Geophysical Research Letters

RESEARCH LETTER

10.1029/2020GL090631

Key Points:

- Observed multi-decadal fluctuations in Arctic surface temperature are a forced response to anthropogenic aerosols and greenhouse gases
- In contrast, Pacific decadal variability is important for understanding observed Antarctic surface temperature fluctuations
- No modeling evidence for the reported 20th century "bipolar seesaw" of Arctic and Antarctic surface temperatures

Supporting Information:

- Supporting Information S1

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Citation:

England, M. R. (2021). Are multi-decadal fluctuations in Arctic and Antarctic surface temperatures a forced response to anthropogenic emissions or part of internal climate variability? *Geophysical Research Letters*, *48*, e2020GL090631. https://doi.org/10.1029/2020GL090631

Received 31 AUG 2020
Accepted 11 FEB 2021

Are Multi-Decadal Fluctuations in Arctic and Antarctic Surface Temperatures a Forced Response to Anthropogenic Emissions or Part of Internal Climate Variability?

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Abstract In this study, we investigate the drivers of observed multi-decadal fluctuations in Arctic and Antarctic surface temperatures using multiple large ensembles of climate simulations and single-forcing ensembles. We find that the observed oscillation in Arctic surface temperature around a linear trend since 1920 is a forced response to emissions of anthropogenic aerosols and greenhouse gases. In contrast, we show that observed multi-decadal Antarctic surface temperature fluctuations are partially related to Pacific decadal variability which influences the climate of West Antarctica. Lastly, we demonstrate that internally driven multi-decadal fluctuations at the two poles are not systematically correlated in any climate model examined here, as had been previously suggested. We conclude by discussing the implications of these results for understanding projections of Arctic and Antarctic surface climate of the coming decades.

Plain Language Summary In this study, we investigate whether long-term variations in Arctic and Antarctic surface temperatures over the past century were caused by emissions due to human activity or internal climate variability. Using a number of climate model simulations, we find that the periods of Arctic cooling during 1930–1975 and enhanced Arctic warming during 1975–2019 can be explained as a response to industrial aerosol and greenhouse gas emissions. In contrast, we show that slow modes of Pacific climate variability are important for understanding observed variations in Antarctic surface temperatures. Lastly, we demonstrate that in all of the climate models examined here, the climates of the Arctic and Antarctic are not connected on multi-decadal timescales due to climate variability, as had been previously suggested. We conclude by discussing the implications of these results for understanding projections of Arctic and Antarctic surface climate of the coming decades.

1. Introduction

Over the past century, surface temperatures of the two polar regions have exhibited substantial multi-decadal variations. For example, although the Arctic has been warming for the last four decades at a rapid rate (Post et al., 2019), as recently as 1940–1970 the Arctic cooled substantially and sea ice cover expanded (Fyfe et al., 2013; Gagne et al., 2017). It is important to understand what is responsible for these fluctuations—are these a response to external forcing or rather driven by slow modes of variability internal to the climate system? Making progress with this question can give us a deeper insight into how our polar climates may change over the coming decades.

Many studies have established the importance of anthropogenic forcing in driving Arctic surface temperature variations over the past century. For example, emissions of greenhouse gases have substantially contributed to surface warming since the 1960s (Fyfe et al., 2013; Haustein et al., 2019; Notz & Stroeve, 2016; Polvani et al., 2020). Modeling evidence also suggests that anthropogenic aerosol emissions are responsible for much of the observed mid 20th century Arctic cooling (Fyfe et al., 2013; Gagne et al., 2017). However, other studies have suggested an important role for internal climate variability in early 20th century Arctic surface temperature trends (Tokinaga et al., 2017) as well as the more recent rapid Arctic warming (Ding et al., 2017, 2019; England et al., 2019). Specifically, these studies point to Pacific and Atlantic multi-decadal variability as drivers of Arctic temperature variability (Castruccio et al., 2019; Tokinaga et al., 2017; Zhang, 2015).

Internal variability also contributes to variations in Antarctic surface temperature, predominantly via Pacific decadal variability (PDV) or via changes to the Southern Annular Mode (SAM), with most studies pointing to PDV as the most important driver (Holland et al., 2019; Meehl, Arblaster, et al., 2016; Meehl et al., 2019; Okumura et al., 2012; Purich et al., 2016; Schneider & Deser, 2018; Turner et al., 2016). With regards to external forcing, stratospheric ozone depletion, which occurred over the second half of the 20th century, potentially influenced Antarctic surface temperatures by causing a shift to a more positive SAM in austral summer (Shindell & Schmidt, 2004; Thompson et al., 2011). Finally, it has been suggested that increased CO_2 concentrations drive a cooling over the high elevations of central Antarctica (Schmithusen et al., 2015; Shindell & Schmidt, 2004) although the robustness of this result has been questioned (Smith et al., 2018).

Are the surface temperature variations at the two poles connected? Chylek et al. (2010) suggest that multi-decadal fluctuations of Arctic and Antarctic surface temperatures over the 20th century are anti-correlated, and hypothesize that this is due to internal climate variability: a 20th century analogue of the millennial-scale “bipolar seesaw” phenomenon (Barbante et al., 2006; Blunier et al., 1998; Broecker, 1998). This modern “bipolar seesaw” has recently been offered as an explanation (Yu et al., 2017) for the conundrum of why Antarctic sea ice cover has expanded since 1979 concurrent with a rapid decline in Arctic sea ice extent. An improved understanding of the drivers of multi-decadal fluctuations of polar surface temperatures will help to determine whether internal variability may indeed act as a bridge connecting the climates of the two poles.

In this study, we take advantage of a new archive of large ensembles (LEs) of climate simulations and single-forcing ensembles, to further our understanding of multi-decadal polar climate variability. In brief, the aim of this study is fourfold: Analyze multiple LEs and single-forcing ensembles to determine the importance of external forcing and internal climate variability in driving observed (a) Arctic, (b) Antarctic multi-decadal surface temperature fluctuations, (c) to determine if surface temperature fluctuations at the two poles are connected, and (d) to understand the implications of these results for polar climate projections of the coming decade.

2. Methods Section

2.1. Observational Data

We analyze two surface temperature observational data sets over the period 1920–2019. The first is an updated version of the Cowtan and Way (2014) data set, based on CRUTEMP4.6 (Jones et al., 2012) over land and HadSST4 (Kennedy et al., 2019) over ocean, with kriging used to cover areas without observations. The second is GISTEMP v4 (GISTEMP, 2020; Lenssen et al., 2019). We note that there is higher observational uncertainty for the Antarctic due to limited observational station data, especially prior to the 1950s; however, the observational results presented here are largely consistent with analyses of Antarctic ice cores (Okumura et al., 2012; Schneider & Steig, 2008; Schneider et al., 2012). We also analyze the ERA5 reanalysis product over the period 1950–2019 (ERA5, 2017; Hersbach et al., 2020).

