Impact of Antarctic meltwater forcing on East Asian climate under greenhouse warming

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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 Inter-Tropical 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. 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 inter-ensemble spread and long-term control simulations.

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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 Inter-Tropical 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.

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 Inter-Tropical 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. 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 inter-ensemble 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 Inter-Tropical Convergence Zone (ITCZ). Here, we examine the distinct regional impacts of Antarctic meltwater forcing over the globe by analyzing experimental simulations 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 (Paolo et al., 2015; Wouters et al., 2015; Konrad et al., 2018; Shepherd et al., 2018; Rignot et al., 2019). In a future warmer world, freshwater release from the Antarctic continent may further accelerate (Fogwill et al., 2015; DeConto & Pollard, 2016; 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 (Kirtman et al., 2013; Colins et al., 2013) in the Coupled Model Intercomparison Project Phase 5 (CMIP5) and Phase 6 (CMIP6) (Taylor et al., 2012; Eyring et al., 2016).

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 (Stouffer et al., 2007; Bintanja et al., 2013, 2015; Fogwill et al., 2015; Pauling et al., 2016; Bronselaer et al., 2018; Park & Latif, 2019). 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 cold surface and warm subsurface temperatures around Antarctica, which causes an expansion of the sea-ice cover (Bintanja et al., 2013, 2015; Fogwill et al., 2015; Pauling et al., 2016; Park & Latif, 2019). This is accompanied by subsurface warming, leading to an acceleration in basal melting at the bases of the ice shelves (Rignot & Jacobs, 2002; Shepherd et al., 2004; Bintanja et al., 2013, 2015; Obase et al., 2017; Bronselaer et al., 2018). 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 (Stoker, 1998) alters the atmospheric heat transport, resulting in a northward shift of the Inter-Tropical Convergence Zone (ITCZ) (Zhang & Delworth, 2005; Kang et al., 2008, 2009; Bozbiyik et al., 2011; Cabré et al., 2017; Bronselaer et al., 2018).

In fact, satellite observations have recorded a significant 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 (Zwally et al., 2002; Turner et al., 2009). Conversely, abyssal warming in the Southern Ocean was observed during that same period (Robertson et al., 2011; Purkey & Johnson, 2010, 2012; Fahrbach et al., 2011), 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 particular, the observational variations are well matched with meltwater-induced climate responses due to Antarctic ice-shelf melting. 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, e.g. 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 (Son et al., 2014; Gong et al., 2015; Kim et al., 2018). 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, where bridge of the tropics is important.

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. KCM is composed of the atmospheric general circulation model (AGCM) ECHAM5 coupled with the NEMO ocean/sea-ice GCM. The experimental design of the present study was the same as that of Park & 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 in the Antarctic Ocean. The first is a preindustrial control simulation over 2300 years (CTRL) applying a constant 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 ($4 \times CO_2$, 1144.8 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 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. It is noteworthy that historical and RCP8.5-projected Antarctic meltwater in Deconto & Pollard (2016) reaches 0.1 Sv around the year 2035. Detailed descriptions of experimental design can be obtained in Park & 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

Park and Latif (2019) showed that the major difference between GW and GWMW is the surface air temperature (SAT) cooling response over the Southern Hemisphere. The fundamental reason for this change is hypothesized to be stabilization in the Southern Ocean due to the freshwater forcing. This causes a cooling tendency at the sea surface and warming in the subsurface, which reduces the oceanic heat loss to the atmosphere and widens the sea-ice cover, eventually leading to a strong positive ice-albedo feedback.

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 and the global-mean SAT. As pointed out by previous studies, Antarctic meltwater forcing isolates the warm CDW from the surface, resulting in an increase in the sea-ice concentration (SIC) in the Southern Ocean. In the presence of a strong positive albedo feedback, the 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 & Delworth, 2016; Zhang et al., 2017). SAT around the Antarctic region 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 primarily via atmospheric heat transport, even in the Arctic (Figure 1b).

