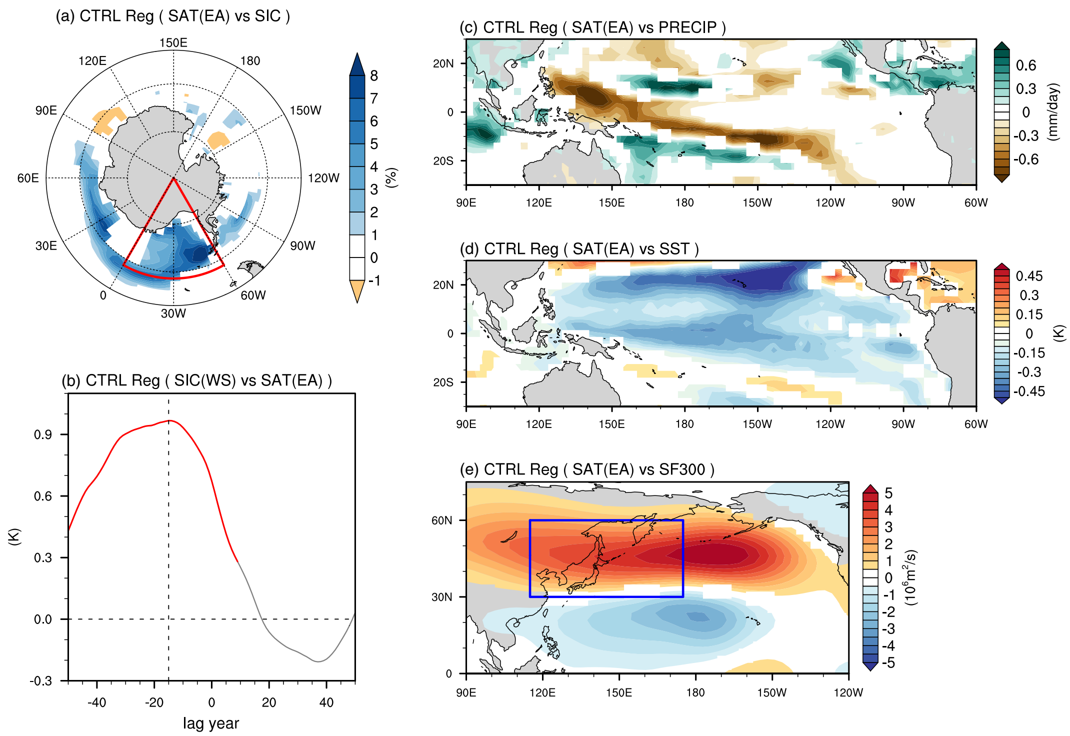

Figure 4. Regression maps of the (a) SIC, (c) precipitation, (d) SST, and (e) stream function at 300 hPa onto the SAT (global-mean removed) in East Asia. (b) Lead-lag regression coefficients of SAT in East Asia onto the SIC in Weddell Sea (red box in panel a). Values are calculated in the CTRL but for the regression results based on the 50-year running mean. In panel (a) SIC leads SAT by 15 years, whereas panels (c)–(e) simultaneous with SAT. The regions denoted by colors and red line in panel (b) indicate where the responses are significant at the 99% confidence level by using student's *t* test, considering the effective degrees of freedom.

Sea, a significant precipitation decreases in WNP also appeared in the study of Latif et al. (2013) and Cabré et al. (2017), which investigated the global impacts of Southern Ocean internal variability driven by deep convection changes in the Weddell Sea. These results from the control simulation indicate that Antarctic sea ice variability can influence the East Asian temperature via the convective response in WNP, supporting our hypothesis for the response of East Asian temperatures to Antarctic meltwater forcing.