2.2. Climate Model Runs

2.2.1. Large Ensembles

To assess the contributions of external forcing and internal variability to Arctic and Antarctic surface temperature fluctuations, we leverage a new collection of Earth system model initial-condition LEs (Deser, Lehner, et al., 2020). LEs of simulations from a single climate model offer a way to isolate the internal climate variability from the forced response to anthropogenic emissions. To date, most analysis has been done on a single LE, and therefore rely on that individual climate model's simulated internal variability. However, the new collection of multi-model LEs (Deser, Lehner, et al., 2020) provides the opportunity to compare both internal variability and the forced response across different climate models in a consistent and coordinated manner. Five of these LEs (CESM1-CAM5, CSIRO-Mk3-6-0, EC-EARTH, GFDL-CM3, and MPI-ESM) simulate the whole period of interest, 1920–2019, and the remaining two (CanESM2 and GFDL-ESM2M) simulate the shorter period 1950–2019. For each of these simulations, historical forcing is used for the years preceding 2006 and RCP8.5 forcing is used for the years 2006–2019. Note that for this later period, the differences between RCP4.5 and RCP8.5 forcings are small. These simulations are summarized in Table S1. For all simulations, we analyze the surface air temperature variable; however, the results are extremely similar for 2 meter air temperature (not shown).

2.2.2. Single-Forcing Runs

To isolate the response to anthropogenic aerosols and greenhouse gases in the 20th century, we analyze three sets of specifically designed single-forcing LEs, summarized in Table S2. The first is the CESM1-CAM5 x-aer ensemble (Deser, Phillips, et al., 2020) which is a 20-member companion ensemble to the CESM1-CAM5 LE (hist, Kay et al. (2015). These two ensembles are identical except that the emission of industrial aerosols are held fixed at 1920 values in the x-aer ensemble. All other forcing agents evolve as in the CESM1-CAM5 LE. Taking the difference between the two ensemble means will isolate the role of anthropogenic aerosol forcing on the climate system in CESM1-CAM5. In the same manner, the second set is the 20-member CESM1-CAM5 x-ghg ensemble (Deser, Phillips, et al., 2020), with greenhouse gases held fixed at 1920 values. Again, the difference between the x-ghg ensemble mean and the full CESM1-CAM5 LE ensemble mean will isolate the role of greenhouse gas forcing. The third single-forcing ensemble analyzed in this study is the 50-member CanESM2 aer ensemble (Gagne et al., 2017; Oudar et al., 2018). In these simulations, anthropogenic aerosols are the only forcing agent and the ensemble mean of these simulations directly shows the impact of aerosol forcing on the climate system in CanESM2.

Note that the CanESM2 aer ensemble is a “nothing-but-one” single-forcing ensemble and the CESM1-CAM5 x-aer/x-ghg ensembles are “all-but-one” single-forcing ensembles. One important distinction between the two approaches is that in the “all-but-one” approach the estimate of the forced response contains the nonlinear interaction between aerosols and greenhouse gases (Deng et al., 2020; Gettelman et al., 2016). This is because these nonlinear interactions are present in the hist ensemble but not the x-aer or x-ghg ensembles, and so are present in the difference between the two ensembles (Deser, Phillips, et al., 2020). Deng et al. (2020) demonstrate that in CESM1 the nonlinear effects are important for the Arctic surface temperature response in different seasons however the effects are small for the annual mean.

2.3. Methods

2.3.1. Calculating Multi-Decadal Fluctuations

In this study, we use two different methods for isolating the contribution of multi-decadal variability within a timeseries. The first method, as in Chylek et al. (2010), is to remove the linear trend for the given time period (either 1920–2019 or 1950–2019). The remaining residuals are referred to as “anomalies.” The second approach is to remove the ensemble mean, and thus removing the externally forced response, from a LE of identically forced climate simulations. The remaining residuals are referred to as “deviations.” In both cases, following Chylek et al. (2010), a 17-year running average is applied to the resulting timeseries to focus on multi-decadal variability. Lastly, we define the Arctic polar-cap average as 60°N–90°N and similarly 60°S–90°S for the Antarctic.

2.3.2. Pacific Decadal Variability

We use two metrics of PDV: indices of the Pacific Decadal Oscillation (PDO) (Mantua & Hare, 2002) and the Inter-decadal Pacific Oscillation (IPO) (Henley et al., 2015). In Section 3.2, we calculate the regression of Antarctic surface temperature on PDV in each LE using the Climate Variability and Diagnostics Package for LEs (Phillips et al., 2020). The surface temperature of each ensemble member is first regressed onto that individual member's PDV index and then an average is taken for each LE.

