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Key Points:
- Both model and proxies show a dominant millennial cooling in the Arctic, with greater cooling rates in the Atlantic sector than in the Pacific sector
- Data-model comparison indicates that irregular sampling in the temporal domain could limit the use of the proxies for diagnosing cooling patterns
- The asymmetric cooling is dynamically supported by a weakened North Atlantic subpolar gyre circulation and a stronger Aleutian Low

Supporting Information:
- Supporting Information S1

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Asymmetric Cooling of the Atlantic and Pacific Arctic During the Past Two Millennia: A Dual Observation-Modeling Study

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Abstract The past 2,000 years provide a critical context for understanding twentieth century climate change. Due to the Past Global Changes 2k initiative, an extensive proxy database provides opportunities to assess regional climate change that have stronger ecological and societal implications than global-mean temperature changes alone. However, the various sources of paleoclimate reconstruction poses serious challenges to scientifically and statistically sound inference within a unified framework. Here we show results from the first transient simulation for the past 2,000 years with the Community Earth System Model, called past2k, and use data-model comparison to refine the interpretation of the proxy data. Our results indicate that the Atlantic Arctic was cooling at a faster rate than the Pacific Arctic over the past two millennia, in both proxy data and models. The model shows that this cooling pattern was dynamically supported by both a weakening of North Atlantic subpolar gyre and a stronger Aleutian Low.

Plain Language Summary The Arctic has become a focus for climate change studies due to the rapid Arctic changes we have already observed and their potential impacts on midlatitude weather and the North Atlantic Ocean circulation. In this study, we use a dual observation-modeling approach to elucidate the spatial pattern of Arctic cooling in the last 2,000 years and to improve the understanding of the physical mechanisms underlying this pattern. Our results indicate that greater cooling in the North Atlantic Arctic relative to the North Pacific Arctic is caused by a weakening of the northward transport of heat by Atlantic surface currents, and a strengthening of the Aleutian Low, with little or no change due to differences in reflectivity related to snow and sea ice coverage between those regions.

1. Introduction

Temperature reconstructions for the past 2,000 years from the Past Global Changes 2k (PAGES2k) Network highlight a millennial cooling trend that was reversed by twentieth century warming everywhere except Antarctica (McGregor, 2018; PAGES2k Consortium, 2013). Compared to global-mean trends, regional expressions of cooling and warming trends are deemed more relevant to ecosystems and societies. In particular, awareness of polar amplification (Serreze & Francis, 2006) and the theoretical pathways by which changing surface conditions at high northern latitudes impact midlatitude weather (Cohen et al., 2014) has made the Arctic one of the top priorities in the research of past and future climate changes. Recent reconstructions of cryosphere expansions reveal substantial snowline depression in the northern North Atlantic region (Anderson et al., 2008; Miller et al., 2012; Miller, Briner, et al., 2013; Miller, Lehman, et al., 2013) and only small changes in snowline in northern Alaska through the late Holocene (Badding et al., 2013; Pendleton et al., 2015). While affirming the pervasive cooling identified by both Arctic-wide (Kaufman et al., 2009; McKay & Kaufman, 2014) and subregional (Clegg et al., 2011; Geirsdottir et al., 2013; Miller et al., 2017) syntheses of proxy temperature records, these cryosphere reconstructions illustrate an asymmetric cooling of the Atlantic and Pacific Arctic. The cause of this differential cooling, however, has remained an open question.

