Environmental Research Letters

OPEN ACCESS

RECEIVED
14 May 2020

REVISED
28 July 2020

ACCEPTED FOR PUBLICATION
30 July 2020

PUBLISHED
17 September 2020



LETTER

# Robust Arctic warming caused by projected Antarctic sea ice loss

M R England[1,2], L M Polvani[3,4] and L Sun[5]

[1] Department of Climate, Atmospheric Science and Physical Oceanography, Scripps Institution of Oceanography, La Jolla, CA, United States of America
[2] Department of Physics and Physical Oceanography, University of North Carolina Wilmington, NC, United States of America
[3] Department of Applied Mathematics and Applied Physics, Columbia University, New York, NY, United States of America
[4] Department of Earth and Environmental Science, Lamont Doherty Earth Observatory, Columbia University, Palisades, NY, United States of America
[5] Department of Atmospheric Science, Colorado State University, Fort Collins, CO, United States of America

**Keywords:** sea ice loss, polar climate change, arctic, antarctic, climate model simulations, climate projections

Supplementary material for this article is available online

## Abstract

Over the coming century, both Arctic and Antarctic sea ice cover are projected to substantially decline. While many studies have documented the potential impacts of projected Arctic sea ice loss on the climate of the mid-latitudes and the tropics, little attention has been paid to the impacts of Antarctic sea ice loss. Here, using comprehensive climate model simulations, we show that the effects of end-of-the-century projected Antarctic sea ice loss extend much further than the tropics, and are able to produce considerable impacts on Arctic climate. Specifically, our model indicates that the Arctic surface will warm by 1 °C and Arctic sea ice extent will decline by $0.5 \times 10^6$ km$^2$ in response to future Antarctic sea ice loss. Furthermore, with the aid of additional atmosphere-only simulations, we show that this pole-to-pole effect is mediated by the response of the tropical SSTs to Antarctic sea ice loss: these simulations reveal that Rossby waves originating in the tropical Pacific cause the Aleutian Low to deepen in the boreal winter, bringing warm air into the Arctic, and leading to sea ice loss in the Bering Sea. This pole-to-pole signal highlights the importance of understanding the climate impacts of the projected sea ice loss in the Antarctic, which could be as important as those associated with projected sea ice loss in the Arctic.

## 1. Introduction

The Arctic has lost over 40% of its summer sea ice extent over the past forty years (see, e.g. the NSIDC Sea Ice Index, Fetterer *et al* 2017). Meanwhile, Antarctic sea ice extent has fallen to record lows over the past four years after a 35-year period of small but significant sea ice growth (Parkinson 2019). More importantly, by the end of this century, climate models project that both Arctic and the Antarctic sea ice covers will shrink considerably (Collins *et al* 2006, Notz *et al* 2020), and a welter of studies have focused on determining if and how the projected sea ice loss at the poles could impact the climate system at lower latitudes (Shepherd 2016, Screen 2017, Screen *et al* 2018, Cohen *et al* 2020).

Observational and modeling evidence has shown that sea ice loss causes a robust warming and moistening of the atmosphere at the high-latitudes, especially in the lower troposphere (Deser *et al* 2010, Screen and Simmonds 2010, Screen *et al* 2013, England *et al* 2018). Sea ice loss also has an important impact on the mid-latitude tropospheric jet, with Arctic sea ice loss causing an equatorward shift of the Northern Hemisphere mid-latitude jet (Peings and Magnusdottir 2014, Screen *et al* 2018), and Antarctic sea ice loss causing a weakening of the Southern Hemisphere mid-latitude jet (England *et al* 2018, Ayres and Screen 2019). In fact, several studies with coupled ocean-atmosphere models have suggested that the response to sea ice loss can be global in nature (Deser *et al* 2015, Deser *et al* 2016, Screen *et al* 2018, Sun *et al* 2020). Specifically, the effects of sea ice loss have been shown to extend to the tropics (Wang *et al* 2018, England *et al* 2020, Kennel and Yulaeva 2020), with enhanced warming and precipitation in the equatorial regions, and even reaching deep into the opposite hemisphere (Deser *et al* 2015, Liu and Fedorov 2018). A detailed examination of the pole-to-pole effects of projected sea ice loss, however, is still lacking.

And yet, from a paleoclimatic perspective the idea that the polar regions may be connected is not new. Evidence from ice cores from the last glacial and deglacial period indicates that past periods of warming in the northern high-latitudes coincided with periods of cooling in the southern high-latitudes, and vice versa (Blunier *et al* 1998, Blunier and Brook 2001, Barbante *et al* 2006, Pedro *et al* 2011): this phenomenon, whereby temperature at the poles are at opposite phases on millennial timescales, is known as the 'bipolar seesaw' hypothesis (Broecker 1998, Marino *et al* 2015, Pedro *et al* 2018). Most studies have pointed to the deep ocean circulation as the likely mediator of this anti-correlated behavior of the climate at the two poles (Crowley 1992, Stocker 1998, Stocker and Johnsen 2003, Knutti *et al* 2004). Recently it has been suggested that the 'bipolar seesaw' mechanism might operate on much shorter—multi-decadal—timescales, and that this may be seen in the observed temperature record from the last century (Chylek *et al* 2010, Wang *et al* 2015). It seems, however, that this phenomenon is likely an artifact of the limited Antarctic data coverage (Schneider and Noone 2012). In any case, most of the literature on pole-to-pole linkages is focused on the two polar regions behaving asynchronously.