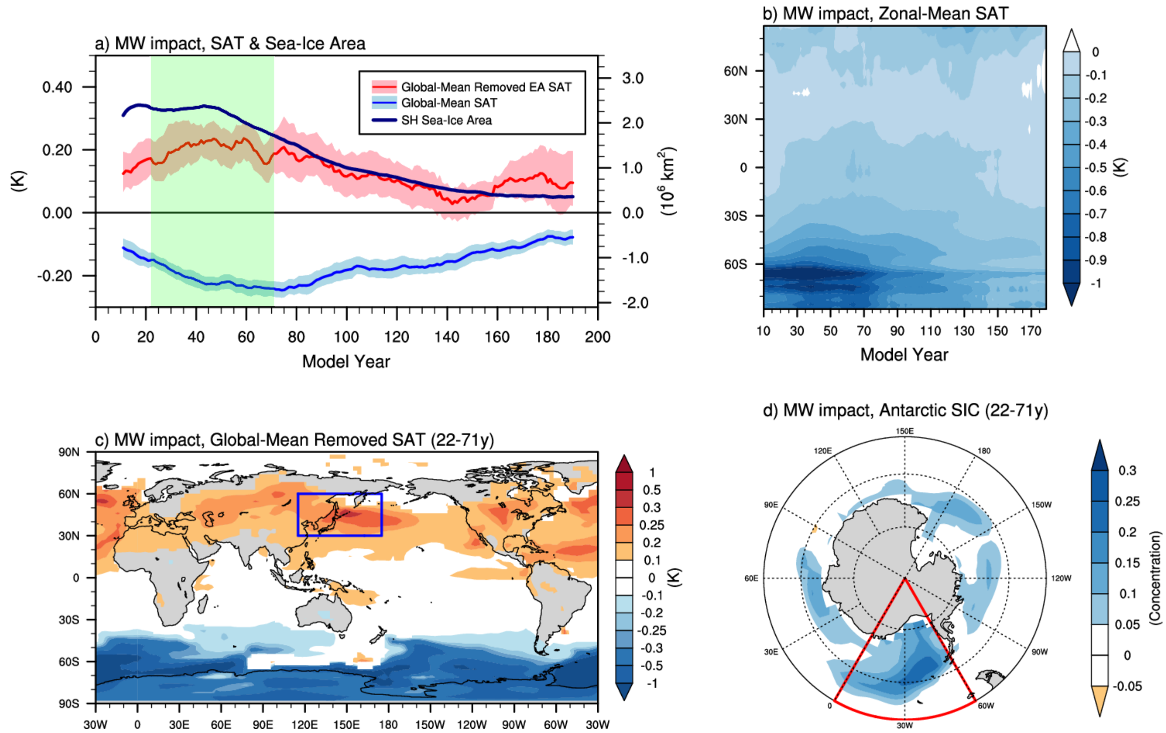

Figure 1. (a) Time series of SAT and sea-ice area in the ensemble-mean difference (GWMW10-GW) smoothed by the 21-year running mean. Global-mean removed SAT in East Asia (blue box in panel (c)) (red), global-mean SAT (blue), and sea-ice area in the Southern Hemisphere (navy blue). The solid lines show the ensemble-mean difference, and the 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)** sea-ice concentration, both averaged over the 22–71-year period (green box in panel (a)). The regions denoted by colors indicate where the responses are significant at the 99% confidence level.

