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- Realistic past and future melt rates of the Antarctic Ice Sheet have impact on Southern Ocean
- Southern Ocean surface air temperature changes lead to ITCZ shifts

Supporting Information:
- Supporting Information S1

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Response of the Intertropical Convergence Zone to Antarctic Ice Sheet Melt

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Abstract Past cooling events in the Northern Hemisphere have been shown to impact the location of the intertropical convergence zone (ITCZ) and therewith induce a southward shift of tropical precipitation. Here we use high resolution coupled ocean-atmosphere simulations to show that reasonable past melt rates of the Antarctic Ice Sheet can similarly have led to shifts of the ITCZ, albeit in opposite direction, through large-scale surface air temperature changes over the Southern Ocean. Through sensitivity experiments employing slightly negative to large positive meltwater fluxes, we deduce that meridional shifts of the Hadley cell and therewith the ITCZ are, to a first order, a linear response to Southern Hemisphere high-latitude surface air temperature changes and Antarctic Ice Sheet melt rates. This highlights the possibility to use past episodes of anomalous melt rates to better constrain a possible future response of low latitude precipitation to continued global warming and a shrinking Antarctic Ice Sheet.

Plain Language Summary Changes in high-latitude climate can impact the tropical regions through so-called atmospheric and oceanic teleconnections. Research has mostly focused on past southward shifts in the band of heavy tropical precipitation, called the intertropical convergence zone (ITCZ), linked to large-scale cooling in the Northern Hemisphere resulting from large-scale continental ice sheet buildup or a slowdown of the large-scale Atlantic meridional ocean circualation. Here we use high resolution climate simulations to show that melting of the Antarctic Ice Sheet can similarly lead to northward shifts of the ITCZ and the displacement of the accompanying rain belt. Future melt rates of the Antarctic Ice Sheet are highly uncertain, but our work shows that it might have a nonnegligible impact on the tropical climate. Moreover, we find that because of the apparent linearity of the system under consideration, studying episodes of past changes in the size of the Antarctic Ice Sheet can help us constrain the possible changes in the low latitude hydroclimate.

1. Introduction

The intertropical convergence zone (ITCZ), a band of intense precipitation and cloud cover encircling the Earth near the equator associated with the ascending branch of the Hadley cell, has been shown early on to be intimately linked with the interhemispheric temperature contrast (Manabe & Stouffer, 1980). Broccoli et al. (2006) found that a Northern Hemisphere (NH) extratropical cooling causes an increase in the total atmospheric energy flux from the tropics to the extratropics of the cooling hemisphere, while the opposite happens in the Southern Hemisphere (SH). The resulting low latitude imbalance in the poleward energy fluxes leads to a reorganization of the mean meridional tropical circulation (Hadley cell), effectively transporting more energy from the SH low latitudes across the equator to the NH low latitudes (Broccoli et al., 2006). As a result, the ITCZ moves away from the cooling hemisphere (e.g., Schneider et al., 2014).

Because of the dependency on the interhemispheric temperature contrast, ITCZ displacements on timescales ranging from seasonal, decadal, to glacial-interglacial have been linked to temperature changes at middle to high latitudes (Donohoe et al., 2013), including the buildup of continental ice sheets and North Atlantic cooling as a result of disruptions of the Atlantic Meridional Overturning Circulation (MOC; Chiang et al., 2003; Chiang & Bitz, 2005; Mulitza et al., 2017; Zhang & Delworth, 2005). Most studies thus far have investigated the response of the ITCZ to NH cooling, but also the SH middle to high latitudes latitude can potentially exhibit strong cooling, for instance as a result of enhanced meltwater input into the Southern Ocean from the Antarctic Ice Sheet (AIS). A large-scale cooling of the Southern Ocean as a response to AIS melt has been shown with a range of different climate models, for example, intermediate complexity climate models (Bakker et al., 2017; Swingedouw et al., 2009), high resolution ocean-only models (Morrison, 2015; Stammer, 2008), and coupled ocean-atmosphere general circulation models (Ma et al., 2013; Ma & Wu, 2011). Because of the lack or highly simplified nature of atmospheric dynamics, the first two types of models do not allow to investigate the impact of Southern Ocean cooling on the ITCZ. The studies using coupled general circulation models did indeed find an impact of Southern Ocean cooling on low latitude climates (Ma & Wu, 2011) as well as changes in the characteristics of ENSO (Ma et al., 2013), but did not analyze the impact on the general atmospheric circulation in the tropics.