More recently, a handful of modeling studies have suggested that future Arctic sea ice loss can potentially impact the climate of Antarctica. Notably, Liu and Fedorov (2018) have reported that in the first fifteen years following a large, abrupt loss of Arctic sea ice, the southern high-latitudes cool and Antarctic sea ice cover expands (via an atmospheric connection), in a manner reminiscent of the 'bipolar seesaw'; however, unlike the initial transient phase, the equilibrium response to Arctic sea ice loss in the same model simulations features a clear warming of the southern high-latitudes. Such Antarctic warming is consistent with the results of Deser *et al* (2015), who show that projected Arctic sea ice loss leads to upper-tropospheric warming in the tropics and lower-tropospheric warming at both poles (termed a 'mini global warming', due to its resemblance to the atmospheric warming pattern caused by increased green-house gases). The potential influence in the other direction, however, remains unexplored.

Hence the goal of our paper: to investigate climate change in the Arctic caused by projected end-of-the-century sea ice loss in the Antarctic. Analyzing model integrations specifically designed for this purpose, we here demonstrate that Antarctic sea ice loss also causes a 'mini global warming' signal, with enhanced warming over the Arctic and a significant reduction in Arctic sea ice cover. To understand the underlying mechanism, we perform atmosphere-only runs, and show that the tropical SST anomalies caused by projected Antarctic sea ice loss drive a substantial portion of the enhanced Arctic warming, via a Rossby wave trains and a deeper Aleutian Low. We start by detailing the model we use and the simulations we analyze, then present the results, and conclude with a brief discussion.

## 2. Methods

### 2.1. Model

In this study we analyze climate model simulation performed with the Community Earth System Model (CESM1) Whole Atmosphere Coupled Chemistry Model (WACCM4). CESM1-WACCM4 is fully documented in Marsh *et al* (2013), to which the reader is referred to for details. The atmospheric component, WACCM4, has a horizontal resolution of 1.9° latitude by 2.5° longitude, with 66 vertical levels and a model top in the lower thermosphere. The representation of the stratospheric chemistry and dymamics in WACCM4 is much superior to the one in typical low-top models, owing to improved vertical resolution, gravity wave parameterisation for the upper atmosphere, and interactive stratospheric chemistry. This is important because previous studies have identified the stratosphere as a potential pathway for polar sea ice loss to influence the lower latitudes (Sun *et al* 2015, Zhang *et al* 2018, De and Wu 2019). The atmospheric component is coupled to land, ocean and sea ice components, making CESM1-WACCM4 a CMIP-class fully-coupled climate system model.

### 2.2. Fully-coupled runs

To understand the climate response to projected Antarctic sea ice loss we analyze two simulations with perturbed sea ice cover, described detail in England *et al* (2020). Both are 350-year long, time-slice integrations of the fully-coupled CESM1-WACCM4 model, with all anthropogenic forcings *fixed* at year 1955 values. These include $CO_2$, methane, nitrous oxide and, most importantly, ozone depleting substances (which may have contributed to the recent warming in the Arctic, as reported in Polvani *et al* 2020). The mid-twentieth century was chosen as the control period so as to avoid the impacts of stratospheric ozone depletion; stratospheric ozone concentrations are severely perturbed at present (WMO 2018), but are expected to return to pre-1960 values in the second half of this century. We discard the first 100-years of these integrations, and focus on the average of the remaining 250-years.

The only difference between these two integrations is their Antarctic sea ice cover. In the 'control' run Antarctic sea ice conditions are nudged to match the mean of a six-member ensemble CESM1-WACCM4 historical runs, averaged over the period 1955-69 (figure S1a(https://stacks.iop.org/ERL/15/104005/mmedia)). In the 'future' run Antarctic sea ice conditions are nudged to match the mean of a three-member ensemble of CESM1-WACCM4 RCP8.5 scenario simulations, averaged over the period 2085-2099 (figure S1b). In both cases, Antarctic sea ice conditions are constrained following the methodology of Deser *et al* (2015), which consists of adding an additional 'ghost flux' to the sea ice component of CESM1-WACCM4 so as to maintain the desired sea ice concentrations. This approach does not conserve energy but it does conserve the fresh water budget, and has been found to be more effective than the commonly-used albedo-reduction method (Sun *et al* 2020). A detailed explanation can be found in England *et al* (2020).

The difference in sea ice concentrations between the control and future runs is shown in figure S1c, and corresponds to reduction in Antarctic sea ice extent of $6.6 \times 10^6$ km$^2$. In the remainder of the paper, we will refer to the difference between these two runs, averaged over the last 250 years, as 'the response' to Antarctic sea ice loss.

### 2.3. Atmosphere-only runs with prescribed tropical SSTs

To investigate the role of tropical SST anomalies in driving Arctic warming, we carry out two additional model integrations. The first is a 251-year-long 'control' run with WACCM4 in *atmosphere-only* configuration, i.e. with sea ice and SSTs prescribed from the climatology (with a monthly-mean repeating seasonal cycle) of the six-member mean of the CESM1-WACCM4 historical runs, averaged over the period 1955-69, and with radiatively active gases fixed at year 1955 levels. The second run is nearly identical, except for the tropical SSTs, where the response to Antarctic sea ice loss is added onto the SSTs used in the control run. Specifically, the SST response to Antarctic sea ice loss—computed with the fully-coupled CESM1-WACCM4 as described above—is added to the control SST equatorward of 25°, and linearly tapered so as to vanish poleward of 30°, as shown in figure 1. By taking the difference between these two atmosphere-only runs, we can isolate the Arctic response to the tropical SST changes caused by Antarctic sea ice loss. We discard the first year of each simulation, and then take the average of the remaining 250 years.