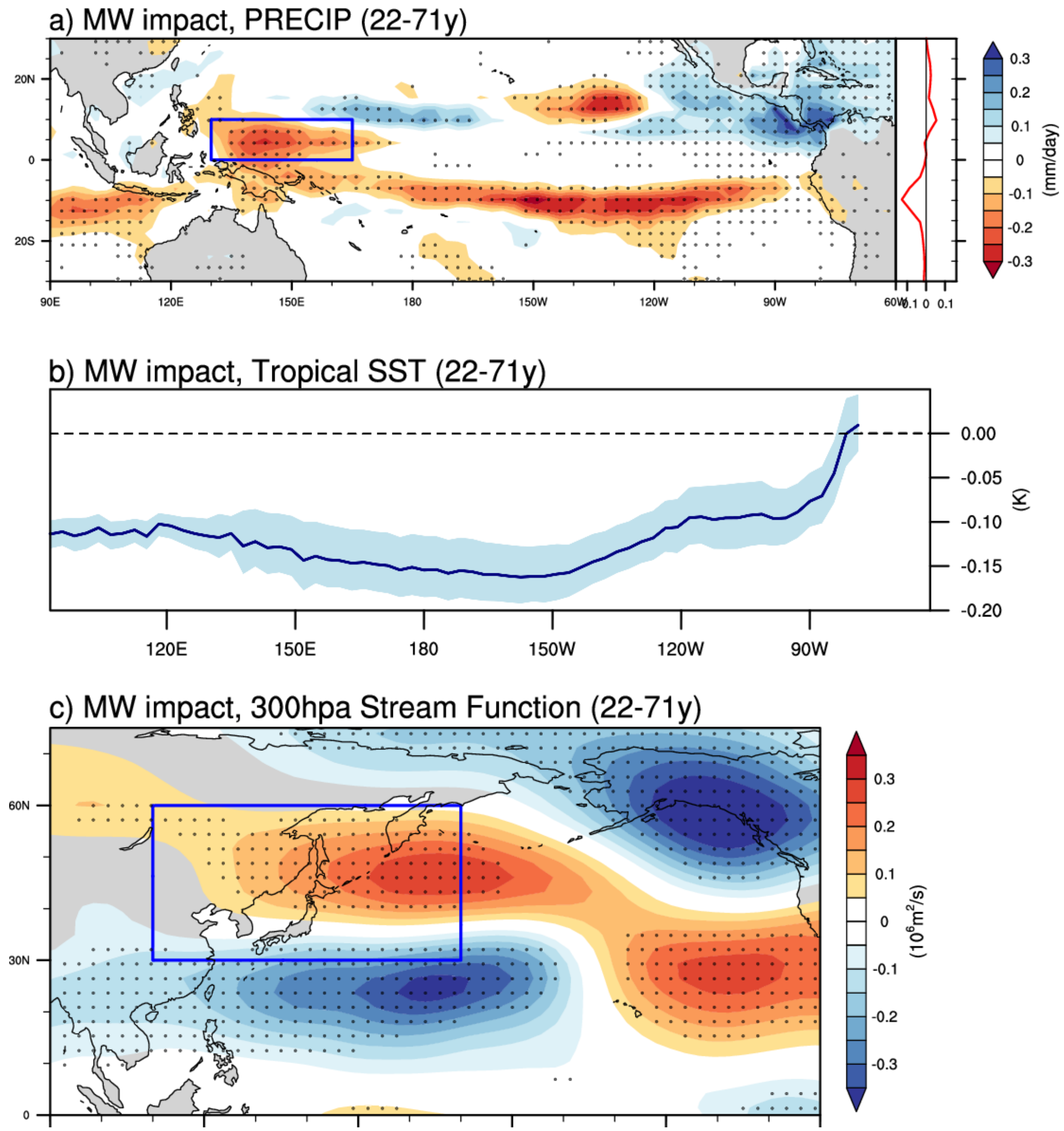

Figure 2. Ensemble-mean difference of the **(a)** precipitation, **(b)** SST (5° S–5° N), and **(c)** stream function at 300 hPa (zonal-mean removed) averaged over the 22–71-year period (green box in Figure 1a). The regions denoted by black dots indicate where the responses are significant at the 99% confidence level, 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–60° W.

The surface cooling is weaker in the mid-latitudes of the Northern Hemisphere than that in 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 Antarctic region and relative warming (actually weak cooling) in the mid-latitudes of the Northern Hemisphere. In particular, the warming is most prominent in East Asia and the western part of the North Pacific. 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 due to the direct and indirect effects of meltwater forcing, respectively. Here, we focus on how Antarctic meltwater forcing leads to the regional warming in East Asia.

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. During this period, the increase in SIC appears in most parts of the Southern Ocean and is strongest in the Weddell Sea, indicating non-uniform sea-ice responses to the meltwater forcing (Figure 1d).

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 associated with the meltwater forcing 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 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; Bozbiyik et al., 2011; Cabré et al., 2017; Bronselaer et al., 2018).

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 significant in the western Pacific than in the eastern Pacific, which indicates a weakened zonal temperature gradient in the equatorial Pacific, reminiscent of an El Niño-like cooling pattern. Such SST variations can induce suppressed atmospheric convection in WNP and activate atmospheric convection in the eastern Pacific.

In a Gill-type response to the suppressed convection in WNP, there is an anticyclonic flow in the lower troposphere and a cyclonic flow in the upper troposphere, as shown in Figure 2c (Gill, 1980; Rui & Wang, 2000). 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 (Son et al., 2014; Kim et al., 2018). 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.