Recent measurements show that the AIS has lost a considerable amount of ice over the last decades (The IMBIE team, 2018). Periods of enhanced meltwater input into the Southern Ocean from the AIS are also thought to have occurred in the past and are projected to occur in the future under the influence of continued global warming. One of the largest pulses of freshwater into the Southern Ocean is postulated to have occurred during the last deglaciation in the so-called meltwater pulse 1A event (Clark et al., 1996). The magnitude of this event (Golledge et al., 2014), although highly uncertain, is similar to the AIS melt rates that are projected for the end of the century under continued future global warming (deConto & Pollard, 2016), up to several tenths of a Sverdrup (1 Sv = 10^6 m^3/s). Less dramatic, but more recent and reoccurring episodes of AIS growth and melt where recently suggested by Bakker et al. (2017) as part of a multicentennial variability in the coupled AIS-climate system.

Here we extend on previous work (e.g., Ma et al., 2013) by employing a state-of-the-science coupled climate model at relatively high spatial resolution and test a range of meltwater fluxes that are realistic in light of estimated past and future changes in the AIS. We focus specifically on the simulated changes at low latitudes resulting from the meltwater-induced changes in SH high-latitude surface conditions and the relationship between the magnitude of the meltwater-induced temperature anomalies and the resulting climatic change in the low latitudes. The latter allows us to deduce whether or not the results are, in the context of this climate model, more generally relevant for the study of past and future climate change regardless of the exact magnitude or even the sign of the imposed melt rates.

2. Methods

The simulations were performed using the Community Earth System Model version1.2, a global climate model that includes interactive atmosphere (CAM4), ocean (POP2), land (CLM4.0; including carbon-nitrogen dynamics), and sea-ice (CICE4) components. For the atmosphere (running with a finite volume dynamical core) and land, a horizontal resolution of 0.9° × 1.25° was used with the former having 26 vertical levels. The ocean and sea-ice components use a displaced dipole grid with a nominal horizontal resolution of 1°. The ocean grid has 60 levels.

The AIS contribution to meltwater pulse 1A (Clark et al., 1996) is highly uncertain, but in the most thorough attempt thus far to quantify this flux, a mean value of 0.034 Sv was found, with maximum values up to 0.11 Sv for a period of 350 years (Golledge et al., 2014). The Holocene AIS variability suggested by Bakker et al. (2017) is 0.048 Sv (1σ). Finally, the future response of the AIS if global warming is to continue in the next centuries again varies widely, ranging from ~0.2 to 0.5 Sv for the year 2100 in, respectively, the so-called Representative Concentration Pathway (RCP) scenario 4.5 and RCP8.5 (Meinshausen et al., 2011), and ranging from ~0.2 to 0.25 Sv for the year 2500 in again RCP4.5 and RCP8.5, respectively (deConto & Pollard, 2016). Taken together, credible past and future rates of AIS meltwater into the Southern Ocean seem to range from slightly negative values, that is, periods of minor AIS growth (Bakker et al., 2017), to positive values of several tenths of Sverdrups. To assess the impact of such AIS meltwater rates, we performed four 200-year-long experiments in which different magnitudes of freshwater forcing (FWF), namely −48, 48, 100 and 200 mSv, were continuously added to the surface of the Southern Ocean south of 60°S (referred to as PIm48, PI48, PI100, and PI200, respectively). The −48 mSv meltwater flux implies that freshwater is removed from the internally calculated freshwater flux that enters the ocean, composing of precipitation, continental runoff, and sea-ice melt. AIS freshwater input is not compensated for elsewhere. All experiments start from the same spinup preindustrial state, and in addition, a 200-year-long control simulation was performed in which no additional freshwater was added to the Southern Ocean (referred to as *PI*). For the analyses, averages over the last 20 years of each simulation are taken.