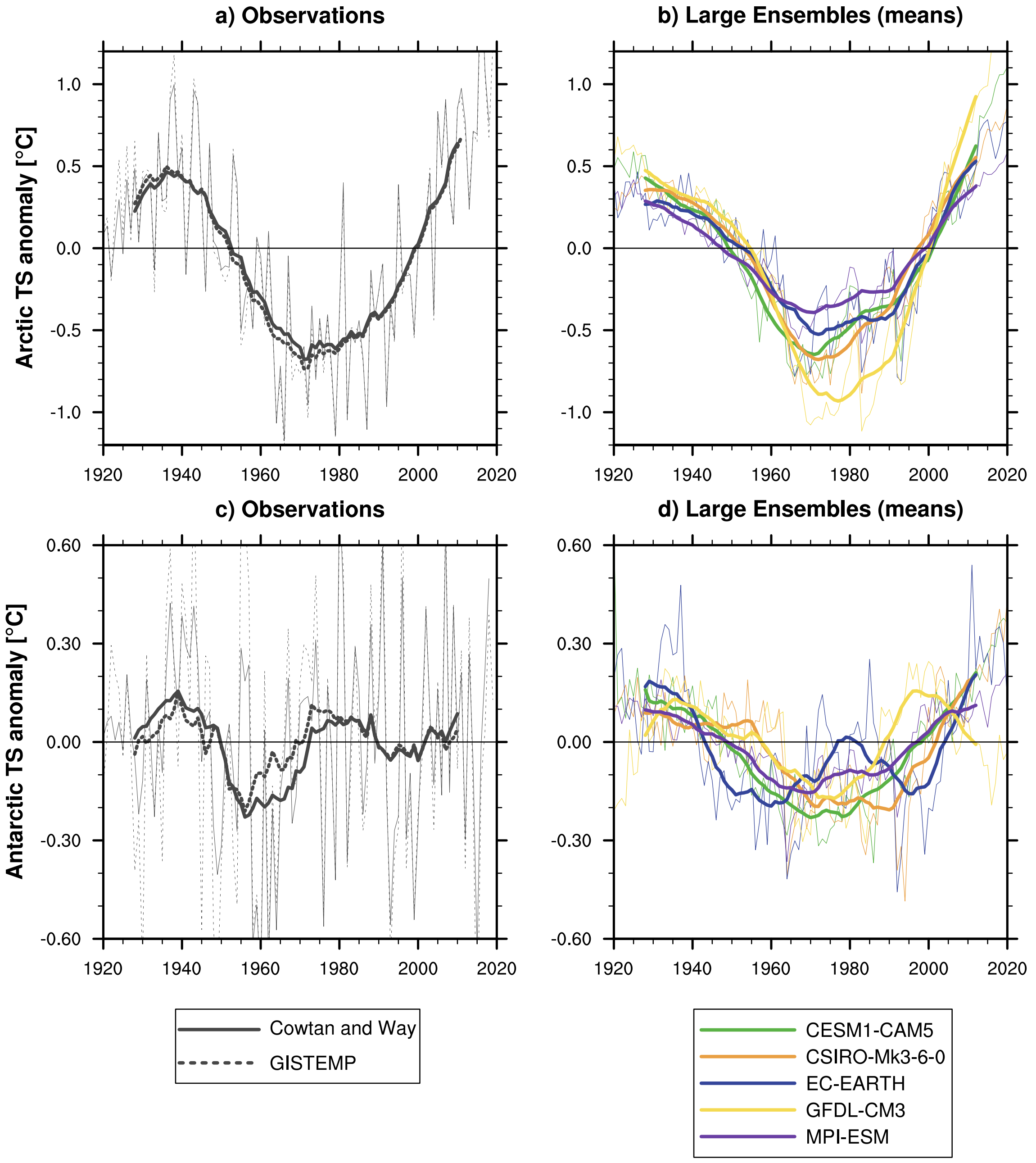

Figure 1. Left: Timeseries for the years 1920–2019 of (a) observed Arctic and (c) observed Antarctic surface temperature anomalies. Right: Ensemble means of the (c) Arctic and (d) Antarctic surface temperature anomalies for the years 1920–2019 for five of the LEs outlined in Table S1. In all panels the thin lines show the annual mean anomalies and the thick lines show the 17-year running means. Note that the range of the *y*-axes for panels (a) and (b) are twice that of panels (c) and (d).

3. Results

Over the past century, Arctic surface temperatures have exhibited striking multi-decadal fluctuations around a long-term linear trend: with positive temperature anomalies for much of the first half of the 20th century and negative temperature anomalies for much of the second half of the 20th century (Figure 1a). Compared to the long-term linear trend, the rate of Arctic surface warming was accelerated between 1975 and 2019 and much slower between 1930 and 1975. In contrast, the magnitude of multi-decadal Antarctic surface temperature anomalies is much smaller. The observations show warm anomalies in the 1940s and 1980s, and cold anomalies in the 1960s (Figure 1c). It is important to emphasize that there is large observational uncertainty for the Antarctic, especially for the first half of the 20th century. However, the anomalous warmth during the 1940s is consistent with ice core data from West Antarctica (Schneider & Steig, 2008).

3.1. The Arctic

If the long-term Arctic surface temperature oscillation about the linear trend (Figure 1a) was due to a slow mode of internal variability, the ensemble means of LE simulations would fail to replicate this signal, since the ensemble mean removes the imprint of internal variability. However, it is clear that the same multi-decadal anomalies from the linear trend are also evident in timeseries of the LE means for the years 1920–2019 (Figure 1b). There is a high correlation between the observations and the LE means, ranging from +0.74 to +0.78 depending on the observational data set and the model, rising to over +0.96 after the running mean is calculated. There is some spread in the amplitude of these anomalies among the different model ensembles (Figure 1b), but the observations lie within this spread. The same agreement is found for the seven LEs which cover the period 1950–2019 (compare panels a and b in Figure S1), with correlations ranging from +0.66 to +0.91.

It is more appropriate, however, to compare the observational record with individual ensemble members because both will contain the forced response and some contribution from internal variability. The spread among the ensemble members is small compared to the fluctuations in the ensemble mean from the linear trend (Figure S2 for 1920–2019 and Figure S3 for 1950–2019); the multi-decadal oscillatory pattern is clearly identifiable in nearly every single ensemble member. All individual members were positively correlated with the observations and 70% of all individual members had correlations greater than 0.75. Therefore, the multi-decadal oscillation in Arctic surface temperature can be explained as a forced response to anthropogenic emissions.

Which anthropogenic forcing agents are responsible for driving the relatively muted Arctic response during 1930–1975 and the accelerated Arctic warming thereafter? To tackle this question, we look to the single-forcing ensembles. Figure 2 shows the role of anthropogenic aerosols (Figure 2a) and greenhouse gases (Figure 2b) in driving Arctic temperature changes from 1920, as diagnosed by the taking the difference between the CESM-LE (with all historical forcings) and the CESM x-aer and x-ghg ensembles, respectively. Anthropogenic aerosols cooled the Arctic at a rate of −0.25°C/decade during 1930–1975, but a subsequent reduction in their emissions resulted in +0.18°C/decade of Arctic warming during 1975–2019 (Figure 2a). Greenhouse gases rapidly warmed the Arctic at a rate at a rate of +0.59°C/decade during 1975–2019, having only contributed to +0.15°C/decade warming during the earlier period 1930–1975 (Figure 2b). Taken together, after removing a linear trend, anthropogenic aerosols (Figure 2d) and greenhouse gases (Figure 2e) can explain the observed multi-decadal Arctic surface temperature anomalies (Figure 2f). We note that this method may slightly overestimate the combined response because the nonlinear interactions between greenhouse gases and anthropogenic aerosols are double-counted here. Similar results are found for the period 1950–2019 (Figures S4a–S4c) and the response to aerosols in a second climate model, CanESM2 (Figure S4d), is in good agreement.

These findings are consistent with the recent results of Deser, Phillips, et al. (2020) which demonstrate that anthropogenic aerosols had a substantial asymmetric cooling effect on the Northern Hemisphere high-latitudes for the years 1930–1979. However, due to large declines in emissions of these aerosols over North America and Europe, by the period 1970–2019 the cooling effects of aerosols were more globally uniform and these effects were dwarfed by the warming response to increased CO_2 emissions (Deser, Phillips, et al., 2020). In addition, our finding regarding the role of greenhouse gases are consistent with results from the recent modeling study of Polvani et al. (2020) which demonstrated that ozone depleting substances, which were not emitted into the atmosphere in substantial quantities before the 1950s, contributed substantially to the accelerated Arctic warming in the latter half of the 20th century.