Arctic cooling over the past two millennia (1 to 1850 CE) is linked in part to the decline in summer insolation caused by changes in the Earth's orbit around the Sun (Kaufman et al., 2009). However, the insolation decline is hemispherically symmetric and therefore cannot explain the observed pattern of asymmetric snowline lowering. The volcanic eruptions repeated on a decadal scale in the first millennium (Figure S1b in the supporting information) potentially contributed to the cooling, while strong volcanism is known as the primary mechanism behind the cooling into the Little Ice Age (LIA; Lehner et al., 2013; Zhong et al., 2010). However, the volcanic forcing is also generally hemispherically symmetric in the high latitudes. In contrast to the Pacific Arctic, important drivers of the Atlantic Arctic climate are sea ice changes and effects of the Atlantic Meridional Overturning Circulation (AMOC), subpolar gyre circulation, and North Atlantic Oscillation (NAO). Previous model studies have shown that sea ice expansion in response to the sequence of decadal-spaced volcanic eruptions during the late thirteenth century suppressed deep water formation in the northern North Atlantic, resulting in a weakened AMOC (Slawinska & Robock, 2018; Zhong et al., 2010). In turn, the weakened AMOC transported less heat poleward, which intensified and helped perpetuate the volcanic cooling and sea ice expansion (Zhong et al., 2010), thereby initiating and amplifying the cooling of the LIA (Lehner et al., 2013; Miller et al., 2012). However, as other studies have shown, this feedback loop could be sensitive to the mean distribution of sea ice (Sevellec et al., 2017; Zhong et al., 2010) and affected by air-sea interactions (Suo et al., 2017; Zhu et al., 2015). In another model study, a weakening subpolar gyre was found to be capable of triggering LIA-type episodes in absence of a weakened AMOC or shifts in NAO (Moreno-Chamarro et al., 2017). Proxy data indicates that a shift to weaker NAO conditions was responsible for the cooling into the LIA (Trouet et al., 2009).

Motivated by the observed pattern of snowline lowering between the Pacific and Atlantic sector (CAPE Project Members, 2001), we here address the questions of whether rates of change in the Arctic surface air temperature (SAT) differed between the Atlantic and Pacific sectors, and whether changes in sea ice and atmospheric and oceanic circulations contributed to the surface cooling and the distinct snowline depression in the North Atlantic realm. To address these questions, we performed the first transient simulation for the past 2,000 years with the Community Earth System Model version 1 (CESM; Hurrell et al., 2013), called past2k. This simulation allows us to assess the spatial pattern of the millennial Arctic cooling and unravel the physical processes underlying this spatial pattern. We also evaluate the utility of PAGES2k proxies in capturing this spatial pattern with data-model comparison.

2. Past2k Simulation

Transient simulations for the past 2,000 years have been proposed for the Paleoclimate Model Intercomparison Phase 4 (PMIP4) contribution to the Coupled Model Intercomparison Project Phase 6 (Jungclaus et al., 2017). We here use the CESM1 at 1° resolution in the ocean and the sea ice and 2° resolution in the atmosphere, the same configuration used for the CESM Last Millennium Ensemble (LME; Otto-Bliesner et al., 2016). There is no coupled land ice model in this configuration. The forcing data for this period have been compiled by the PMIP4 (Jungclaus et al., 2017), including changes in solar irradiance, volcanic aerosols (Toohey et al., 2016), land use and land cover (Goldewijk et al., 2010), and greenhouse gas levels (MacFarling Meure et al., 2006). A comparison with the forcing data used for the CESM LME indicates that the past2k has slightly greater solar irradiance for the period from 850 to 1850 CE (+0.18 W/m^2), lower solar irradiance for the period from 1850 to 2005 CE (−0.14 W/m^2), and much smaller volcanic aerosol loading for major eruptions (e.g., ~0.5 times for Samalas 1258 CE and Tambora 1812 CE; Figures S1a and S1b). Yet for the past 1,000 years, the climate of the past2k simulation lies largely within the range of the 13 members of the LME, despite the different forcing data (Figures S1c and S1d).

The past2k simulation successfully reproduces the proxy-based Arctic-wide cooling from 1 to 1900 CE and the following sharp rise in temperature (Figure S1c). In addition to the millennial cooling, the past2k faithfully delineates centennial-scale fluctuations such as the warm Medieval episode from 950 to 1250 CE and the LIA from 1300 to 1850 CE, as well as abrupt cooling in response to major explosive eruptions. In contrast, the Northern Hemisphere sea ice in the past2k is dominated by the millennial cooling trend, with some indication of centennial-scale fluctuations (Figure S1d).