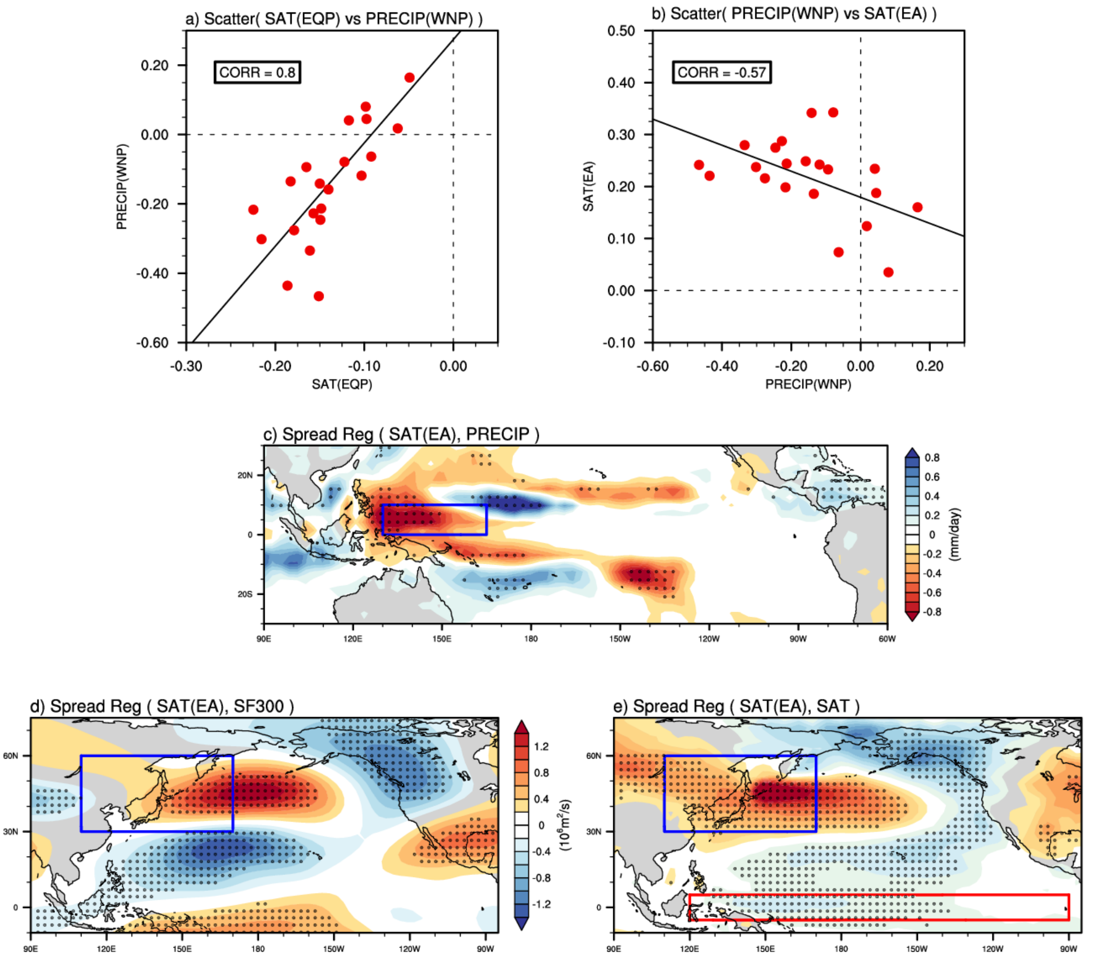

Figure 3. (a) Scatter diagram of SAT in the Equatorial Pacific (red box in panel (e)) versus the precipitation in WNP (blue box in panel (c)) calculated in the inter-ensemble spread for the same period as in Figure 2. **(b)** Same as panel (a) but for the precipitation in WNP versus SAT (global-mean 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.

So far, from the ensemble-mean result, 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 inter-ensemble spread.

If the hypothesis is correct, it should work not only in the ensemble-mean but also in the inter-ensemble spread. The precipitation anomaly in WNP has a strong positive correlation with SAT in the equatorial Pacific with a correlation coefficient of 0.8 (Figure 3a), which is significant at the 99% confidence level. This suggests that, at the given meltwater forcing, the strength of the suppressed convective response in WNP depends on how fast the equatorial Pacific cools down. Further, Figure 3b shows the relationship between precipitation in WNP and SAT in East Asia. It is apparent that ensemble members with more strongly suppressed convection in WNP are prone to simulating stronger warming in East Asia. The correlation between the two is −0.57, which is significant at the 99% confidence level.

To further support this argument, the regression with respect to the East Asian SAT index (averaged SAT over the blue box area in Fig. 3d) was computed from the inter-ensemble 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 to the meltwater forcing (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 ensemble spread space (Figure 3d). It is also seen that the East Asian warming is related to 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 inter-ensemble spread strongly support our hypothesis concerning how Antarctic meltwater forcing induces regional warming in East Asia through a bridging role of the tropical Pacific.

In addition to the inter-ensemble spread, we also analyzed the 2300-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 21-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 correlation coefficient between the global-mean removed SAT in East Asia and the SIC in the Weddell Sea has a maximum value when the SIC leads the SAT by 22 years (not shown). This is consistent with the meltwater-induced result that the regional warming in East Asia has a maximum value 21 years after the initialization of Antarctic meltwater forcing.