3.2. The Antarctic

In comparison to the Arctic, the externally forced Antarctic surface temperature anomalies are smaller and there is less agreement among the different models (Figure 1d for 1920–2019 and Figure S1d for 1950–2019). The magnitude of the ensemble mean anomalies are also small compared to the spread across each

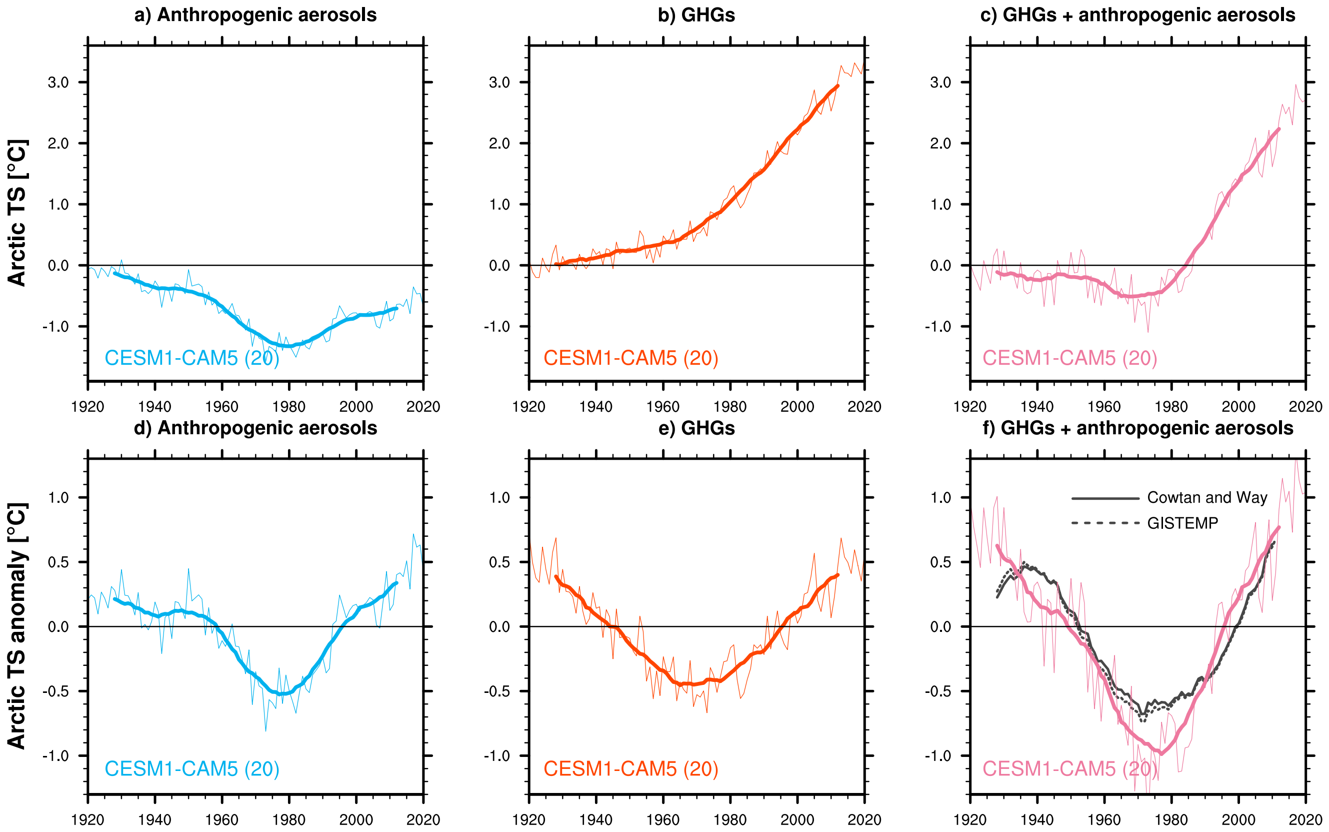

Figure 2. The top row shows the ensemble mean Arctic surface temperature response, relative to 1920, in CESM1-CAM5 to (a) anthropogenic aerosols (hist – x-aer, blue), (b) greenhouse gases (hist – x-ghg, red), and (c) anthropogenic aerosols and greenhouse gases (2 × hist – x-ghg – x-aer, pink). The bottom row is the linearly detrended counterpart of the top row, denoted the anomaly, with the observed Arctic surface temperature anomaly added in panel (f) in gray. In all panels the thin lines show the annual means and the thick lines show the 17-year running means.

ensemble and the sign of the response is not robust across the different model ensembles (Figure S5 for 1920–2019 and Figure S6 for 1950–2019). In contrast with the Arctic case, the observed Antarctic surface temperature anomalies show little systematic correlation with the LE means: the correlation values range from −0.04 to +0.29 depending on the observational data set and the model. The different models appear to separate into two different categories: models which have a forced response in the Antarctic similar to the Arctic (including CanESM2, CSIRO-Mk3-6-0, and CESM1-CAM5), and those which show very little temporal structure in the forced response (including EC-EARTH, GFDL-CM3, and GFDL-ESM2M). Due to the large spread among the LE means (well demonstrated by the seven LEs in Figure S1d), we cannot exclude a role for externally forced variations. However, the lack of agreement between the LE means and the observed Antarctic surface temperature anomalies suggest a potentially important role for multi-decadal internal variability.

We next examine the relationship between observed multi-decadal Antarctic surface temperature anomalies and indices of PDV. Figure 3a demonstrates that both the PDO and IPO bear a strong resemblance to the timeseries of Antarctic surface temperature anomalies. When the PDO and IPO are in their positive phase, which corresponds to warmer central and eastern Tropical Pacific sea surface temperatures (SSTs), Antarctic surface temperatures are generally warmer than the linear trend, and vice versa. The correlations between the indices of PDV and multi-decadal Antarctic surface temperature anomalies, documented in Table S3, range between +0.68 and + 0.92.

We explore whether this link between PDV and Antarctic surface temperatures is also present in the LEs. Figures 3b–3g show the regression of Antarctic surface temperatures on the PDO in each LE. One advantage of LEs is that, unlike in observations, the modes of decadal variability and their teleconnections can be sampled a large number of times. Although the spread among the different models is quite large, all six

