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Key Points:
- Simulated impacts of the NAO on the interannual variability of precipitation in summer in eastern China are investigated
- The model CCSM 2.0.1 was able to roughly produce the general features of the teleconnection climate influences in eastern China
- Precipitation anomalies in eastern China associated with the summer NAO are linked to the "North Atlantic-Eurasian teleconnection pattern"

Supporting Information:
- Supporting Information S1

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Simulated Interannual Teleconnection Between the Summer North Atlantic Oscillation and Summer Precipitation in Eastern China During the Last Millennium

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Abstract The interannual teleconnections between the summer North Atlantic Oscillation and summer precipitation in eastern China over the last millennium are investigated in a 1,000-year simulation by the global climate model Community Climate System Model version 2.0.1. The model was able to roughly produce the general features of the teleconnection influences in eastern China, with negative (positive) precipitation anomalies north of 30°N and positive (negative) precipitation anomalies south of 30°N, associated with the positive (negative) phase of the North Atlantic Oscillation. The composite analysis reveals that the influence of the North Atlantic Oscillation on precipitation in summer in eastern China is chiefly via the "North Atlantic-Eurasian teleconnection pattern," which extends from the subtropical North Atlantic to East Asia.

Plain Language Summary The impacts of the North Atlantic Oscillation on the climate in eastern China have been highlighted over the last decade. Recently, the observed impacts of the North Atlantic Oscillation on precipitation in eastern China in summer, chiefly via the "North Atlantic-Eurasian teleconnection pattern," have been noted. This pattern propagates along a high-latitude pathway and is different from the midlatitude circumglobal teleconnection pattern. Here this teleconnection pattern is investigated in a millennium context using a 1,000-year simulation of the Community Climate System Model version 2.0.1. The model results reveal that the simulated NAO-related teleconnection pattern during the summer season is very similar to the observed pattern. Along its path through Eurasia, a positive NAO index causes anomalously high sea level pressures and 500-hPa geopotential heights over Mongolia-north China that correspond to the anomalous anticyclone in the 850-hPa wind anomalies and hence cause reduced precipitation in north China. The opposite occurs during negative summer NAO phases. The model's teleconnection patterns of the summer NAO capture the reconstructed and observed patterns of the summer precipitation changes in eastern China and provide further evidence for the climate model-based implications for predictions and future projections of seasonal precipitation in eastern China.

1. Introduction

The North Atlantic Oscillation (NAO) is a primary mode of internal dynamics in the atmosphere and is characterized by the difference in sea level pressure (SLP) between the Azores high and Icelandic low (Hurrell, 1995). The NAO governs large changes in surface temperature, precipitation, cloudiness, etc., around the North Atlantic region (Hurrell et al., 2003). However, the NAO also has a downstream climate influence over remote regions via the NAO-related downstream wave train. For example, remote influences of the NAO on the interannual variability in summer precipitation in eastern China have been explored to some extent. Early studies on this subject have focused on the influence of the winter or spring NAO (Bollasina & Messori, 2018; Fu & Zeng, 2005; Gu et al., 2009; Sung et al., 2006; Tian & Fan, 2012; Wu et al., 2009, 2012; Yang et al., 2004; Zheng et al., 2016; Zuo et al., 2012) and have suggested that their influence on East Asian summer precipitation is chiefly via the subtropical Asian jet waveguide-trapped wave train (e.g., Bollasina & Messori, 2018; Sung et al., 2006). Recently, a high-latitude remote climatic teleconnection in summer in eastern China from the North Atlantic Ocean has garnered considerable attention. Wu et al. (2009, 2012) and Zuo et al. (2012) investigated the influences of the spring NAO on the East Asian summer monsoon. They found that spring NAO can trigger a tripole pattern of sea surface temperature anomalies (SSTAs) in the North Atlantic Ocean. The tripole SSTA pattern can persist into the following summer and excite a remote teleconnection over northern Eurasia. This teleconnection pattern, which originates in the subtropical North Atlantic, is different from the pattern with the Asian jet waveguide path and was first termed the "North Atlantic-Eurasian teleconnection pattern" by Li and Ruan (2018). The summer NAO variation has been shown to influence large-scale summer precipitation anomalies over East Asia via this teleconnection pattern (Bollasina & Messori, 2018; Folland et al., 2009; Linderholm et al., 2011, 2013; Liu & Yin, 2001; Zheng et al., 2016). Significant negative correlations between the teleconnection pattern index and summer precipitation were found in northern China. However, most of these previous studies have focused on interannual teleconnections between the NAO and precipitation in summer over eastern China during the instrumental period, with relatively less emphasis on this topic beyond the era of instrumental measurements.