## 3. Results

### 3.1. Response of the Arctic to Antarctic sea ice loss

Let us start by examining the global impacts of Antarctic sea ice loss in the fully-coupled runs: the responses of sea ice and temperature—indicated by the letter $\Delta$ – are shown in figure 2 (for context, we show the imposed annual mean Antarctic sea ice loss in the black box in panel 2a). First, we note that the response involves an overall surface warming across the planet (figure 2b), with the largest increase in the southern high-latitudes. The enhanced warming in the tropical Pacific was documented in England *et al* (2020). Here, we focus on the pole-to-pole impacts, notably the amplified surface warming in the Arctic. In our simulations, the Arctic polar cap (60-90°N) surface warms by approximately 1 °C in response to Antarctic sea ice loss. This is a substantial effect, as it accounts for 10–15% of the projected end-of-century Arctic warming of 7.5 °C under RCP8.5. Viewed another way, although this signal has traveled all the way from the southern high-latitudes to the northern high-latitudes, it is still 20% as large as the 5 °C Antarctic polar cap (60–90°S) surface warming, and twice as large as the 0.5 °C tropical (25°S–25°N) surface warming.

This results in an Arctic amplification factor, which we define here as the ratio of the Arctic (60–90°N) warming to tropical (25°S–25°N) warming, of 2.2. We note that this is not statistically different from the Arctic amplification factor of 2.1 under projected changes under RCP8.5 for this model, as determined from the difference between the period 2085–2099 for the RCP8.5 simulations and the period 1955–69 for the historical transient simulations. We note that the warming under RCP8.5 would include the effects of projected Antarctic sea ice loss. This could suggest that this Arctic warming is part of the 'mini global warming' response, where local feedbacks are the dominant processes in Arctic amplification (Stuecker *et al* 2018). However, in section 3.2, we show that a sizable fraction of the Arctic warming response to projected Antarctic sea ice loss is actually driven remotely from the lower latitudes.

Zooming into the Arctic, one sees that the amplified atmospheric warming at low-levels in response to Antarctic sea ice loss (figure 3a), which extends up to the tropopause (figure 4a), is associated with a deepened Aleutian Low and high pressure over the central Arctic (figure 3(b), Svendsen *et al* 2018). This is consistent with the atmosphere-only experiments of Tomas *et al* (2016). The low pressure response in the Pacific sector brings warmer air from the south into the Arctic and carries colder air into Northern Eurasia (Trenberth and Hurrell 1994). We note that a deepened Aleutian Low is also a robust feature of the modeled response to Arctic sea ice loss (Screen *et al* 2018). In addition to the warming and sea level pressure response, Antarctic sea ice loss also causes a reduction in Arctic sea ice cover, with an annual mean loss of $0.5 \times 10^6$ km$^2$ of Arctic sea ice extent, largely concentrated in the Bering Sea (figure 3c), and thinning of sea ice across the central Arctic (figure 3d).

This Arctic response to Antarctic sea ice loss has an important seasonal dependence. Since the Aleutian Low occurs primarily in boreal winter (Trenberth and Hurrell 1994, Bograd *et al* 2002, Gan *et al* 2017), the deepening of this low pressure circulation is found to be strongest in that season (figure S3(b)). By contrast, in boreal summer the North Pacific high extends further westward, limiting the extent of the Aleutian Low (Bograd *et al* 2002); the summertime mean sea level pressure response involves high pressures across much of the northern high-latitudes with a swath of

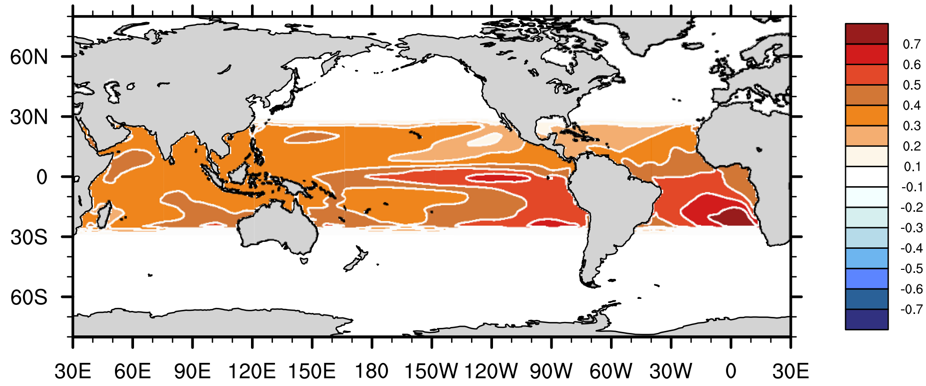


**Figure 1.** Difference in prescribed SSTs ( °C) between the two atmosphere-only runs, from the fully-coupled tropical response to Antarctic sea ice (England *et al* 2020).

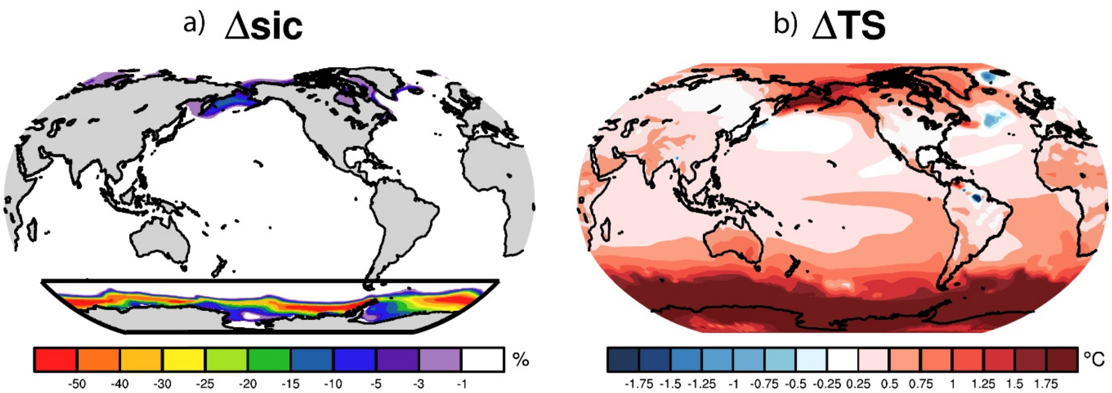


**Figure 2.** The annual mean response of (a) sea ice (in percentage) and (b) surface temperature (in °C) to projected Antarctic sea ice loss. The imposed sea ice loss is shown in the black-bordered box at high Southern latitudes in (a).

low pressure further south across the North Pacific (figure S4(b)). Thus the warming response is largest in wintertime and weakest in summertime (compare figure S3(a) and figure S4(a)).