The millennial cooling is highly heterogeneous across the Arctic (poleward of 60°N) based on the two-millennium difference as a surrogate of the first-order trend (Pendleton et al., 2017). The greatest cooling rates occur in the Canadian Archipelago during summer (June-July-August) and in adjacent seas and the southern tip of Greenland during winter (December-January-February; Figure 1), with a general cooling during both seasons in the central Arctic Ocean. However, in the North Pacific in winter and in the Greenland, Iceland, and Norwegian Seas in both seasons, there is an increase in SAT between the two millennia, although the magnitude is statistically insignificant. In areal averages, the terrestrial Atlantic

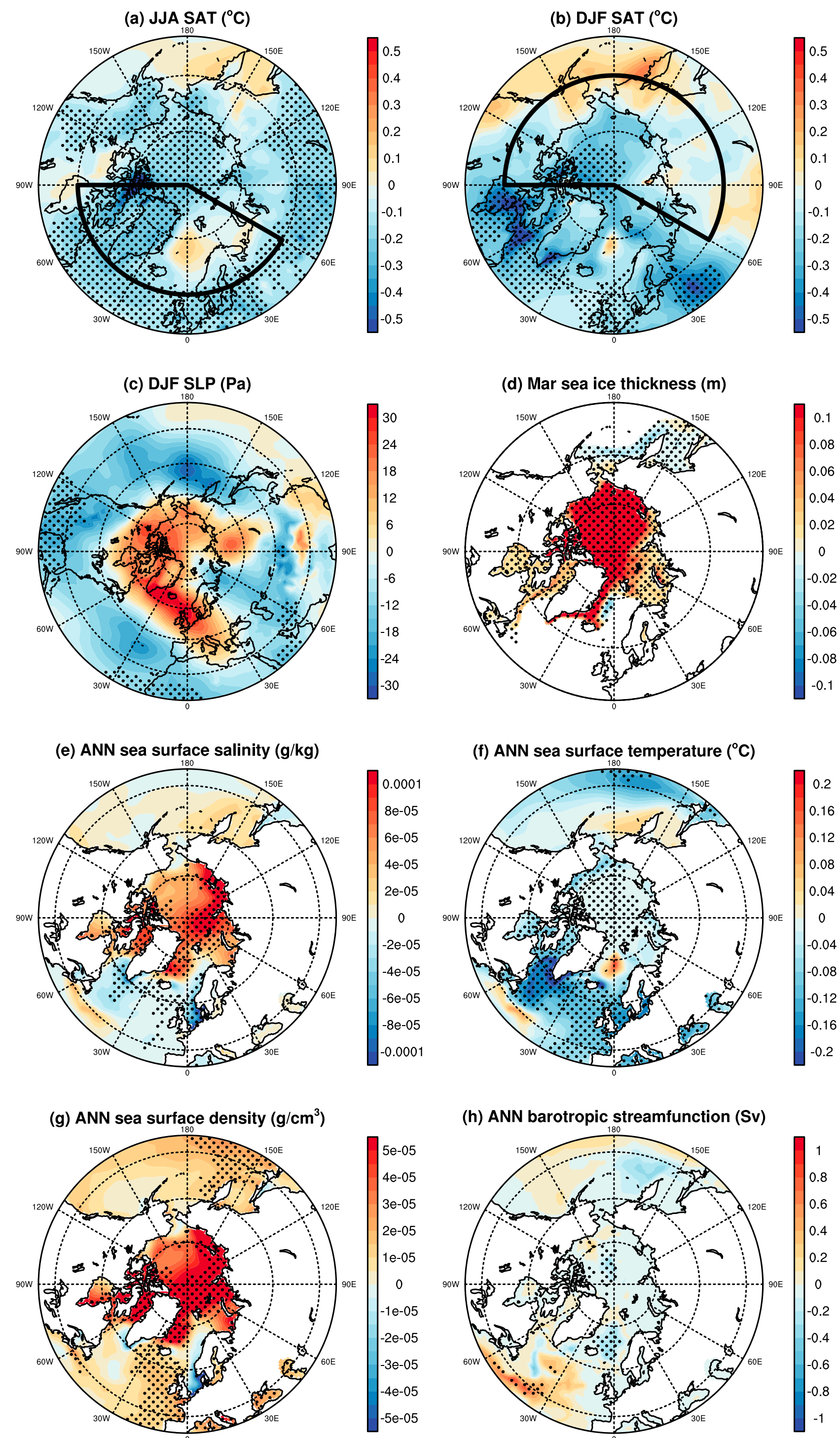

Figure 1. Modeled change in (a) JJA surface air temperature (SAT; °C), (b) DJF SAT, (c) DJF sea level pressure (SLP; Pa), (d) March sea ice thickness (m), (e) annual sea surface salinity, (f) annual sea surface temperature, (g) annual sea surface density (g/cm^3), and (h) annual barotropic stream function (Sv) from 1–1000 to 1000–1850 CE. Stippling indicates significant change at $p = 0.05$ according to two-tailed t test. The Atlantic Arctic and the Pacific Arctic are outlined with thick black lines in (a) and (b), respectively. JJA = June-July-August; DJF = December-January-February.

Arctic has a cooling rate of 0.18 to 0.20 °C between the two millennia, considerably larger than the 0.04 to 0.12 °C of the terrestrial Pacific Arctic (Figure 2). When ocean areas are included, the accelerated cooling of Atlantic Arctic compared with the Pacific Arctic is found in winter but not in summer.