4. Summary and Discussion

We investigated the global teleconnection and associated regional impacts over East Asia due to meltwater forcing in the Southern Ocean under greenhouse warming with a series of climate simulations. In response to the meltwater forcing, surface cooling, abyssal warming in the Southern Ocean, and a northward shift of ITCZ were seen in this study, as in previous studies (Bronselaer et al., 2018; Park & Latif, 2019). Despite the overall surface cooling trend, the response in East Asia shows slight warming rather than cooling, implying that another process is at work besides the global cooling. This regional warming in East Asia is related to the suppressed convection in WNP, which is caused by both zonally asymmetric cooling in the tropical Pacific and the northward shift of ITCZ. The suppressed convection in WNP induces the Kuroshio anticyclone in the western part of the North Pacific, which ultimately accompanies warm advection in East Asia. It was also shown that this meltwater-induced regional warming occurs in East Asia with a time lag of approximately 20 years. A statistical analysis of the interensemble spread well coincides with the mechanism for the regional warming in East Asia suggested by the ensemble-mean results.

The teleconnection mechanism from the Southern Ocean to East Asia can be also realized as a natural mode of variability. Latif et al. (2013) reported that the internal centennial variability originating from the Southern Ocean may have affected the recent decadal trends observed in the Southern Hemisphere, such as overall cooling and Antarctic sea ice expansion. They also showed anomalous warming in the western part of the North Pacific and a weakening of the Aleutian low in the case of the cold phase in the Southern Ocean owing to internal variability. Their arguments correspond well with the meltwater-induced responses found in this study. Cooling over the Southern Ocean in their study occurred in response to the shutdown of deep convection due to the internal variability, while cooling in our study is due to meltwater forcing. Even though the cooling sources are different, the resulting teleconnection and remote influence on East Asia may share a similar mechanism.

For example, the patterns simulated in the control simulation in Figure 4 result from internal variability in the model because there is no external forcing in that case. This means that the Antarctic-to-East Asia connection is naturally an intrinsic mode in a coupled climate system. In fact, many modeling studies have suggested that the long-term internal variability of the SST and sea ice extent in the Southern Ocean possibly originate from changes in the deep convection in the Weddell Sea (Latif et al., 2013, 2017; Wang & Dommenget, 2016; Zunz et al., 2013). Our results under their conclusions suggest that Antarctic meltwater forcing possibly triggers this internally intrinsic process, resulting in East Asian regional warming.

According to recent studies investigating the impact of Antarctic meltwater on climate, meltwater could induce global cooling and Antarctic sea ice expansion in the future climate (Bronselaer et al., 2018; Park & Latif, 2019; Pauling et al., 2017), though its magnitude is too small to make a significant global hiatus under greenhouse warming. However, our results suggest that Antarctic meltwater possibly induces relative regional warming in East Asia, contrary to the global cooling effect. That is, the strong meltwater forcing cannot induce significant cooling changes in East Asia, unlike the global average. This emphasizes the variety of climate responses associated with Antarctic meltwater in a regional context.

Our study includes some limitations. First, our results were based on only one particular climate model, so that they could be model dependent. Nevertheless, Bronselaer et al. (2018) examined the impact of meltwater on the climate system using the Geophysical Fluid Dynamics Laboratory's Earth System Model Version 2M (GFDL ESM 2M) and showed similar responses to our results even though they did not emphasize the regional impact. If more models are utilized, more robust features can be derived. Second, the added meltwater forcing is idealized in this experimental design. The magnitude of the meltwater forcing applied to Antarctica was constant at 0.1 Sv and did not change from the beginning of the model. In addition, the meltwater was only introduced to the surface layer even though some meltwater may be discharged at depth due to basal melting. However, Pauling et al. (2016) reported that this simplification does not have a critical impact on sea ice and surface temperature variations. Nonetheless, the impact of the meltwater on East Asia and the related possible mechanism is first addressed here, which can be further investigated by an approach with a multimodel intercomparison and advanced coupled climate-land ice model.

Data Availability Statement

The model data, used in this study, are described in Park and Latif (2019) and available on request to W. P.

Acknowledgments

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