### 3.2. Connecting Antarctic sea ice loss to the Arctic

Having shown that Antarctic sea ice loss can have important impacts on Arctic climate, we now ask: how does the signal reach all the way to the other pole? We propose that the tropics play a key role in enabling these substantial pole-to-pole effects. As documented in England *et al* (2020), Antarctic sea ice loss in these model simulations causes enhanced surface warming and increased precipitation in the Equatorial Pacific, as well as a warming of the tropical upper troposphere (see figure 4a): ocean dynamics was shown to be key for connecting the loss of Antarctic sea ice to the tropics. Now, we suggest that the tropical response signal is quickly propagated into the Arctic by atmospheric teleconnections. Our suggested pathway is in line with the modeling study of Tomas *et al* (2016), which showed that many of the impacts of Arctic sea ice loss on the northern mid- and high-latitudes are first mediated through the tropical SST response to sea ice loss. It is also consistent with the previous modeling (Yoo *et al* 2012, Kosaka and Xie 2016, Svendsen *et al* 2018, Ding *et al* 2019, Screen and Deser 2019, McCrystall *et al* 2020) and observational studies (Lee 2012, Ding *et al* 2014, Yoo *et al* 2014, Flournoy *et al* 2016, Hu *et al* 2016) which have identified the tropical Pacific as a potential driver of Arctic warming.

We investigate this proposed mechanism by performing and analyzing two additional, atmosphere-only model simulations, to isolate the Arctic impacts of the tropical SST response to Antarctic sea ice loss. These runs are detailed in section 2.3. In essence, one is a control simulation, the other is forced by the SSTs in the control simulation plus the tropical SSTs anomalies resulting from Antarctic sea ice loss in the fully-coupled model simulations (see figure 1). The difference between these two runs illustrates the impact of such SST anomalies onto the Arctic, as communicated by the atmosphere alone.

These prescribed-SST runs reveal five important points. (i) As expected, the tropical upper tropospheric warming response to Antarctic sea ice loss (figure 4a) is driven from below by the tropical SST anomalies (figure 4b). (ii) The tropical SST anomalies cause amplified warming throughout the lower troposphere in the Arctic (figure 4b), albeit

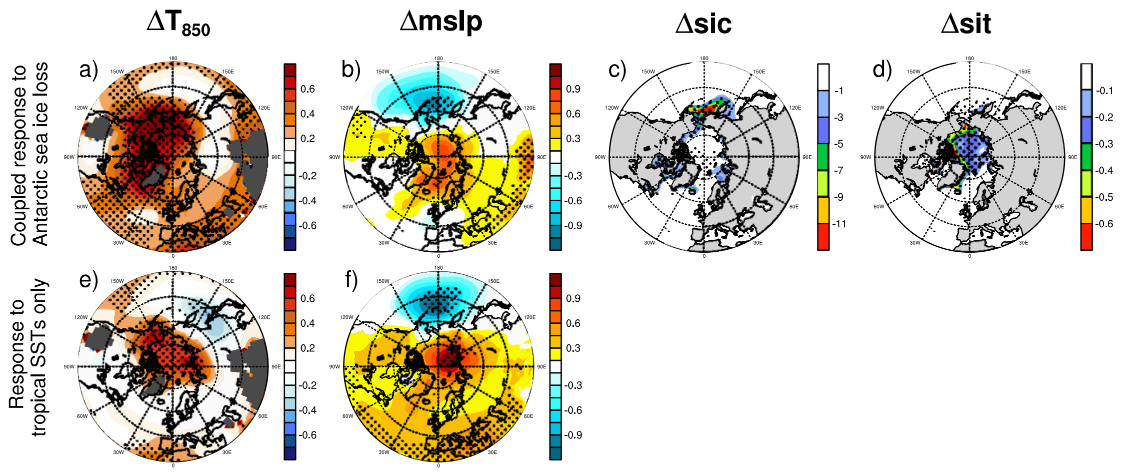


**Figure 3.** The annual mean response of (a) 850hPa temperature ( °C) , (b) sea level pressure (hPa), (c) sea ice concentration (in percentage) and (d) sea ice thickness (m) to Antarctic sea ice loss in the fully-coupled simulations. The annual mean response of (e) 850 hPa temperature ( °C) and (f) sea level pressure (hPa) to prescribed tropical SSTs (see figure 1) in the atmosphere-only configuration. Stippling indicates a statistically significant response at the 95% confidence level.