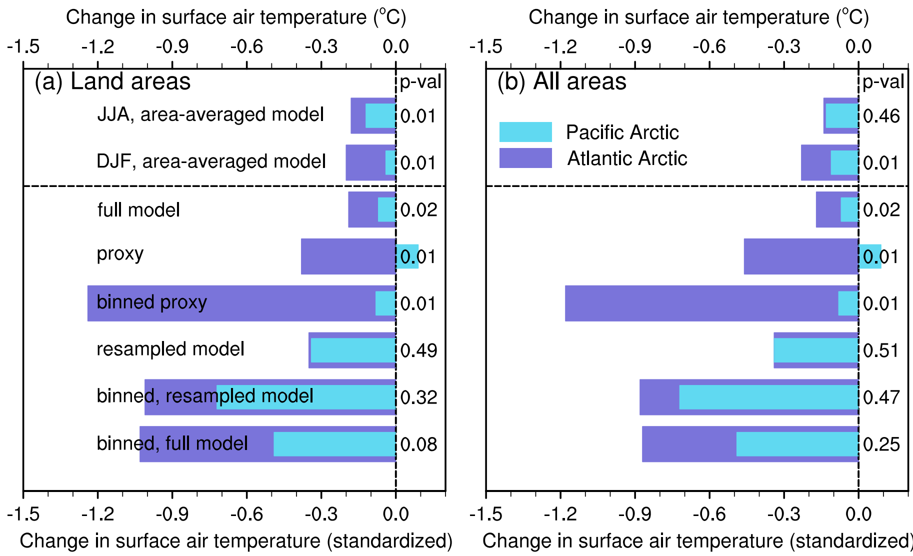

Figure 2. A comparison of the surface air temperature change for 1–1000 to 1000–1850 CE between the Atlantic Arctic (90°W to 60°E, 60–90°N; dark blue) and the Pacific Arctic (60°E to 90°W, 60–90°N; light blue) for (a) land areas only and (b) all areas. The eight bars, from top to bottom, represent (1) area-averaged temperature change (°C) for model simulation during June-July-August (JJA) and (2) December-January-February (DJF), (3) temperature change (standardized relative to the mean and standard deviation of the interval from 1500 to 1900 CE) averaged across a selection of Arctic sites from Past Global Changes 2k's 2017 version based on the full model data for proxy-represented seasons, (4) averaged temperature change (standardized) based on the selected proxy data and (5) 50-year bins of the proxy data, (6) resampled model data, (7) 50-year bins of the resampled model data, and (8) 50-year binned full model data for proxy-represented seasons. The statistical significance level (*p* value) is indicated for each bar, showing whether the temperature decrease across the Atlantic Arctic is greater than that across the Pacific Arctic, determined by one-tailed *t* test for the area-averaged change from the model simulation, and by Mann-Whitney *U* test for all the temperature changes averaged across the Arctic sites. More details on the calculation of temperature change can be found in the supporting information. Similar results are obtained when defining the Atlantic Arctic as 90°W to 90°E, 60–90°N or 90°W to 30°E, 60–90°N, and the Pacific Arctic as the remainder of the Arctic.