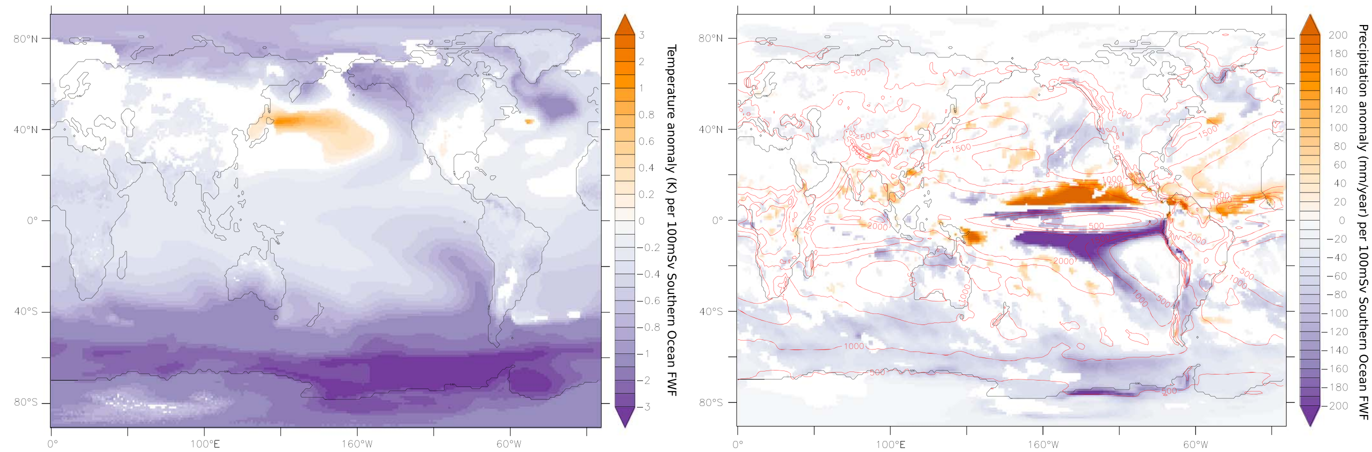

Figure 1. Annual mean surface air temperature (left) and precipitation (right) changes as a function of the imposed FWF over all five experiments from linear regression analysis (K per 100 mSv and mm·year^{-1} per 100 mSv for the left and right panels, respectively). For both figures, results are only shown if the linear correlation is robust (i.e., significant at $\alpha = 0.1$). For reference, the contours in the right-hand-side figure give the absolute precipitation values (mm/year) for the PI simulation. Note unevenly spaced colors in left-hand panel. FWF = freshwater forcing.

To investigate the robustness of the relationship between the magnitude of the imposed AIS meltwater forcing and the resulting climatic impact, we calculate for every grid cell the correlation between the imposed AIS meltwater forcing and the climatic variable under consideration (e.g., annual mean temperature anomalies), only showing the result if the linear correlation coefficient exceeds the critical value (for a two-sided t test with five data pairs and $\alpha = 0.1$) of 0.805 and presenting the relationship as the slope of the linear regression. In the remainder of the manuscript the term *robust* is thus used in the context of a significant linear correlation between the imposed FWF and the resulting climatic impact, indicating that the effect is to a first order linear over the range of applied positive and negative FWFs.