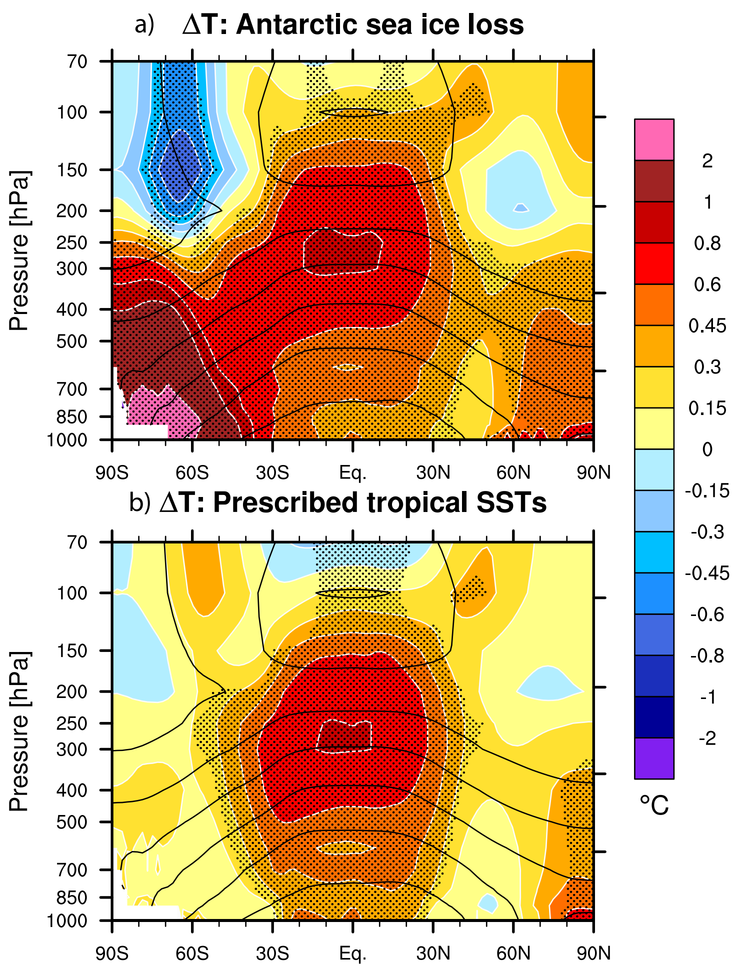


**Figure 4.** The latitude versus height cross section of the annual mean response of zonally averaged temperature ( °C) to (a) Antarctic sea ice loss in the fully-coupled configuration and to (b) prescribed tropical SSTs in an atmosphere-only configuration. Stippling indicates a statistically significant response at 95% confidence.

somewhat smaller than in the fully-coupled Antarctic sea ice loss runs (figure 4a). This is clearly seen in the warming response at 850 hPa (compare figure 3a and figure 3e). (iii) The enhanced Arctic warming in response to tropical SST anomalies, as in the fully-coupled runs, is related to a deepening of the Aleutian Low (compare figure 3b and figure 3f). This suggests that the tropical SSTs anomalies, via a Rossby wave

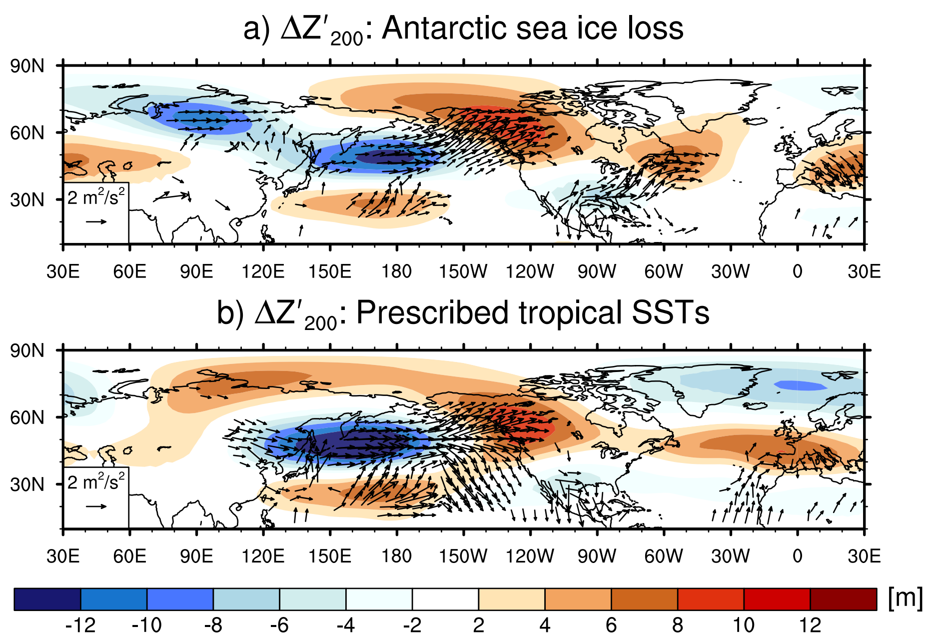


**Figure 5.** The annual mean response of the 200 hPa eddy (deviation from the zonal mean) geopotential height (m) to (a) Antarctic sea ice loss in the fully-coupled configuration and to (b) prescribed tropical SSTs in an atmosphere-only configuration. Vectors indicate the annual mean response of wave activity flux ($m^2\ s^{-2}$) (Takaya and Nakamura 2001) associated with the 200 hPa eddy geopotential height response. Vectors with a magnitude less than 1 $m^2\ s^{-2}$ are omitted.

train, are also responsible for the deepened Aleutian Low—and accompanying Arctic warming—in response to Antarctic sea ice loss in the fully-coupled runs. This is in agreement with the findings of Svendsen *et al* (2018), who identify the same mechanism as contributing to recent Arctic warming in the observed record, as well as the modeling study of Screen and Deser (2019). (iv) We are, of course, unable to diagnose the response of Arctic sea ice cover to the tropical SSTs anomalies because the surface conditions are prescribed in the atmosphere-only runs; however, both the near surface circulation response and the near surface warming in these runs are consistent with a loss of Arctic sea ice in the Pacific sector. Finally, (v) the wintertime response to prescribed tropical SSTs anomalies well captures the response to Antarctic sea ice loss in the fully-coupled simulations (compare the top and bottom rows in figure S3), whereas that response is much weaker, and less similar, in the summertime (compare top and bottom rows in figure S4). Also, note that in that season the sea ice loss occurs most prominently over the central Arctic (figure S4(c)), rather than over the Bering Sea (figure S3(c)). A different mechanism from the one examined here, in which the ocean and ice feedbacks are likely involved and persist throughout the year, may be needed to fully explain the summertime response.