3. Data-Model Comparison

To assess whether this asymmetric cooling of the Atlantic and Pacific Arctic is also evident in proxy temperature records, we analyze the PAGES2k database, which has a focus on the SAT in the past 2,000 years and includes all publicly available records with sufficient data quality. The PAGES2k database was updated in 2017, and the 2017 version differs substantially from the 2013 version due to the addition of new records and the exclusion or re-generation of old records based on more stringent selection criteria (PAGES2k Consortium 2017). In our assessment of the PAGES2k SAT change between the two millennia, a total of 29 records (23 from land) in the 2017 version meet the criterion that each record spans over 80% of the time between 1 and 1000 CE and also between 1000 and 1850 CE (Figure S2). The records have various units and temporal resolution due to the diverse proxy sources. Tree ring records are annually resolved and precisely dated, whereas records from ice cores, lake and marine sediments, speleothems, and historical documents are nonannually resolved, unevenly spaced, and each integrates climate signals differently. To make the PAGES2k proxies comparable between themselves, each record is first standardized (relative to the mean and standard deviation of the interval from 1500 to 1900 CE) with the directionality of the proxy interpretation for temperature incorporated, following the practice typical for Composite Plus Scale reconstruction of regional-to-global temperatures (Mann et al., 2005).

The averaged change rates across the 24 proxies in the Atlantic Arctic and across the 5 proxies in the Pacific Arctic are −0.46 and + 0.09 standard deviation, respectively (Figure 3a). A Mann-Whitney *U* test applied to the two arrays of SAT change rates indicates that the Atlantic Arctic cooling is stronger than the Pacific Arctic at $p = 0.01$ (Figure 2). Since variability in temperature usually decreases with time scales, standardization of the proxy records would inflate the temperature change rates for those records with low resolutions. Moreover, given the well-known cooling into the LIA, the increased sampling after 1400 CE for some of the proxies