3. Results

The imposed changes in surface salinity in the Southern Ocean south of 60°S induce a strong response of the coupled ocean-atmosphere-sea-ice system. A decrease of sea surface salinity leads to a stabilization of the water column in the Southern Ocean, reduced vertical mixing and convection (not shown) and a resulting cooling of the surface (Figure 1) and an increased sea-ice cover (not shown), in line with previous studies (Bakker et al., 2017; Ma & Wu, 2011; Ma et al., 2013; Morrison, 2015; Stammer, 2008; Swingedouw et al., 2009). For the negative FWF experiment PIm48, the increase in surface salinity leads to a surface warming. The largest cooling, up to 2 K per 100 mSv of AIS meltwater, takes place in the Southern Ocean, but a robust temperature response can be found almost globally, with the exception of the NH midlatitudes (Figure 1). For precipitation, the situation looks quite different. A robust annual mean drying of up to 100 mm·year^{-1} per 100 mSv of AIS meltwater is simulated over the Southern Ocean and the Antarctic continent (Figure 1). However, outside of the SH high latitudes, a robust precipitation response is largely confined to the low latitudes of the eastern/central Pacific and the Atlantic. In both regions, a positive AIS meltwater forcing leads to a drying south of the equator and a precipitation increases to the north of the equator, most clearly so in the eastern Pacific. However, here the negative precipitation response to AIS melt is likely to be overestimated due to the simulation of an unrealistic double ITCZ. As such, the Southern Ocean cooling may partly remedy this well-known model artifact (cf. Hwang & Frierson, 2013). Note that no robust precipitation response is simulated over the low latitude continents or over the Indian ocean except for the West African, Australian, and Venezuelan monsoon regions, which are known to be sensitively affected by ITCZ shifts (Mohtadi et al., 2016). In line with the findings of Baker et al. (2018), we find that, in contrast to the temperature anomalies (not shown), the precipitation anomalies in the low latitudes show a clear seasonal dependency (supporting information Figure S1). Nonetheless, the overall picture of meridional shifts of the low latitude precipitation maxima in the eastern Pacific and Atlantic persists.

This spatial pattern of low latitude precipitation anomalies is a strong indication of meridional shifts of the ITCZ, northward for a Southern Ocean cooling and southward for a Southern Ocean warming. To further investigate these changes in low latitude atmospheric circulation, we plot the meridional atmospheric

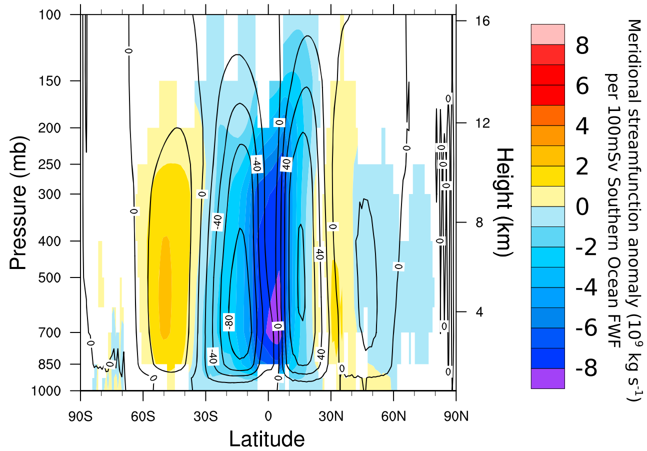

Figure 2. Atmospheric meridional streamfunction changes as a function of the imposed FWF over all five experiments from linear regression analysis (10^9 kg·s^{-1} per 100 mSv). Results are only shown if the linear correlation is robust (i.e., significant at α = 0.1). For reference, the contours give the absolute atmospheric meridional streamfunction values (10^9 kg/s) for the PI simulation. FWF = freshwater forcing.

streamfunction changes as a function of the applied meltwater forcing (Figure 2) and find that for a positive AIS melt rate, the Hadley cell to the south of the equator strengthens while it weakens to the north of the equator, involving a northward shift of the mean ITCZ. We find that there is to the first order a linear negative relationship between the degree of surface air temperature change in the SH high-latitudes (south of 50°S) and the meridional location of the ITCZ (Figure 3; the ITCZ location is defined here as the latitude of zero meridional streamfunction at 500 hPa in the low latitudes). Moreover, we find positive (negative) linear relationships between SH high-latitude surface air temperature changes and the change in strength of the northerly maximum (southerly minimum) of the Hadley cell (Figure 3). We focus here on the relationship between these metrics of the low latitude atmospheric circulation and SH high-latitude surface air temperatures because of the mechanistic link; however, the relationships are very similar if we look at the imposed FWFs because those are in turn closely related to SH high-latitude surface air temperatures (Figure S2).