An increasing number of high-resolution proxy records and global climate model simulations covering the last millennium make it possible to obtain more insight into this teleconnection on long, century-length time scales. Several studies using tree ring records extended summer NAO-related hydroclimate changes in eastern China several centuries back in time (Folland et al., 2009; Linderholm et al., 2013; Linderholm & Folland, 2017). These studies suggested that the influence of the teleconnection pattern related to the summer NAO on precipitation in eastern China could also be found in the climate change beyond the instrumental period (Folland et al., 2009; Linderholm et al., 2013). However, few studies have focused on determining whether the model is simulating the interannual teleconnections between the summer NAO and summer precipitation in eastern China as revealed by the observations and reconstructions. The objective of this study is to examine the relationship between the summer NAO and eastern China's summer precipitation during the last millennium based on model data from a 1,000-year global climate model simulation.

2. Data and Methods

To investigate the regional summer precipitation changes in eastern China associated with the summer NAO, we analyzed a 1,000-year (1,000–1,999) simulation performed by the Community Climate System Model (CCSM, version 2.0.1). The CCSM was developed by the National Center for Atmospheric Research (NCAR; Kiehl & Gent, 2004). The main forcings driving the model include global and seasonal changes in orbital insolation (Berger, 1978), solar variations and volcanic eruptions (Crowley et al., 2003), and greenhouse gases (Ammann et al., 2007). A model-observation comparison shows that the model effectively simulates the zonal gradient of summer precipitation over East Asia, which is very similar to the observed pattern (Shen et al., 2009). A model-proxy comparison shows the simulation produces a temporal variability similar to that observed in proxy data in eastern China during the last millennium (Peng et al., 2009, 2014). The modeled summer NAO index (NAOI; shown in Figure S1) was defined as the June-July-August mean of the difference between normalized SLP anomalies over two boxes in the North Atlantic, a low-latitude/high-pressure box located between 20°N–40°N and 70°W–10°W and a high-latitude/low-pressure box located between 45°N–65°N and 50°W–10°E (Lorenz et al., 2006). The definition of the NAOI here is based on the permanent action centers of the Azores high and Icelandic low because the two boxes are located at the same latitudes as the Azores high and Icelandic low, respectively, as suggested by the observation (Hameed & Piontkovski, 2004). Through a systematic comparison of the NAO indices, Pokorná and Huth (2015) suggested that both the central-based NAO indices and the principal component analysis-based NAO indices are equally physically plausible. However, the action centers of high covariability defined by the principal component analysis show a northward migration from the Azores high and Icelandic low in summer (Pokorná & Huth, 2015).

To further investigate whether the characteristics of the interannual teleconnection between the NAO and precipitation in summer in eastern China revealed by CCSM2.0.1 are robust across multiple model experiments, monthly mean precipitation flux data from the past 1,000 simulations of the Coupled Model Intercomparison Project phase 5 (CMIP5) and the Paleoclimate Model Intercomparison Project phase 3 (PMIP3) are also used here. Atmosphere-ocean general circulation models from the CMIP5/PMIP3 used in our study include CCSM4, CSIRO-Mk3L-1-2 (CSIRO), MPI-ESM-P (MPI), and HadCM3.