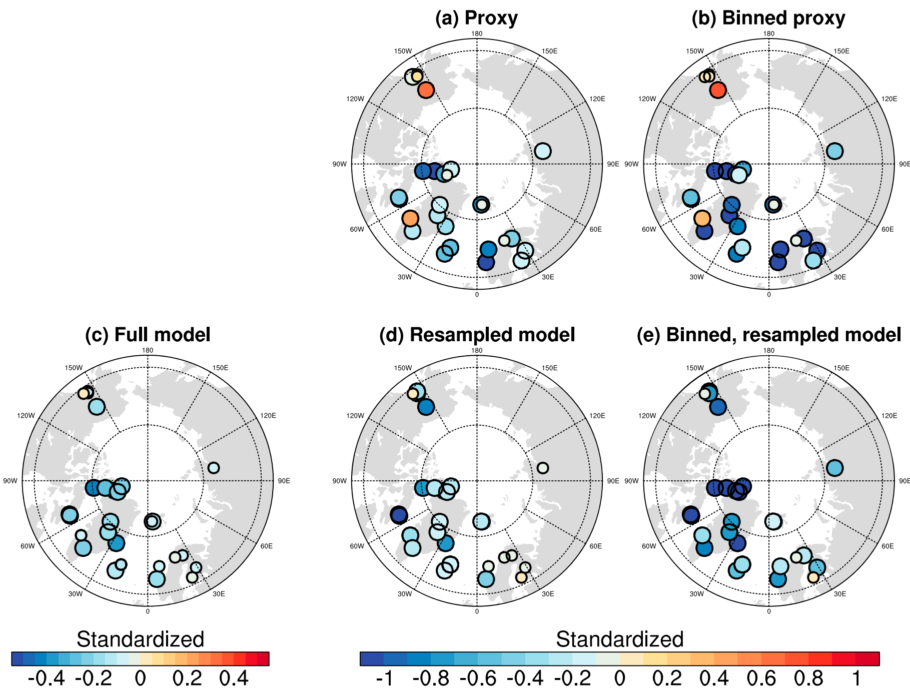

Figure 3. Change in surface air temperature (standardized) from 1–1000 to 1000–1850 CE for proxy-represented seasons at Arctic sites from PAGES2k 2017 version according to (a) PAGES2k proxies, (b) 50-year bins of the proxies, (c) full model data, (d) resampled model data, and (e) 50-year bins of the resampled model data. Large circles indicate significant changes at $p = 0.05$ according to two-tailed t test, and small circles indicate insignificant changes. A list of the proxy sites and more details on the calculation of these changes can be found in the supporting information. PAGES2k = Past Global Changes 2k.

(Figure S2) would result in a cold bias in estimates of the millennial average over 1000–1850 CE. To mitigate the impact of the variable resolutions, all proxy records are averaged into 50-year bins before calculating the millennial averages. The change rates based on the 50-year binned data are −1.18 and +0.08 standard deviation in the Atlantic and Pacific Arctic, respectively (Figure 3b). These cooling rates suggests that the accelerated cooling of the Atlantic Arctic relative to the Pacific Arctic is a robust feature in the 2017 version of PAGES2k database.

To examine how irregular proxy sampling in the temporal and spatial domains might affect the depiction of the millennial cooling, we emulate the proxy sampling procedures with the SAT data from the past2k simulation. Considering the highly heterogeneous cooling across the Arctic, irregular sampling in space could bias the comparison of the Atlantic versus Pacific Arctic cooling. As a first test, the SAT data are extracted for the grids representing the 29 proxy sites from PAGES2k 2017 version and for the proxy-represented seasons that differ by proxy site (Table S1). The extracted data cover all years of 1–1850 CE. As for the proxy data, this extracted model data are standardized relative to the mean and standard deviation of the interval from 1500 to 1900 CE and then used to calculate the SAT change between the two millennia. The result shows that the millennia cooling across the Atlantic Arctic sites is significantly stronger than the cooling across the Pacific Arctic sites ($p = 0.02$, Figure 2). Using proxy sites over land only leads to similar results (Figure 3c). It follows that the irregular sampling in space does not alter the model expression of the asymmetric cooling between the Atlantic and Pacific Arctic.

For the second test, we resample the extracted model data in the temporal domain to assess the effect of the sampling on the millennial cooling rates. The yearly SAT data extracted for each of the 29 Arctic sites from the PAGES2k 2017 version and the corresponding season are smoothed with the mean resolution of the proxy data and are then resampled at the sampling times of the proxy data. These resampled data are likewise standardized before calculation of the SAT change (see supporting information for more details on calculation of SAT change at proxy sites). This resampling inflates the cooling rates from the full model data for the sites with low proxy resolution (Figure 2), yielding overall similar cooling rates in the Atlantic Arctic and in the Pacific Arctic (Figure 3d). The resampling in the temporal domain masks the stronger cooling evident in the full model data for the Atlantic Arctic, partially due to the greater inflation of cooling rates in the Pacific Arctic associated with the overall lower resolutions in the Pacific Arctic relative to the Atlantic Arctic (Figure S3a).