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 (Figure 4b) and the anticyclonic flow at mid-latitudes are distinctive. It seems that the WNP precipitation is sensitive to the sea-ice variability in the Weddell Sea, possibly because WNP is a downstream region of the Weddell Sea under background westerlies in the Southern Hemisphere. In the case of the non-convective phase in the Weddell 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, strongly 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 appeared in this study, as in previous studies (Park & Latif, 2019; Bronselaer et al., 2018). 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 (Son et al., 2014; Kim et al., 2018), 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 inter-ensemble spread strongly supports the proposed mechanism for the regional warming in East Asia.

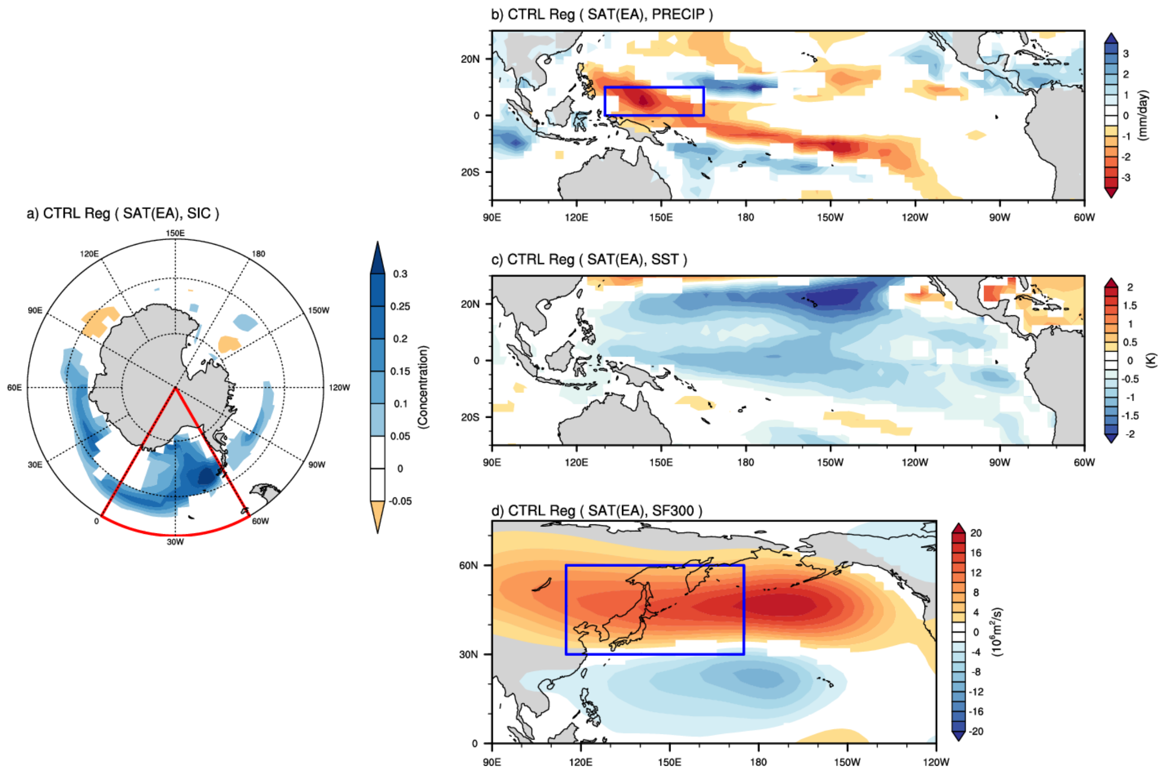

Figure 4. Regression maps of the **(a)** SIC, **(b)** precipitation, **(c)** SST, and **(d)** stream function at 300 hPa onto the SAT (global-mean removed) in East Asia. Values are calculated in the CTRL simulation but for the regression results based on the 50-year running mean. In panel (a) SIC leads SAT by 21 years, whereas panels (b), (c), and (d) simultaneous with SAT. The regions denoted by colors indicate where the responses are significant at the 99% confidence level.

.The teleconnection mechanism from the Southern Ocean to East Asia can be also realized in 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. In addition, they argued that the observed weakening of the Aleutian low in recent decades might be related to internal variability originating in the Southern Ocean. 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 (Martin et al., 2013; Latif et al., 2013, 2017; Zunz et al., 2013; Wang & Dommenget, 2016). 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). It is conjectured that the global warming expectation during the 21st century, projected without the impact of Antarctic meltwater, could be delayed by a decade due to meltwater input to the Southern Ocean. However, our results suggest that Antarctic meltwater possibly induces regional warming in East Asia, contrary to the global cooling effect, emphasizing 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 ESM2M), 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 firstly addressed here, which can be further investigated by an approach with a multi-model intercomparison and advanced coupled climate-land ice model.

Acknowledgments

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