We confirm that, in the coupled simulations, a Rossby wave train initiates in the tropical Pacific and connects to the North Pacific, by showing the eddy geopotential height response at 200 hPa and the associated wave activity flux (figure 5(a)). It is clear that this wave train is driven by Antarctic sea ice induced changes in tropical SSTs because the same mechanism occurs in the atmosphere-only simulations in response to prescribed tropical SSTs (figure 5(b)). This wave train mechanism is largely consistent with the one reported in the modelling and observational studies of Wettstein and Deser 2014, Tokinaga *et al* (2017), Svendsen *et al* (2018), Screen and Deser (2019), but opposite to the tropical-polar teleconnections reported in Ding *et al* (2014), Baxter *et al* (2019), and Ding *et al* (2019). This discrepancy is likely explained by the differing spatial patterns of anomalous SSTs imposed in these studies, especially in the West Pacific. In addition, the fact that Baxter *et al* (2019) and Ding *et al* (2019) focus on the relationship between tropical SSTs and Arctic conditions in summer rather than the winter could play a role; however it is also possible that climate models have limitations in their representation of tropical-polar linkages (Topal *et al* 2020).

We conclude, therefore, that fast atmospheric teleconnections from anomalous tropical SSTs offer a plausible pathway allowing the signal caused by Antarctic sea ice loss to reach into the Arctic, with the amplitude of the Arctic response largest in the boreal winter. This suggests that once the tropics begin to respond to Antarctic sea ice loss (England *et al* 2020), which could take multiple decades owing to the long timescale of the ocean response (Wang *et al* 2018), the effects on the Arctic would then appear relatively quickly (on a timescale of years, rather than decades). To be clear, the ocean plays a pivotal role in this process, because there is no Arctic response to Antarctic sea ice loss in atmosphere-only model runs, as shown in England *et al* (2018) (which use exactly the same model as the one employed here).

## 4. Summary and Discussion

In this study, we have demonstrated the existence of a substantial Arctic impact from projected twenty-first century Antarctic sea ice loss. In our fully-coupled climate model runs, in response to imposed Antarctic sea ice loss, the Aleutian Low deepens causing approximately 1 °C warming in Arctic near-surface air temperature ( 0.7 °C at 850 hPa), with a larger warming over the Bering Sea, East Siberia Sea, Chukchi Sea, and Alaska regions than in the Atlantic sector of the Arctic Ocean. The loss of Antarctic sea ice also leads to an annual mean loss of $0.5 \times 10^6$ km$^2$ of sea ice extent in the Arctic, primarily in the Bering Sea. With the aid of additional atmosphere-only model runs, we have shown that a fast atmospheric response to the Antarctic-sea ice-loss-induced tropical SST anomalies is responsible for at least half of this pole-to-pole signal.

We acknowledge that the pole-to-pole effects documented here are relatively small compared to the internal variability of the climate system in the high-latitudes. However, the polar cap warming and loss of Arctic sea ice in our model are statistically significant at a 95% confidence level for every month of the year, not just in the annual mean. Furthermore, the sheer fact that as much as 10–15% of the end-of the century Arctic warming projected under RCP8.5 could be induced from climate change at the opposite pole offers a striking example of the huge geographical extent of the couplings at play among various components in the Earth's climate system.

We also acknowledge that the magnitude of the Arctic warming in our atmosphere-only runs with prescribed tropical SST anomalies is, approximately, only half as large as the one in the fully-coupled runs (compare figure 4a and 4e). It is important to appreciate, however, that our aim was not to fully replicate the exact Arctic response from the fully-coupled simulations (which, in fact, may no be feasible with an atmosphere-only model). Instead, our goal has been to demonstrate a plausible pathway which could explain the pole-to-pole connection. In fact, since prescribing SSTs and sea ice cover does not allow them to freely evolve with the atmospheric conditions, the Arctic warming response is likely underestimated. For example, one would expect Arctic warming to be amplified if sea ice cover is allowed to change, via the sea ice albedo feedback. There may also be other pathways through which Antarctic sea ice loss could influence the Arctic, the main candidates being atmosphere-ocean coupling and ocean circulation changes which could alter the heat transport into the northern high-latitudes. However, the results presented above suggest that tropics-to-pole mechanism we have proposed is likely a dominant one in facilitating the pole-to-pole response, especially in the boreal winter.

Taken together, previous studies (e.g. Ding *et al* 2014, Dong *et al* 2019, McCrystall *et al* 2020) suggest that the Arctic response to tropical warming is sensitive to the exact tropical forcing pattern and is likely model-dependent. This is an important caveat for our results, which are only based on one climate model. Consistent with our study, however, most mechanisms that have been proposed to explain a connection between the tropics and the Arctic have been based on tropospheric Rossby waves initiating in the tropical Pacific (Yuan *et al* 2018). In our fully-coupled model simulations, we find warming throughout the tropics, but the strongest warming is located in the Central and Eastern Equatorial Pacific (figure 1). However, results from Dong *et al* (2019), in agreement with earlier studies (Yoo *et al* 2012, Ding *et al* 2019), suggest that the Arctic is responding primarily to the warming in the Western Equatorial Pacific, the region of tropical ascent. Dong *et al* (2019) show that in abrupt 4 × $CO_2$ experiments, despite the Eastern Pacific warming more, it is the warming in the Western Pacific which is responsible for the temperature increase over the Arctic. Additional experiments with our atmosphere-only model could be carried out to test the relative importance of the Eastern vs Western Tropical Pacific for Arctic climate warming. However, such work is beyond the scope of this short letter, whose primary goal is to highlight the pole-to-pole impact of future Antarctic sea ice loss.

## Acknowledgment

We appreciate the constructive feedback from two anonymous reviewers which have led to considerable improvements in the manuscript. The work of MRE is funded by grants OPP-1643445 and OPP-1744835 from the US National Science Foundation. The work of LMP is funded, in part, by a grant from the US National Science Foundation to Columbia University.