Additionally, the availability of the tree ring-based Monsoon Asia Drought Atlas (MADA; Cook et al., 2010) and a reconstructed NAOI developed by Ortega et al. (2015) are used here to explore remote influences from the NAO on the interannual variability in summer precipitation in eastern China during the last millennium. The data underlying the MADA provide annual tree ring drought reconstruction for 1300–2005 AD on a 2.5° by 2.5° gridded network of summer (June-July-August) Palmer drought severity index (PDSI) data. The proxy record of NAOI is available for 1049–1969 AD at an annual resolution.

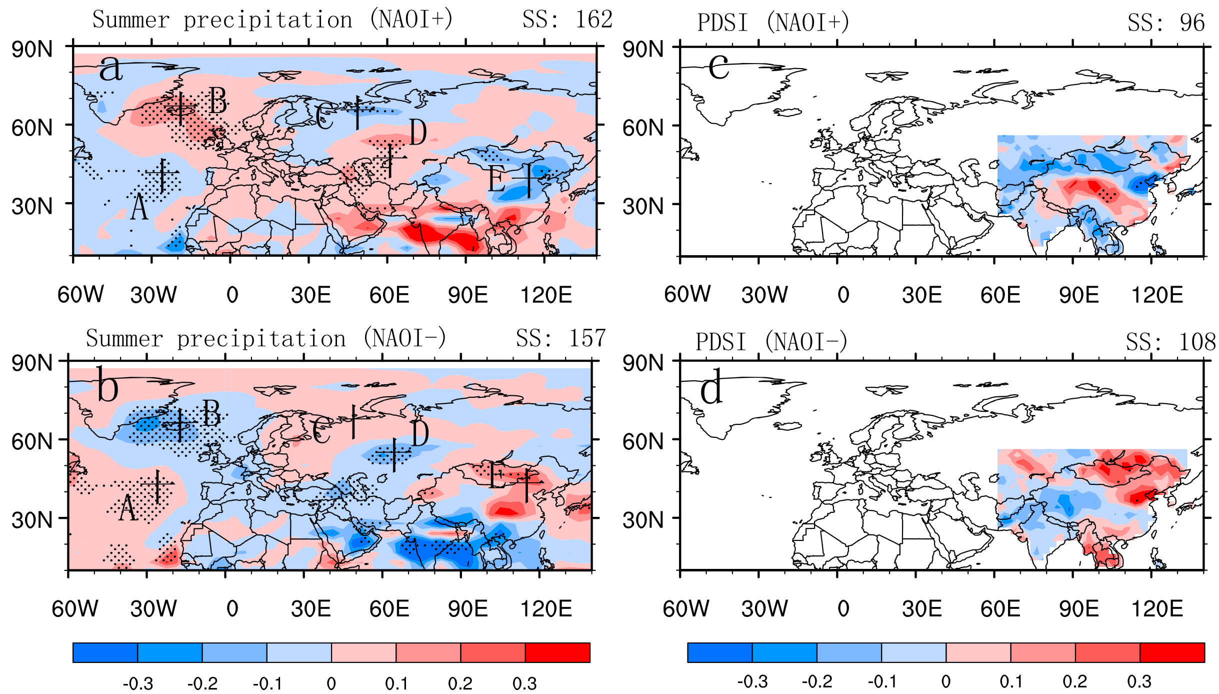

Figure 1. (a and b) Composites of the JJA hydroclimate patterns for the positive and negative NAOI calculated using simulated data for 1000–1999 and (c and d) the reconstructions by Cook et al. (2010) and Ortega et al. (2015) for 1300–1969. The unit of the summer precipitation is mm day^{-1}. The crosses denote the five action centers of the "North Atlantic-Eurasian teleconnection pattern." Positive (negative) NAOI is defined as NAOI above (below) 1 (−1) standard deviation. SS on the top right of each plot indicates the sample size. Anomalies with statistical significance levels higher than 90% are marked with black dots.