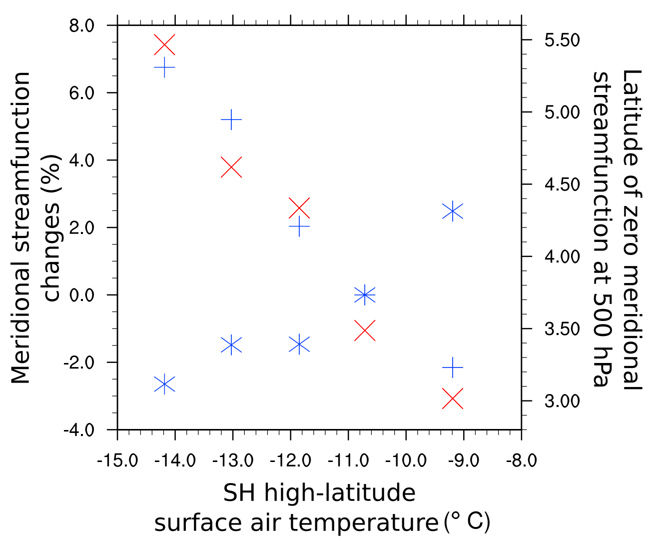

Figure 3. Low latitude atmospheric dynamics as a function of SH high-latitude surface air temperatures. In blue the changes in the minimum (pluses) and maximum (asterisks) meridional streamfunction (left-hand-side vertical axis; %) and in red the location of the intertropical convergence zone (right-hand-side vertical axis; °N) as a function of the SH high-latitude surface air temperatures (south of 50°S; °C). The latitude of zero meridional streamfunction at 500hPa in the low latitudes is used as a measure of the position of the mean intertropical convergence zone. PSI = paleomagnetic stability index; SH = Southern Hemisphere.

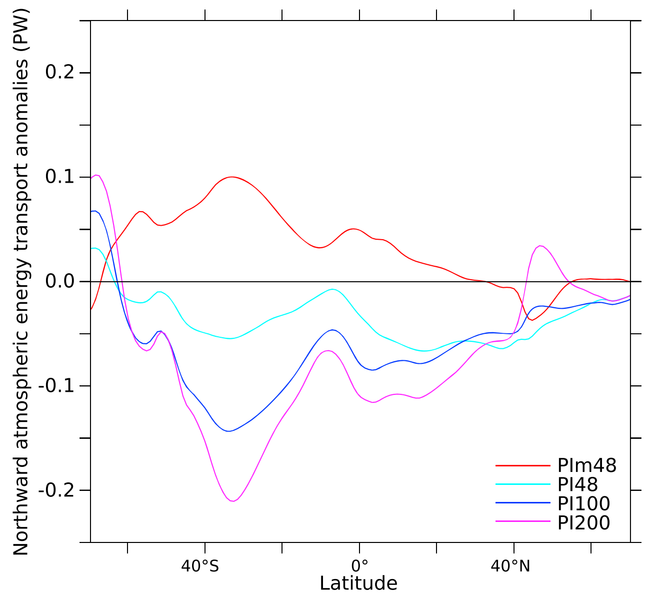

Figure 4. Northward atmospheric energy transport anomalies. Shown are anomalies compared to the PI reference case (PW) for freshwater forcing magnitudes of −48, 48, 100, and 200 mSv. Atmospheric energy transport is calculated by integrating the residual between the total top-of-the-atmosphere and surface energy fluxes.

In line with the findings of Broccoli et al. (2006), our results show that changing the pole-to-equator temperature gradient leads to a meridional reorientation of the Hadley cell and the typical corresponding low latitude precipitation finger print. This meridional shift effectively changes the cross-equatorial energy transport, which is determined by the upper branch of the Hadley cell (e.g., Schneider et al., 2014) and possibly transient eddies (Xiang et al., 2018), toward the hemisphere that is being cooled, similar to what is found on a seasonal basis (Donohoe et al., 2013). In the simulations presented here we similarly find that a cooling (warming) of the SH midlatitude to high latitude strengthens (weakens) the southward atmospheric energy transport in the SH and weakens (strengthens) the northward energy transport in the NH (Figure 4). The net result is a change in the cross-equatorial energy transport toward the hemisphere that is cooled relative to the other hemisphere. Due to their mutual association with the Hadley cell, this change in the cross-equatorial energy transport is directly related to a meridional displacement of the mean ITCZ (Donohoe et al., 2013).