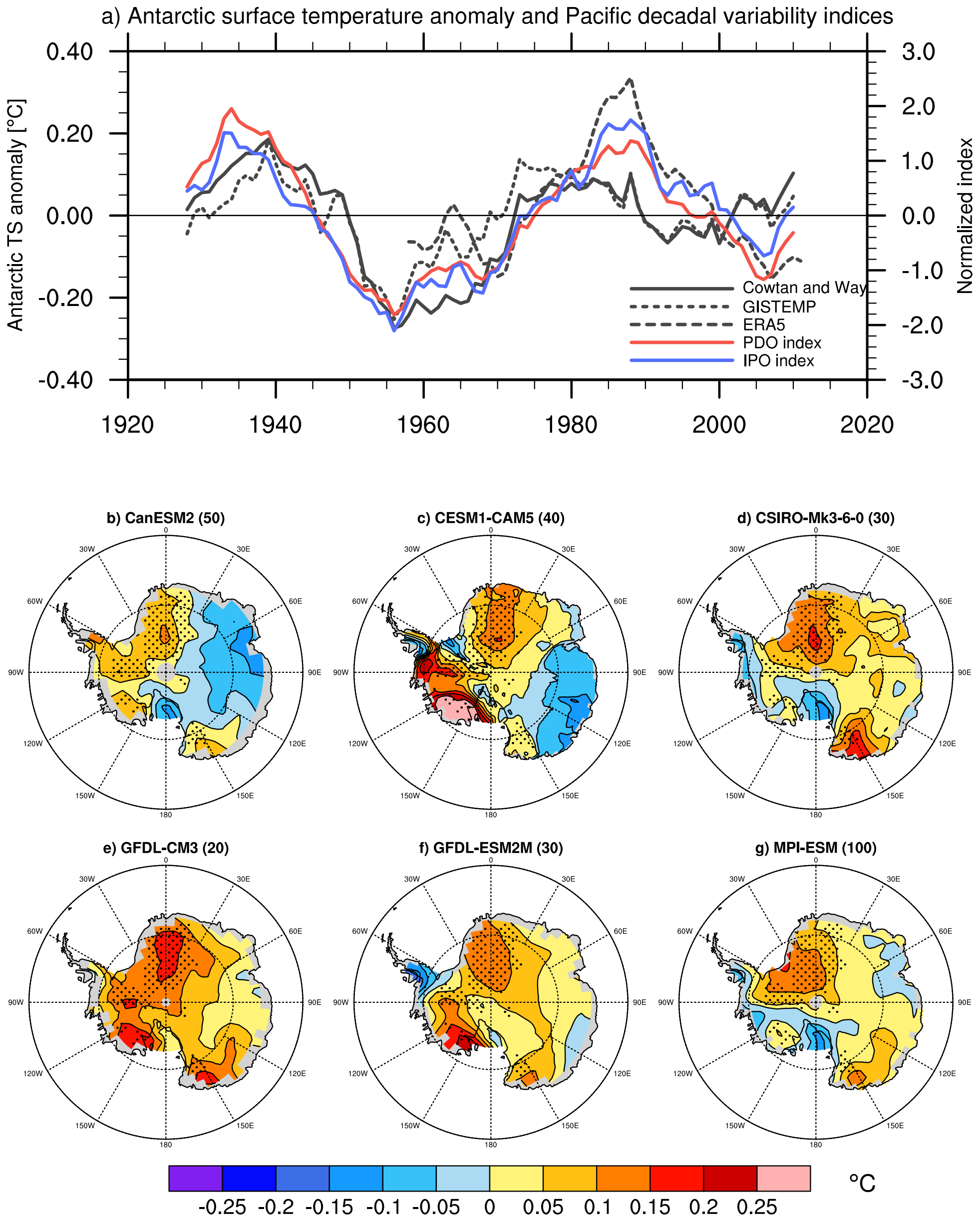

Figure 3. (a) Seventeen-year running mean of the PDO index (red lines), the IPO index (blue lines), shown on the right *y*-axis, compared to observed Antarctic surface temperature anomalies (gray lines), shown on the left *y*-axis. (b–g) Regression of the PDO index on Antarctic anomalous surface temperature in six of the LEs for the period of analysis. The number of members are shown in parentheses. EC-EARTH is omitted because we did not have the relevant fields to perform the analysis. The stippling shows regions in which at least five out of the six LEs agree on the sign of the relationship.

models agree that the positive phase of PDV is associated with enhanced warming in the West Antarctic and in Coats Land (see stippling in Figures 3b–3g). This is consistent with the previously suggested mechanism (Meehl, Arblaster, et al., 2016; Purich et al., 2016), which operates as follows: Pacific SST variability forces convectively generated Rossby waves into the extratropical Southern Hemisphere, modulating surface temperatures in the West Antarctic. There is little agreement among the models, however, on the sign of the surface temperature response to Pacific variability in the East Antarctic. These results are largely consistent with the findings of Schneider and Steig (2008), Okumura et al. (2012), and Schneider and Deser (2018).