## Data Availability

The data that support the findings of this study are available upon reasonable request from the authors.

## ORCID iDs

M R England https://orcid.org/0000-0003-3882-872X
L M Polvani https://orcid.org/0000-0003-4775-8110
L Sun https://orcid.org/0000-0001-8578-9175

## References


WMO 2018 Scientific Assessment of Ozone Depletion: 2018. Global Ozone Research and Monitoring Project-Report No. 58 (Geneva: WMO)

Ayres H and Screen J 2019 Multimodel analysis of the atmospheric response to Antarctic sea ice loss at quadrupled co2 *Geophys. Res. Lett.* **46** 9861–9

Barbante C*et al* and 2006 One-to-one coupling of glacial climate variability in Greenland and Antarctica *Nature* **444** 195–8

Baxter I *et al* 2019 How Tropical Pacific surface cooling contributed to accelerated sea ice melt from 2007 to 2012 as ice is thinned by anthropogenic forcing *J. Clim.* **32** 8583–602

Blunier T *et al* 1998 Asynchrony of Antarctic and Greenland climate change during the last glacial period *Nature* **394** 739–43

Blunier T and Brook E 2001 Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period *Science* **291** 109–12

Bograd S, Schwing F, Mendelssohn R and Green-Jessen P 2002 On the changing seasonality over the North Pacific *Geophys. Res. Lett.* **29** 9

Broecker W 1998 Paleocean circulation during the last deglaciation: A bipolar seesaw? *Paleoceanography* **13** 119–21

Chylek P, Folland C, Lesins G and Dubey M 2010 Twentieth century bipolar seesaw of the Arctic and Antarctic surface air temperatures *Geophys. Res. Lett.* **37** L08703

Cohen J *et al* 2020 Divergent consensuses on Arctic amplification influence on midlatitude severe winter weather *Nat. Clim. Change* **10** 20–9

Collins M *et al* 2006 *Long-Term Climate Change: Projections, Commitments and Irreversibility* chapter 12 (Cambridge, United Kingdom: Cambridge University Press) pp 1029–136

Crowley T 1992 North Atlantic deep water cools the Southern Hemisphere *Paleoceanography* **7** 489–97

De B and Wu Y 2019 Robustness of the stratospheric pathway in linking the Barents-Kara Sea sea ice variability to the mid-latitude circulation in CMIP5 models *Clim. Dyn.* **53** 193–207

Deser C, Sun L, Tomas R and Screen J 2016 Does ocean coupling matter for the northern extratropical response to projected Arctic sea ice loss? *Geophys. Res. Lett.* **43** 2149–57

Deser C, Tomas R, Alexander M and Lawrence D 2010 The seasonal atmospheric response to projected Arctic sea ice loss in the late twenty-first century *J. Clim.* **23** 333–51

Deser C, Tomas R and Sun L 2015 The role of ocean-atmosphere coupling in the zonal-mean atmospheric response to Arctic sea ice loss *J. Clim.* **28** 2168–86

Ding Q *et al* 2019 Fingerprints of internal drivers of Arctic ea ice loss in observations and model simulations *Nat. Geosci.* **12** 28–33

Ding Q, Wallace J, Battisti D, Steig E, Gallant A, Kim H and Geng L 2014 Tropical forcing of the recent rapid Arctic warming in northeastern Canada and Greenland *Nature* **509** 209–12

Dong Y, Proistosescu C, Armour K and Battisti D 2019 Attributing historical and future evolution of radiative feedbacks to regional warming patterns using a Green's Function approach: The preeminence of the Western Pacific *J. Clim.* **32** 5471–91

England M, Polvani L and Sun L 2018 Contrasting the Antarctic and Arctic atmospheric response to projected sea ice loss in the late 21st Century *J. Clim.* **31** 6353–70

England M, Polvani L, Sun L and Deser C 2020 Tropical climate responses to projected Arctic and Antarctic sea ice loss *Nat. Geosci.* **13** 275–81

Fetterer F, Knowles K, Meier W N, Savoie M and Windnagel A K 2017 Sea Ice Index, Version 3 (Last accessed on April 31 2020) https://nsidc.org/data/G02135/versions/3

Flournoy M, Feldstein S, Lee S and Clothiaux E 2016 Exploring the tropically excited Arctic warming mechanism with station data: Links between tropical convection and Arctic downward infrared radiation *J. Atmos. Sci.* **73** 1143–58

Gan B *et al* 2017 On the response of the Aleutian Low to greenhouse warming *J. Clim.* **30** 3907–25

Hu C *et al* 2016 Shifting El Nino inhibits summer Arctic warming and Arctic sea-ice melting over the Canada Basin *Nat. Commun.* **7** 11721

Kennel C and Yulaeva E 2020 Influence of Arctic sea-ice variability on Pacific trade winds *PNAS* **117** 2824–34

Knutti R, Fluckiger J, Stocker T and Timmermann A 2004 Strong hemispheric coupling of glacial climate through freshwater discharge and ocean circulation *Nature* **430** 851–6

Kosaka Y and Xie S 2016 The tropical Pacific as a key pacemaker of the variable rates of global warming *Nat. Geosci.* **9** 669–73

Lee S 2012 Testing of the Tropically Excited Arctic Warming Mechanism (TEAM) with traditional El Nino and La Nina *J. Clim.* **25** 4015–22

Liu W and Fedorov A 2018 Global impacts of Arctic sea ice loss mediated by the Atlantic meridional overturning circulation *Geophys. Res. Lett.* **46** 944–52

Marino G, Rohling E, Rodriguez-Sanz L, Grant K, Heslop D, Roberts A, Stanford J and Yu J 2015 Bipolar seesaw control on last interglacial sea level *Nature* **522** 197–201

Marsh D, Mills M, Kinnison D and Lamarque J 2013 Climate change from 1850 to 2005 simulated in CESM1(WACCM) *J. Clim.* **26** 7372–91