4. Discussion

The experiments presented here have been performed using preindustrial boundary conditions. Possibly the response in the Southern Ocean to FWFs as well as the remote tropical response is depending on the climatic boundary conditions. For a first estimate of the applicability of these results in the broader context of past or future climate change, we performed additional experiments in which enhanced AIS meltwater input is combined with increasing greenhouse-gas concentrations. Following an RCP scenario in which the radiative forcing in the year 2100 stabilizes at +4.5 Wm^{-2} relative to the preindustrial (RCP4.5 ; Meinshausen et al., 2011), we analyze three simulations in which a constant AIS meltwater flux of 0, 100, and 200 mSv, respectively, is applied (similar to the preindustrial experiments). The results shown here are averaged over the years 2080–2100, thus making them somewhat different from the 200-year-long preindustrial experiments described before. Despite these differences in the experimental setup, and, more importantly, despite the fact that these simulations combine the effects of enhanced AIS meltwater input and global warming, we see that the dependency (linear trend) of the low latitude atmospheric circulation (minimum and maximum of the Hadley cell and the location of the ITCZ) on the imposed Southern Ocean cooling is quite similar to the preindustrial results (Figure S3). Notwithstanding the many differences between the preindustrial and global warming simulations and the smaller number of global warming experiments analyzed here, the teleconnections that convey the SH high-latitude temperature changes to the tropical region appear stable. Our results further suggest that the effect of Antarctic meltwater on the location of the ITCZ may be as strong as (or even stronger than) the direct radiative effect in global warming scenarios.

Several mechanisms are proposed in the literature to act as teleconnections between the SH high latitudes and the tropics. They include fast oceanic waves (Ivchenko et al., 2004, 2006; Richardson et al., 2005), fast atmospheric teleconnections (Blaker et al., 2006), and a coupled wind-evaporation-sea surface temperature feedback (Ma & Wu, 2011). In any case, changes in tropical sea surface temperature gradient are intimately linked to ITCZ displacements (Lindzen & Nigam, 1987; Donohoe et al., 2013). More recently it was proposed that in coupled atmosphere-ocean models changes in atmospheric cross-equatorial energy transport and corresponding ITCZ shifts are limited because the majority of the change in cross-equatorial energy transport is taken up by the ocean (Hawcroft et al., 2017; Kay et al., 2016; Tomas et al., 2016; Yoshimori et al., 2018) in an anomalous Ekman-driven subtropical-tropical overturning cell (Green & Marshall, 2017). Even though our experiments show a similar response in the shallow wind-driven cell (Figure S4), we still find that the changes in atmospheric cross-equatorial energy transport are larger than the oceanic changes (Figures 4 and S5). A comparison to the study by Kay et al. (2016), who used almost the same climate model, reveals that in our experiments the anomalous wind-driven overturning cell that transports energy across the equator (Green & Marshall, 2017) is shallower and hence less efficient. Moreover, in contrast to Kay et al. (2016), we find changes in the thermohaline-driven middepth and deep-ocean MOC below the wind-driven cell (Figure S4), which modify the cross-equatorial oceanic energy transport in opposite direction to the atmospheric energy transport. We argue that the different oceanic responses can be attributed to the different ways that high-latitude SH temperature changes are generated. In the work by Kay et al. (2016), modification of cloud physics resulted in reduced absorbed shortwave radiation leading to both surface and subsurface cooling in the SH extratropics. By contrast, imposing an AIS meltwater forcing leads to a freshening of the ocean surface which decreases the air-sea energy exchange and results in a surface cooling accompanied by a subsurface warming. This change in vertical density gradient in turn impacts deep vertical mixing, convection, and hence the MOC. Subsurface warming and salinity changes possibly interact with the wind-driven changes in the shallow subtropical-tropical cell (Green & Marshall, 2017), explaining the much smaller changes in cross-equatorial oceanic energy transport compared to previous studies (Hawcroft et al., 2017; Kay et al., 2016; Tomas et al., 2016; Yoshimori et al., 2018). The response in atmospheric and oceanic cross-equatorial energy transport to different types of perturbations of the meridional surface temperature gradient is an interesting avenue for future research.