Averaging the resampled model data into 50-year bins mitigates the impact of the variable temporal resolutions of the proxies, so that the inflation of the cooling rates between the full model data and the binned, resampled data exhibits little linear dependence on resolution (Figure S3b). However, binning the resampled data over 50 years fails to uncover the stronger cooling in the Atlantic Arctic, with $p = 0.47$ for the Mann-Whitney *U* test. It appears that the inflation of the cooling rates depends positively on the magnitude of the cooling rates and tends to be greater for the sites in the Pacific Arctic than for those in the Atlantic Arctic exhibiting similar cooling rates in the full model data (Figure S3c). This is also true for the comparison between 50-year bins of the full model data and the full model data (Figure S3d), as binning the full model data incurs incongruous inflation of the cooling rates between the Atlantic and Pacific sectors of the Arctic as signified by $p = 0.25$ for the Mann-Whitney *U* test (Figure 2b). This undesirable incongruous inflation could be a random outcome due to insufficient sites on the Pacific side. The long spells of missing values before the LIA for the sites in the Pacific Arctic aggravate the problem of incongruous inflation of the cooling rates (Figure S3c vs. S3d). Given a general cooling trend through the two millennia, the sparse sampling before the LIA would cause a cold bias in estimates of the millennial average over 1000–1850 CE, and, therefore, an overestimation of the cooling rates between the two millennia. This alludes to the issue of irregular temporal sampling, which is especially important when individual records are relied on to characterize regional expressions of climate changes. The result is similar if only land-based sites are used.

4. Roles of Thermodynamic Versus Dynamic Processes

The Arctic-wide cooling of the past 2 ka is thought to be driven by insolation and enhanced by positive feedbacks related to changes in terrestrial snow cover, sea ice, and land cover (Kaufman et al., 2009). In particular, as the Arctic surface cools, changes in the surface albedo cause more reflection of shortwave radiation to space, leading to additional cooling. To assess whether the surface albedo feedback can explain the differential cooling between the Atlantic and Pacific Arctic, we separately calculate the surface albedo feedback based on the conventional definition (Winton, 2006) for the Atlantic and Pacific sectors of the Arctic. Theoretically, the radiative sensitivity to changes in sea ice could boost the cooling in the Atlantic Arctic relative to the Pacific Arctic, due to larger sea ice variability in the Atlantic sector (Hanhijarvi et al., 2013). However, in the past2k simulation, the surface albedo feedback is found to be slightly stronger in the Pacific Arctic than in the Atlantic Arctic, both during summer and in the annual mean. Other top feedbacks supporting Arctic amplification (Pithan & Mauritsen, 2014; Taylor et al., 2013) cannot explain the amplification of cooling in the Atlantic Arctic compared to the Pacific Arctic either (see discussion in the supporting information).

As none of the possible thermodynamic factors are able to explain the amplification of cooling in the Atlantic Arctic, we now turn to dynamical drivers. We find that associated with the general Arctic cooling between the two millennia, the cryosphere expanded in the central Arctic and northern North Atlantic (Figure 1d), resulting in increased sea ice export through the Fram Strait (by 3.3%) and the Labrador Sea. As more sea ice melted in the northern North Atlantic, the surface water salinity decreased, primarily in the western portion of the subpolar North Atlantic (Figure 1e). This freshening counteracted the impact of the millennial cooling on surface water density. As a result, the increase in surface water density due to the millennial cooling is smaller in the western portion of the subpolar North Atlantic than in the eastern portion (Figure 1g). It indicates a slowdown of the subpolar gyre circulation (Moreno-Chamarro et al., 2017), as depicted by positive anomalies in sea surface height and barotropic stream function across the subpolar North Atlantic (Figure 1h). This slowdown of subpolar gyre acts to reduce the heat advection in the northern North Atlantic, intensifying the cooling near the surface. This extra cooling may be extended poleward through reduced heat flux from the ocean to the lower atmosphere, decreasing the poleward heat transport by near-surface winds. The simulated AMOC shows a ~1-Sv increase in overall strength between the two millennia, disfavoring the cooling of the Atlantic Arctic. These results point to the important role of the subpolar gyre and its interactions with the Arctic, in agreement with recent model studies (Lehner et al., 2013; Moreno-Chamarro et al., 2017; Nummelin et al., 2016).

On the Pacific side, the Aleutian Low strengthens (Figure 1c), promoting warmer winters around the Bering Sea (Figure 1b) as storm systems preferentially pump warm air poleward (Niebauer et al., 1999; Rodionov et al., 2005; Stabeno et al., 2001). This strengthening of the Aleutian Low could be a result of the enhanced temperature contrast between the tropics and the Arctic that is associated with Arctic amplification of the millennia cooling (Figure S4), since the low tends to be associated with large-scale upper-level planetary waves and derives energy from the lower tropospheric temperature gradient (Pickart & Macdonald, 2009).