The relationship between NAO and precipitation changes over eastern Asia is evaluated by composite analysis. The significance of the composite analysis is evaluated using a two-sample Student's *t* test that is assumed to have different population variances.

3. Results

The simulated relationship between NAO and precipitation changes over eastern Asia is evaluated by compositing the summer precipitation for positive or negative NAOI (Figures 1a and 1b). The 1,000-year simulated data suggest that the teleconnected precipitation pattern in eastern China with the NAO is characterized by a north-south dipole pattern, with negative (positive) precipitation anomalies located north of 30°N and positive (negative) precipitation anomalies located south of 30°N associated with the positive (negative) anomalies of the NAOI; however, the relationship in southern China is not statistically significant. The same type of analysis was applied to the MADA PDSI and shows that there is close agreement between the NAO-related MADA PDSI patterns and simulated hydroclimate impacts in eastern China. The impact of the positive (negative) NAO phases in eastern China revealed by MADA is also "dipolar," with the negative (positive) center located north of 35°N and the positive (negative) center located south of 35°N (Figures 1c and 1d). However, there is an uncertainty about whether the PDSI composites shown in Figures 1c and 1d are related to the winter or summer NAO in the proxy data with an annual resolution. These climatic effects of the teleconnection pattern in eastern China revealed by the simulation and MADA PDSI are very similar to the observations, as shown by Figure 5b in Li and Ruan (2018). Their observation results indicate that such precipitation anomalies in eastern China associated with the NAO are strongly linked to a high-latitude Rossby wave train pattern. This train pattern, termed the "North Atlantic-Eurasian teleconnection pattern," has five centers of action from the subtropical North Atlantic Ocean across the Eurasian continent. This five-pole pattern extending from the North Atlantic to East Asia could be observed in Figures 1a and 1b and is similar to the observations, as shown by Li and Ruan (2018). Under positive NAOI in summer, less precipitation occurs in the subtropical North Atlantic Ocean (A in Figure 1a), Eastern Europe (C in Figure 1a), and Mongolia-north China (E in Figure 1a), and more precipitation occurs in the northeastern North Atlantic Ocean (B in