Our results suggest that the low latitude atmospheric response to a Southern Ocean temperature change is to a first order linear. Nonetheless, in line with previous work and connected to the discussion in the previous paragraph, our results also indicate that the changes in the deep-ocean thermohaline circulation are more complex and dependent on the magnitude of the imposed meltwater forcing. A number of studies have shown that changing the surface salinity of the Southern Ocean impacts the formation of Antarctic Bottom Water, North Atlantic Deep Water, and therewith the Atlantic MOC as a whole (Bakker et al., 2017; Brix & Gerdes, 2003; Rooth, 1982; Seidov et al., 2001; Stocker et al., 1992; Swingedouw et al., 2009). Swingedouw et al. (2009) showed that the oceanic response to imposing a freshening of the Southern Ocean surface is strongly dependent on the magnitude and duration of the forcing, with different mechanisms acting at different time scales and in opposite directions. Indeed, we find a nonlinear relationship between the applied meltwater forcing and the simulated changes in the global MOC. The strength of the deep MOC cell rapidly decreases when applying increasingly large meltwater fluxes, but a saturation effect is found for very large meltwater input when the magnitude of the deep MOC cell approaches zero. On the contrary, the strength of the upper thermohaline-driven MOC cell hardly changes for small meltwater fluxes of up to 48 mSv, but starts to weaken more significantly when larger fluxes are applied (−6% and −14% for PI100 and PI200 mSv, respectively). This complexity in the relationship between the applied meltwater forcing and the resulting changes in the MOC partly explains the lack of a robust response in oceanic heat transport and in NH extratropical atmospheric heat transport (Figures 4 and S5).

The impact of AIS melting on the climate of the low latitudes presented in this study first of all depends on the simulated changes in the surface characteristics of the Southern Ocean for a given FWF. The ocean model is not eddy-resolving with a horizontal resolution of $\sim$1°, nor does it resolve some of the details of the boundary currents encircling the Antarctic continent, potentially impacting the validity of the presented results. However, high resolution ocean-only simulations show that the decadal time-evolution of the spreading of the freshwater from the Antarctic continent into the Southern Ocean depends on model resolution, but the long-term equilibrium response is less affected (Morrison, 2015; Stammer, 2008).

5. Conclusions

A number of studies examined the impact of North Atlantic freshening and resulting cooling on the tropical atmospheric circulation and the location of the ITCZ. Here we have used a high resolution coupled Earth system model to show that changes in Southern Ocean surface temperatures as a result of reasonable past and future AIS melt rates can also lead to substantial climatic changes in the tropics. This shows that the position of the ITCZ cannot only be changed by large-scale cooling of the NH, but similarly by temperature changes in the SH extratropics. Moreover, the induced tropical changes scale to a first order linearly with the imposed meltwater fluxes and associated SH high-latitude surface air temperature changes. This also suggests that the multicentennial Holocene variations in AIS meltwater fluxes described by Bakker et al. (2017), despite being relatively small, could have an imprint in low latitude climate variability by moving the position of the ITCZ back and forth, changes that can potentially be recorded by precipitation-sensitive low latitude climate proxies (e.g., Collins et al., 2013). The first order linear relationship between the imposed AIS melt rates and the tropical climatic changes and the finding of similar results if AIS melting is imposed on top of increasing greenhouse-gas concentrations provides confidence that investigating past episodes of climate change could help to constrain model-based projections on the role of AIS melt in driving future changes in Southern Ocean temperatures as well as in the tropical climate.

Acknowledgments
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