In conclusion, the asymmetric cooling between the Atlantic and Pacific Arctic is dynamically supported by a weakening of North Atlantic subpolar gyre circulation and an intensification of the Aleutian Low, which collectively amplify Atlantic Arctic cooling and reduce Pacific Arctic cooling resulting from the summer insolation decline over the past two millennia. Thermodynamic factors act in the opposite way and hence are not the cause for the observed asymmetric cooling.

5. Discussion and Conclusions

In response to the need for a long-term perspective on climate change, the PAGES2k Network compiled existing proxy data and generated new climate reconstructions for the last 2,000 years (PAGES 2 k Consortium 2017). The expanding database provides opportunities to improve the interpretation of site-specific paleoclimate reconstructions. However, the various sources of paleoclimate reconstructions poses serious challenges to a statistically sound inference within a unified framework (Tingley et al., 2012). Of the several existing methods for climate reconstructions from multiple proxy sources, only two can handle proxy records of variable resolution and do not require standardization of the proxy records to a common scale before reconstruction (Hanhijarvi et al., 2013; Li et al., 2010). However, these advantages come at a cost of losing information about the magnitude of change in a proxy record or being computationally intensive. As an alternative, we use a data-model comparison to assist in the interpretation of the proxy observations and offer insights into the limitation of the PAGES2k temperature records for diagnosing patterns of Arctic cooling.

The CESM past2k is the first transient simulation for the past 2,000 years, with forcing data from the PMIP4 compilation. It produces a 0.14–0.23 °C change in SAT between the two millennia for the Atlantic Arctic, that is, a cooling trend of 0.14–0.23 °C/1,000 years. This is qualitatively similar to the 0.22 °C estimate for circum-Arctic (Kaufman et al., 2009) and the 0.36 °C estimate for the Atlantic Arctic (Hanhijarvi et al., 2013) based on proxy data. The simulated greater cooling in the Atlantic Arctic than in the Pacific Arctic is in accordance with the finding of Hanhijarvi et al. (2013) that the millennial cooling was stronger in the North Atlantic region than Arctic as a whole and the asynchronous snowline/summer temperature change records from the Atlantic and Pacific Arctic (CAPE Project Members, 2001).

With the past2k simulation we were able to gain a deeper understanding of the physical mechanisms responsible for the observed asymmetric Arctic cooling. The altered surface heat and freshwater fluxes associated with sea ice expansion caused the subpolar gyre circulation to slow down, resulting in additional cooling of the Atlantic Arctic. This agrees with the finding of Moreno-Chamarro et al. (2017) that a weakening subpolar gyre was responsible for the transition from the relatively warm medieval climate to the cold LIA and that this transition was not associated with a weakening AMOC. In the Pacific realm, a stronger Aleutian Low during the second millennium led to warmer-than-normal winters in the Bering Sea, counteracting the general cooling trend. The stronger Aleutian Low could result from the enhanced temperature contrast between the tropics and the Arctic that is associated with Arctic amplification of the millennial cooling. The surface albedo feedback related to changes in terrestrial snow, sea ice, and land cover is slightly stronger for the Pacific Arctic than the Atlantic Arctic and hence does not contribute to the observed asymmetric cooling.

Irregular sampling in temporal domain and insufficient sampling in spatial domain could limit the use of the proxies for diagnosing cooling patterns, as emulation of the sampling procedures with model data failed to uncover the asymmetric cooling of the Arctic as captured by the full model data. It calls on increased data coverage in both temporal and spatial domains, in particular, for the period before the LIA and for the Pacific Arctic. Given the current PAGES2k database, a potential way to increase the data coverage is to fill in the missing values using covarying information among the records. For data-model comparison, large model fields should be included as best representing the truth of the model simulation. Resampling model data can demonstrate the robustness of results and provide insights into comparisons with proxy data.

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