McCrystall M, Hosking J, White I and Maycock A 2020 The impact of changes in tropical sea surface temperatures over 1979-2012 on Northern Hemisphere high latitude climate *J. Clim.* **33** 5103-5121

Notz D *et al* 2020 Arctic sea ice in CMIP6 *Geophys. Res. Lett.* **47** e2019GL086749

Parkinson C 2019 A 40-y record reveals gradual Antarctic sea ice increases followed by decreases at rates exceeding the rates seen in the Arctic *PNAS* **116** 14414–23

Pedro J, Jochum M, Buizert C, He F, Barker S and Rasmussen S 2018 Beyond the bipolar seesaw: Toward a process understanding of interhemispheric coupling *Quat. Sci. Rev.* **192** 27–46

Pedro J, van Ommen T, Rasmussen S, Morgan V, Chappellaz J, Moy A, Masson-Delmotte V and Delmotte M 2011 The last deglaciation: timing the bipolar seesaw *Climate of the Past* **7** 671–83

Peings Y and Magnusdottir G 2014 Response of the wintertime Northern Hemisphere atmospheric circulation to current and projected Arctic sea ice decline: A numerical study with CAM5 *J. Clim.* **27** 244–64

Polvani L, Previdi M, England M, Chiodo G and Smith K 2020 Substantial twentieth-century Arctic warming caused be ozone depleting substances *Nat. Clim. Change* **10** 130–3

Schneider D and Noone D 2012 Is a bipolar seesaw consistent with observed antarctic climate variability and trends? *Geophys. Res. Lett.* **39** L06704

Screen J and Deser C 2019 Pacific Ocean variability influences the time of emergence of a seasonally ice-free Arctic Ocean *Geophys. Res. Lett.* **46** 2222–2231

Screen J, Deser C, Smith D, Zhang X, Blackport R, Kushner P, Oudar T, McCusker K and Sun L 2018 Consistency and discrepancy in the atmospheric response to Arctic sea-ice loss across climate models *Nat. Geosci.* **11** 155–63

Screen J 2017 Far-flung effects of Arctic warming *Nat. Geosci.* **10** 253–54

Screen J, Simmonds I, Deser C and Tomas R 2013 The atmospheric response to three decades of observed Arctic sea ice loss *J. Clim.* **26** 1230–48

Screen J and Simmonds I 2010 The central role of diminishing sea ice in recent Arctic temperature amplification *Nature* **464** 1334–7

Shepherd T 2016 Effects of a warming Arctic *Science* **353** 989–90

Stocker T and Johnsen S 2003 A minimum thermodynamic model for the bipolar seesaw *Paleoceanography* **18**

Stocker T 1998 The seesaw effect *Science* **282** 61–62

Stuecker M *et al* 2018 Polar amplification dominated by local forcing and feedbacks *Nat. Clim. Change* **8** 1076–81

Sun L, Deser C, Tomas R and Alexander M 2020 Global coupled climate response to polar sea ice loss: Evaluating the effectiveness of different ice-constraining approaches *Geophys. Res. Lett.* **47** e2019GL085788
Sun L, Deser C and Tomas R 2015 Mechanisms of stratospheric and tropospheric circulation response to projected Arctic sea ice loss *J. Clim.* **28** 7824–45
Svendsen L, Keenlyside N, Bethke I, Gao Y and Omrani N 2018 Pacific contribution to the early twentieth-century warming in the Arctic *Nat. Clim. Change* **8** 793–7
Takaya K and Nakamura H 2001 A formulation of a phase-independent wave activity flux for stationary and migratory quasigeostrophc eddies on a zonally varying basic flow *J. Atmos. Sci.* **58** 608–27
Tokinaga H, Xie S and Mukougawa H 2017 Early 20th-century Arctic warming intensified by Pacific and Atlantic multidecadal variability *PNAS* **114** 6227–32
Tomas R, Deser C and Sun L 2016 The role of ocean heat transport in the global climate response to projected Arctic sea ice loss *J. Clim.* **29** 6841–59
Topal D, Ding Q, Mitchell J, an M, Herein I B, Haszpra T, Luo R and Li Q 2020 An internal atmospheric process determining summertime Arctic sea ice melting in the next three decades: Lessons learned from five large ensembles and multiple CMIP5 climate simulations *J. Clim.* **33** 7431–7454
Trenberth K and Hurrell J 1994 Decadal atmosphere-ocean variations in the Pacific *Clim. Dyn.* **9** 303–19
Wang K, Deser C, Sun L and Tomas R 2018 Fast response of the tropics to an abrupt loss of Arctic sea ice via ocean dynamics *Geophys. Res. Lett.* **45** 4264–4272
Wang Z, Zhang X, Guan Z, Sun B, Yang X and Liu C 2015 An atmospheric origin of the multi-decadal bipolar seesaw *Sci. Rep.* **5** 8909
Wettstein J and Deser C 2014 Internal variability in projections of twenty-first-century Arctic sea ice loss: Role of the large-scale atmospheric circulation *J. Clim.* **27** 527–50
Yoo C, Feldstein S and Lee S 2014 The prominence of a tropical convective signal in the wintertime Arctic temperature *Atmos Sci Lett* **15** 7–12
Yoo C, Lee S and Feldstein S 2012 Arctic response to an MJO-like tropical heating in an idealised GCM *J. Atmos. Sci.* **69** 2379–93
Yuan X, Kaplan M and Cane M 2018 The interconnected global climate system - a review of tropical-polar teleconnections *J. Clim.* **31** 5765–92
Zhang P, Wu Y, Simpson I, Smith K, Zhang X, De B and Callaghan P 2018 A stratospheric pathway linking a colder Siberia to Barents-Kara Sea sea ice loss *Sci. Adv.* **4** eeat6025