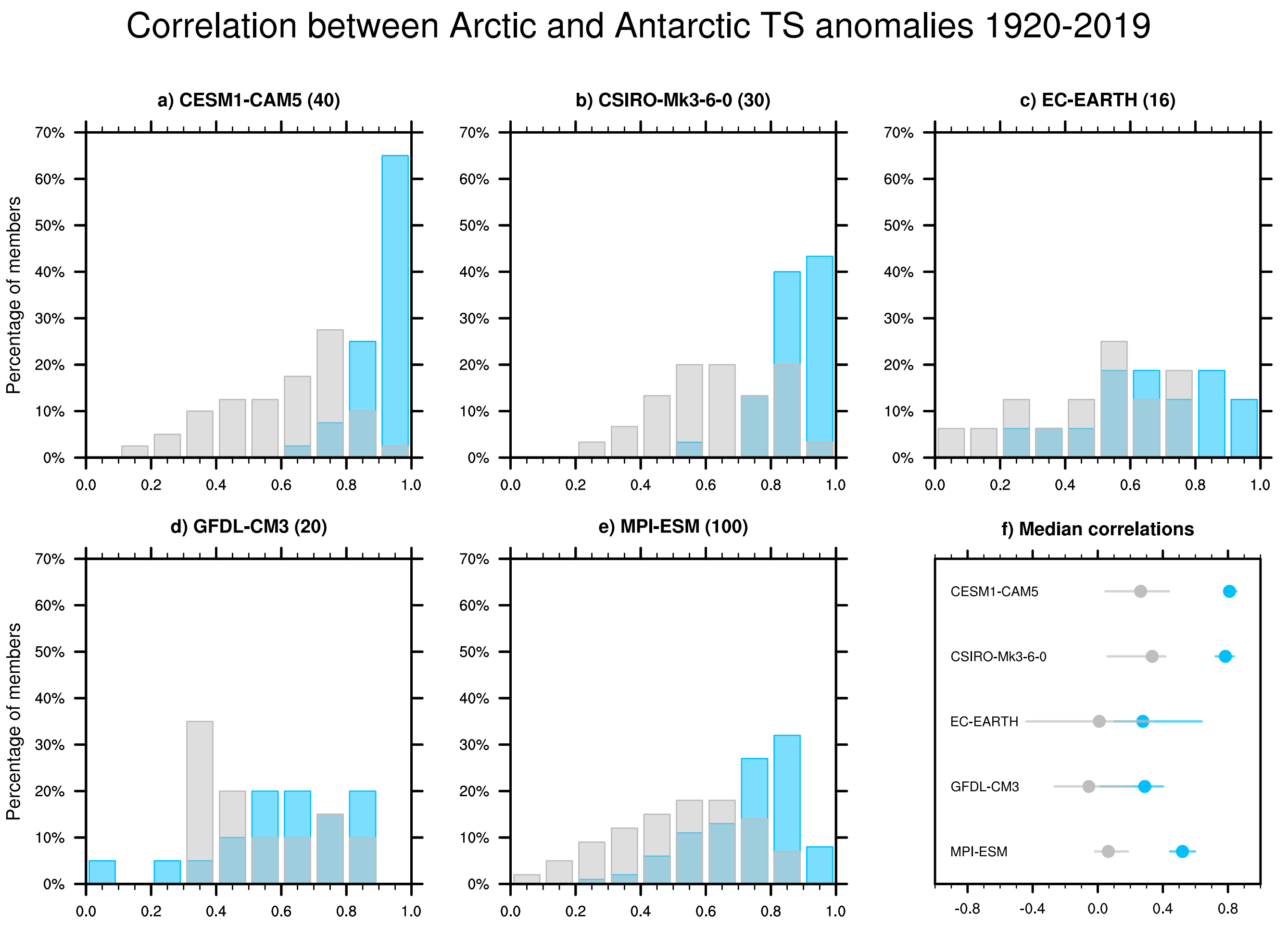

Figure 4. Histograms of correlation coefficients between Arctic and Antarctic multi-decadal surface temperature fluctuations in individual members of five of the LEs (a–e) for the period 1920-2019. The number of members in each LE is shown in parentheses. (f) An estimate of the median correlation value for each model with the 95% confidence interval. In each panel, the blue indicates the correlation of the anomalies from the linear trends and the gray instead indicates the correlations of the deviations from the ensemble mean.

Taken together, these results suggest that PDV has an important influence on Antarctic surface temperatures, especially over West Antarctica, and can partially explain the observed fluctuations in Antarctic surface temperature over the past century. The considerable spread among the ensemble means of the seven LEs examined here precludes us from determining the importance of externally forced variations such as greenhouse gases and stratospheric ozone depletion. However, it is clear that external forcing plays a greater and more robust role in driving multi-decadal variations in Arctic surface temperature than for the Antarctic.

3.3. Are Temperature Fluctuations at the Two Poles Connected?

Next, we examine whether the multi-decadal surface temperature fluctuations at the two poles are out of phase, as suggested by Chylek et al. (2010). Figure 4 shows histograms (blue) of the correlation of multi-decadal temperature anomalies at the two poles for the period 1920–2019 in individual ensemble members. Counter to the multi-decadal “bipolar seesaw” hypothesis of Chylek et al. (2010), there is no model which simulates a systematic anti-correlation at the two poles; in fact, models show a consistent positive correlation using this methodology (Figure 4f, blue). The same conclusion is evident from the seven LEs which cover the period 1950–2019 (Figure S7). This is most evident for CESM1-CAM5 and CSIRO-Mk3-6-0: the models which had similar forced responses of surface temperature anomalies in the Arctic and the Antarctic (e.g., compare Figure S2 and S5). This suggests that if there was a connection between the climate of the two poles over the past century, it would be a positive correlation and this relationship would be a manifestation of the forced response, not internal variability.

After removing the ensemble mean from each LE, rather than removing a linear trend, we find that the median correlation between Arctic and Antarctic surface temperature deviations in individual ensemble members on multi-decadal timescales is close to zero for each of the five LEs which cover the period 1920–2019 (Figure 4f, gray) and for each of seven LEs which cover the period 1950–2019 (Figure S7h, gray). The different models provide a variety of estimates for the widths of the possible distributions of correlations (Figures 4a–4e and Figures S7a–S7g, gray histograms), however, they are all centered near zero and show no systematic correlation or anti-correlation between deviations in surface temperatures at the two poles. Therefore, the suggestion that temperature fluctuations at the two poles are asynchronous, driven by internal climate variability, is not supported by any of the seven climate models we examine here.

Lastly, given that we have demonstrated that observed multi-decadal temperature fluctuations at the two poles have potentially different drivers—anthropogenic forcing driving fluctuations in the Arctic and internal climate variability important for fluctuations in the Antarctic—a lack of connection between the two poles should not be surprising.

4. Conclusions

In this study, we have investigated the drivers of Arctic and Antarctic multi-decadal surface temperature variability over the past century. To summarize our results, we return to the first three questions posed in Section 1. Using multiple LEs and single-forcing ensembles, we demonstrated that: (a) the observed slow oscillation of Arctic surface temperature about a linear trend is a forced response to anthropogenic aerosols and greenhouse gases; (b) internal climate variability, specifically PDV, is likely important in driving observed Antarctic surface temperature variations, with the largest influence in the West Antarctic, and (c) in all climate models examined here, there is no systematic connection between multi-decadal fluctuations at the two poles due to internal climate variability.

We now move on to the fourth question: What are the implications of these results for projections of polar climate for the coming decades? In regard to the Arctic, given that the emission of greenhouse gases are projected to increase and the emission of aerosols will continue to strongly decrease, our results would suggest that Arctic surface temperatures will continue to warm faster than the long-term linear trend for the coming decade. In regard to the Antarctic, if the projection of a transition from the negative phase of the IPO to the positive phase (Meehl, Hu, & Teng, 2016) continues to materialize, this would imply that the Antarctic surface temperatures, especially in the West Antarctic, would be anomalously warm for the coming years.

Lastly, this study showcases another powerful use of LEs (Deser, Phillips, et al., 2020) and single-forcing ensembles (Oudar et al., 2018; Deser, Phillips, et al., 2020; Polvani et al., 2020). We have demonstrated how both of these sets of tools can help inform a nuanced interpretation of the observational record, in terms of both internal variability and the response to different forcing agents. In addition, this study is a warning that removing the linear trend from the observational record (either for 1920–2019 or 1950–2019) does not adequately remove the imprint of external forcing; instead doing so conflates internal variability and the forced response to anthropogenic emissions.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The HadCRUT4 observational data set can be downloaded from https://crudata.uea.ac.uk/cru/data/temperature/. The GISTEMPv4 observational data set can be downloaded from https://data.giss.nasa.gov/gistemp/. ERA5 reanalysis data can be downloaded from the Copernicus Climate Change Service Data Store at https://cds.climate.copernicus.eu/#!/search?text=ERA5&type=dataset. The multiple large ensemble archive can be found at http://www.cesm.ucar.edu/projects/community-projects/MMLEA/. The CESM1-CAM5 single-forcing runs are accessible via the NCAR Climate Data Gateway. The CanESM2 aer runs are accessible from https://open.canada.ca/data/en/dataset/aa7b6823-fd1e-49ff-a6fb-68076a4a477c.

Acknowledgments
This work was supported by NSF grants OPP-1744835 and OPP-1643445.

References

Barbante, C., Barnola, J.-M., Becagli, S., Beer, J., Bigler, M., Boutron, C., et al. (2006). One-to-one coupling of glacial climate variability in Greenland and Antarctica. *Nature*, *444*, 195–198. https://doi.org/10.1038/nature05301

Blunier, T., Chappellaz, J., Schwander, J., Dallenbach, A., Stauffer, B., Stocker, T., et al. (1998). Asynchrony of Antarctic and Greenland climate change during the last glacial period. *Nature*, *394*, 739–743. https://doi.org/10.1038/29447

Broecker, W. (1998). Paleocean circulation during the last deglaciation: A bipolar seesaw? *Paleoceanography*, *13*, 119–121. https://doi.org/10.1029/97PA03707

Castruccio, F., Ruprich-Robert, Y., Yeager, S., Danabasoglu, G., Msadek, R., & Delworth, T. (2019). Modulation of Arctic sea ice loss by atmospheric teleconnections from Atlantic multidecadal variability. *Journal of Climate*, *32*, 1419–1441. https://doi.org/10.1175/JCLI-D-18-0307.1

Chylek, P., Folland, C., Lesins, G., & Dubey, M. (2010). Twentieth century bipolar seesaw of the Arctic and Antarctic surface air temperatures. *Geophysical Research Letters*, *37*, L08703. https://doi.org/10.1029/2010GL042793

Cowtan, K., & Way, R. (2014). Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. *Quarterly Journal of the Royal Meteorological Society*, *140*, 1935–1944. https://doi.org/10.1002/qj.2297

Deng, J., Dai, A., & Xu, H. (2020). Nonlinear climate responses to increasing CO_2 and anthropogenic aerosols simulated by CESM1. *Journal of Climate*, *33*, 281–301. https://doi.org/10.1175/JCLI-D-19-0195.1

Deser, C., Lehner, F., Rodgers, K., Ault, T., Delworth, T., DiNezio, P., et al. (2020). Insights from Earth system model initial-condition large ensembles and future prospects. *Nature Climate Change*, *10*, 277–286. https://doi.org/10.1038/s41558-020-0731-2

Deser, C., Phillips, A., Simpson, I., Rosenbloom, N., Coleman, D., Lehner, F., & Pendergrass, A. (2020). Isolating the evolving contributions of anthropogenic aerosols and greenhouse gases: A new CESM1 large ensemble community resource. *Journal of Climate*, *33*(18), 7835–7858.

Ding, Q., Schweiger, A., L'Heureux, M., Battisti, D., Po-Chedley, S., Johnson, N., et al. (2017). Influence of high-latitude atmospheric circulation changes on summertime Arctic sea ice. *Nature Climate Change*, *7*, 289–295. https://doi.org/10.1038/nclimate3241

Ding, Q., Schweiger, A., L'Heureux, M., Steig, E., Battisti, D., Johnson, N., et al. (2019). Fingerprints of internal drivers of Arctic sea ice loss in observations and model simulations. *Nature Geoscience*, *12*, 28–33. https://doi.org/10.1038/s41561-018-0256-8

England, M., Jahn, A., & Polvani, L. (2019). Non-uniform contribution of internal variability to recent Arctic sea ice loss. *Journal of Climate*, *32*, 4039–4053. https://doi.org/10.1175/JCLI-D-18-0864.1

ERA5. (2017). *Fifth generation of ECMWF atmospheric reanalyses of the global climate*. Retrieved from https://cds.climate.copernicus.eu/cdsapp#!/home

Fyfe, J., von Salzen, K., Gillett, N., Arora, V., Flato, G., & McConnell, J. (2013). One hundred years of Arctic surface temperature variation due to anthropogenic influence. *Scientific Reports*, *3*(2645), 1–2. https://doi.org/10.1038/srep02645

Gagne, M., Fyfe, J., Gillett, N., Polyakov, I., & Flato, G. (2017). Aerosol-drive increase in Arctic sea ice over the middle of the twentieth century. *Geophysical Research Letters*, *44*, 7338–7346. https://doi.org/10.1002/2016GL071941

Gettelman, A., Lin, L., Madeiros, B., & Olson, J. (2016). Climate feedback variance and the interaction of aerosol forcing and feedbacks. *Journal of Climate*, *29*, 6659–6675. https://doi.org/10.1175/JCLI-D-16-0151.1

GISTEMP. (2020). *Giss surface temperature analysis version 4*. Retrieved from data.giss.nasa.gov/gistemp/

Haustein, K., Otto, F., Venema, V., Jacobs, P., Cowtan, K., Hausfather, Z., et al. (2019). A limited role for unforced internal variability in twentieth century warming. *Journal of Climate*, *32*, 4893–4917. https://doi.org/10.1175/JCLI-D-18-0555.1

Henley, B., Gergis, J., Karoly, D., Power, S., Kennedy, J., & Folland, C. (2015). A tripole index for the interdecadal Pacific oscillation. *Climate Dynamics*, *45*, 3077–3090. https://doi.org/10.1007/s00382-015-2525-1

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., & Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*, 1999–2049. https://doi.org/10.1002/qj.3803

Holland, P., Bracegirdle, T., Dutrieux, P., Jenkins, A., & Steig, E. (2019). West Antarctic ice loss influenced by internal climate variability and anthropogenic forcing. *Nature Geoscience*, *12*, 718–724. https://doi.org/10.1038/s41561-019-0420-9

Jones, P., Lister, D., Osborn, T., Harpham, C., Salmon, M., & Morice, C. (2012). Hemispheric and large-scale land-surface air temperature variations: An extensive revision and an update to 2010. *Journal of Geophysical Research*, *117*, D05127. https://doi.org/10.1029/2011JD017139

Kay, J., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., et al. (2015). The Community Earth System Model (CESM) large ensemble project: A community resource for studying climate change in the presence of internal climate variability. *Bulletin of the Australian Mathematical Society*, *96*, 1333–1349. https://doi.org/10.1175/BAMS-D-13-00255.1

Kennedy, J., Rayner, N., Atkinson, C., & Killick, R. (2019). An ensemble data set of sea surface temperature change from 1850: The met office Hadley Centre HadSST.4.0.0.0 data set. *Journal of Geophysical Research: Atmospheres*, *124*, 7719–7763. https://doi.org/10.1029/2018JD029867

Lenssen, N., Schmidt, G., Hansen, J., Menne, M., Persin, A., Ruedy, R., & Zyss, D. (2019). Improvements in the GISTEMP uncertainty model. *Journal of Geophysical Research: Atmospheres*, *124*, 6307–6326. https://doi.org/10.1029/2018JD029522

Mantua, N., & Hare, S. (2002). The Pacific decadal oscillation. *Journal of Oceanography*, *58*, 35–44. https://doi.org/10.1023/A:1015820616384

Meehl, G., Arblaster, J., Bitz, C., Chung, C., & Teng, H. (2016). Antarctic sea-ice expansion between 2000 and 2014 driven by tropical Pacific decadal climate variability. *Nature Geoscience*, *9*, 590–595. https://doi.org/10.1038/ngeo2751

Meehl, G., Arblaster, J., Chung, C., Holland, M., DuVivier, A., Thompson, L., et al. (2019). Sustained ocean changes contributed to sudden Antarctic sea ice retreat in late 2016. *Nature Communications*, *10*(14), 1–9. https://doi.org/10.1038/s41467-018-07865-9

Notz, D., & Stroeve, J. (2016). Observed Arctic sea-ice loss directly follows anthropogenic CO_2 emission. *Science*, *11*, 747–750. https://doi.org/10.1126/science.aag2345

Okumura, Y., Schneider, D., Deser, C., & Wilson, R. (2012). Decadal–interdecadal climate variability over Antarctica and linkages to the tropics: Analysis of ice core, instrumental, and tropical proxy data. *Journal of Climate*, *25*, 7421–7441. https://doi.org/10.1175/JCLI-D-12-00050.1

Oudar, T., Kushner, P., Fyfe, J., & Sigmond, M. (2018). No impact of anthropogenic aerosols on early 21st century global temperature trends in a large initial-condition ensemble. *Geophysical Research Letters*, *45*, 9245–9252. https://doi.org/10.1029/2018GL078841

Phillips, A., Deser, C., Fasullo, J., Schneider, D., & Simpson, I. (2020). *Assessing climate variability and change in model large ensembles: A user's guide to the climate variability diagnostics package for large ensembles*. https://doi.org/10.5065/h7c7-f961

Polvani, L., Previdi, M., England, M., Chiodo, G., & Smith, K. (2020). Substantial twentieth-century Arctic warming caused be ozone depleting substances. *Nature Climate Change*, *10*, 130–133. https://doi.org/10.1038/s41558-019-0677-4

Post, E., Alley, R., Christensen, T., Macias-Fauria, M., Forbes, B., Goosseff, M., et al. (2019). The polar regions in a 2°C warmer world. *Science Advances*, *5*, eaaw9883. https://doi.org/10.1126/sciadv.aaw9883

Purich, A., England, M., Chikamoto, Y. W. C., Timmermann, A., Fyfe, J., Frankcombe, L., et al. (2016). Tropical Pacific SST drivers of recent Antarctic sea ice trends. *Journal of Climate*, *29*, 8931–8948. https://doi.org/10.1775/JCLI-D-16-0440.1

Schmithusen, H., Notholt, J., Konig-Langlo, G., Lemke, P., & Jung, T. (2015). How increasing CO_2 leads to an increased negative greenhouse effect in Antarctica. *Geophysical Research Letters*, *42*, 10422–10428. https://doi.org/10.1002/2015GL066749

Schneider, D., & Deser, C. (2018). Tropically driven and externally forced patterns of Antarctic sea ice change: reconciling observed and modeled trends. *Climate Dynamics*, *50*, 4599–4618. https://doi.org/10.1007/s00382-017-3893-5

Schneider, D., Okumura, Y., & Deser, C. (2012). Observed Antarctic interannual climate variability and tropical linkages. *Journal of Climate*, *25*, 4048–4066. https://doi.org/10.1175/JCLI-D-11-00273.1

Schneider, D., & Steig, E. (2008). Ice cores record significant 1940s Antarctic warmth related to tropical climate variability. *Proceedings of the National Academy of Sciences of the United States of America*, *105*, 12154–12158. https://doi.org/10.1073/pnas.0803627105

Shindell, D., & Schmidt, G. (2004). Southern Hemisphere climate response to ozone changes and greenhouse gas increases. *Geophysical Research Letters*, *31*, L18209. https://doi.org/10.1029/2004GL020724

Smith, K., Chiodo, G., Previdi, M., & Polvani, L. (2018). No surface cooling over Antarctic from the negative greenhouse effect associated with instantaneous quadrupling of CO_2 concentrations. *Journal of Climate*, *31*, 317–323. https://doi.org/10.1175/JCLI-D-17-0418.1

Thompson, D., Solomon, S., Kushner, P., England, M., Grise, K., & Karoly, D. (2011). Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change. *Nature Geoscience*, *4*, 741–749. https://doi.org/10.1038/ngeo1296

Tokinaga, H., Xie, S., & Mukougawa, H. (2017). Early 20th-century Arctic warming intensified by Pacific and Atlantic multidecadal variability. *Proceedings of the National Academy of Sciences of the United States of America*, *115*, 6227–6232. https://doi.org/10.1073/pnas.1615880114

Turner, J., Lu, H., White, I., King, J., Phillips, T., Hosking, J., et al. (2016). Absence of 21st century warming on Antarctic Peninsula consistent with natural variability. *Nature*, *535*, 411–415. https://doi.org/10.1038/nature18645

Yu, L., Zhong, S., Winkler, J., Zhou, M., Lenschow, D., Li, B., et al. (2017). Possible connections of the opposite trends in Arctic and Antarctic sea-ice cover. *Scientific Reports*, *7*, 45804. https://doi.org/10.1038/srep45804

Zhang, R. (2015). Mechanisms for low-frequency variability of summer Arctic sea ice extent. *Proceedings of the National Academy of Sciences of the United States of America*, *112*, 4570–4575. https://doi.org/10.1073/pnas.1422296112

References From the Supporting Information

Hazeleger, W., & Severijns, C. (2010). EC-Earth. *Bulletin of the Australian Mathematical Society*, *91*, 1357–1364. https://doi.org/10.1175/2010BAMS2877.1

Jeffrey, S., Rotstayn, L., Collier, M., Dravitzki, S., Hamalainen, C., Moeseneder, C., et al. (2013). Australia's CMIP5 submission using the CSIRO-Mk3.6 model. *Australian Meteorological and Oceanographic Journal*, *63*, 1–13. https://doi.org/10.22499/2.6301.001

Kirchmeier-Young, M., Zwiers, F., & Gillett, N. (2017). Attribution of extreme events in Arctic sea ice extent. *Journal of Climate*, *30*, 553–571. https://doi.org/10.1175/JCLI-D-16-0412.1

Maher, N., & Milinski, S. (2019). The Max Planck Institute Grand Ensemble: Enabling the exploration of climate system variability. *Journal of Advances in Modeling Earth Systems*, *11*, 2050–2069. https://doi.org/10.1029/2019MS001639

Rodgers, K., Lin, J., & Frolicher, T. (2015). Emergence of multiple ocean ecosystem drivers in a large ensemble suite with an Earth system model. *Biogeosciences*, *12*, 3301–3320. https://doi.org/10.5194/bg-12-3301-2015

Sun, L., Alexander, M., & Deser, C. (2018). Evolution of the global coupled climate response to Arctic sea ice loss during 1990–2090 and its contribution to climate change. *Journal of Climate*, *31*, 7823–7843. https://doi.org/10.1175/JCLI-D-18-0134.1