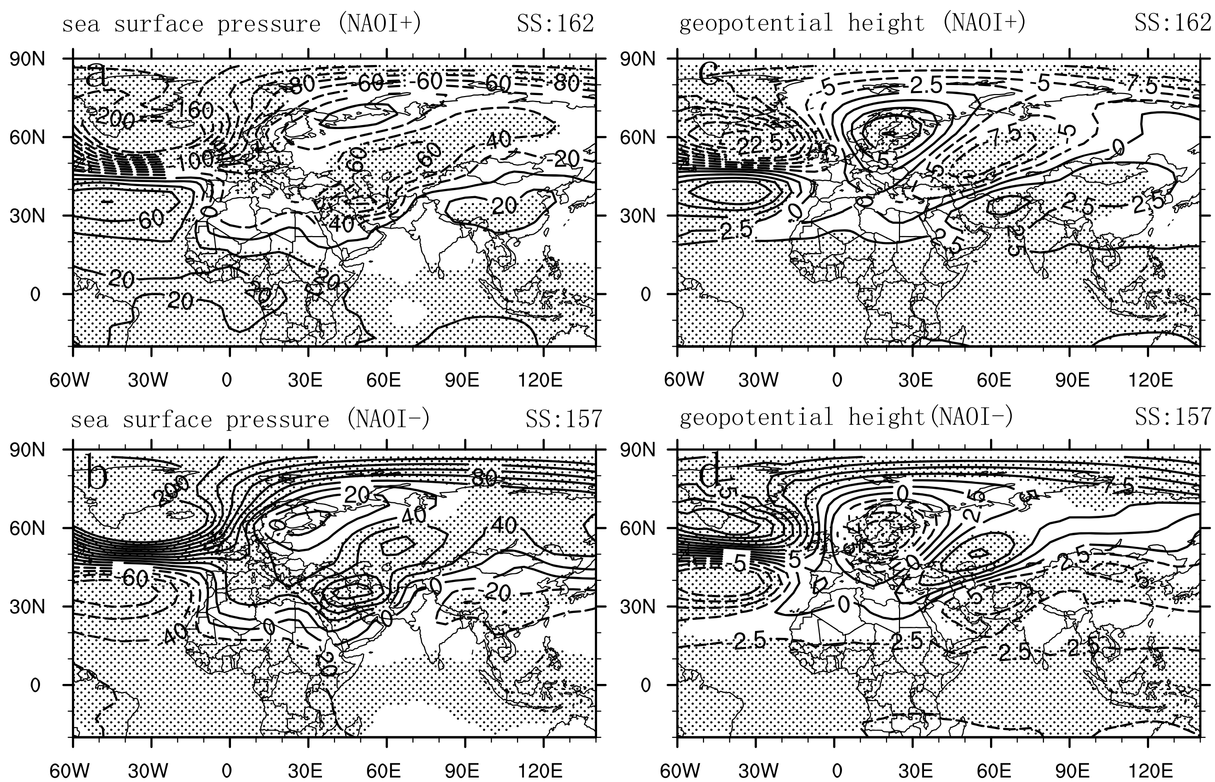

Figure 2. (a and b) Composites of the JJA sea surface pressure (contour interval is 20 Pa) and (c and d) geopotential height at 500 hPa (contour interval is 2.5 gpm) for the positive and negative NAOI calculated using simulated data for the last millennium. Positive (negative) NAOI is defined as NAOI above (below) 1 (−1) standard deviation. SS on the top right of each plot indicates the sample size. Anomalies with statistical significance levels higher than 90% are marked with black dots.

Figure 1a) and Urals (D in Figure 1a). During negative NAOI, the patterns are largely reversed (Figure 1b). The five-pole pattern observed in Figures 1a and 1b indicates that the interannual teleconnection pattern between the simulated summer NAO and precipitation in eastern China may be the eastern end of the regional climate response linked to the wave train along its path through northern Eurasia.

To check if the five-pole pattern is physically consistent with the summer precipitation composite results, the simulated SLP anomalies and geopotential height anomalies at 500 hPa composited using the simulated NAOI were examined (Figure 2). The most striking feature identified in the SLP anomalies is a five-core wave train pattern extending from the subtropical North Atlantic to East Asia (Figures 2a and 2b), similar to the precipitation anomaly pattern in Figures 1a and 1b. The spatial pattern of the first two centers located over the North Atlantic bears the structure of the NAO as expected. The patterns seen in the geopotential height anomalies at 500 hPa are qualitatively similar to those found in the SLP composite analysis, except that they are stronger over Eastern Europe (Figures 2c and 2d). The composite anomalies in the geopotential height anomalies at 500 hPa that are associated with the NAOI indicate that three positive (negative) geopotential height anomaly regions occur over the subtropical North Atlantic, Eastern Europe, and Mongolia-north China, and another two negative (positive) geopotential height anomaly regions occur over the high-latitude North Atlantic and the Ural Mountains during positive (negative) NAOI years. This five-core Rossby wave train associated with the NAO has been discussed by Li and Ruan (2018) and Li et al. (2008) during the instrumental period. They suggested that the five-core Rossby wave train should be regarded as another teleconnection pattern between the North Atlantic Ocean and the Eurasian continent because it generally propagates along a high-latitude pathway, which is different from the midlatitude circumglobal teleconnection pattern. As shown in Figure 3, the positive anomaly centers in the pressure field of the wave train correspond to the centers of the anomalous anticyclone in the 850-hPa wind anomalies and vice versa. The anomalous anticyclonic circulation centers linked with the wave train originating from the North Atlantic tend to accompany anomalous subsidence and reduced precipitation in the regions where they are located. In contrast, surplus

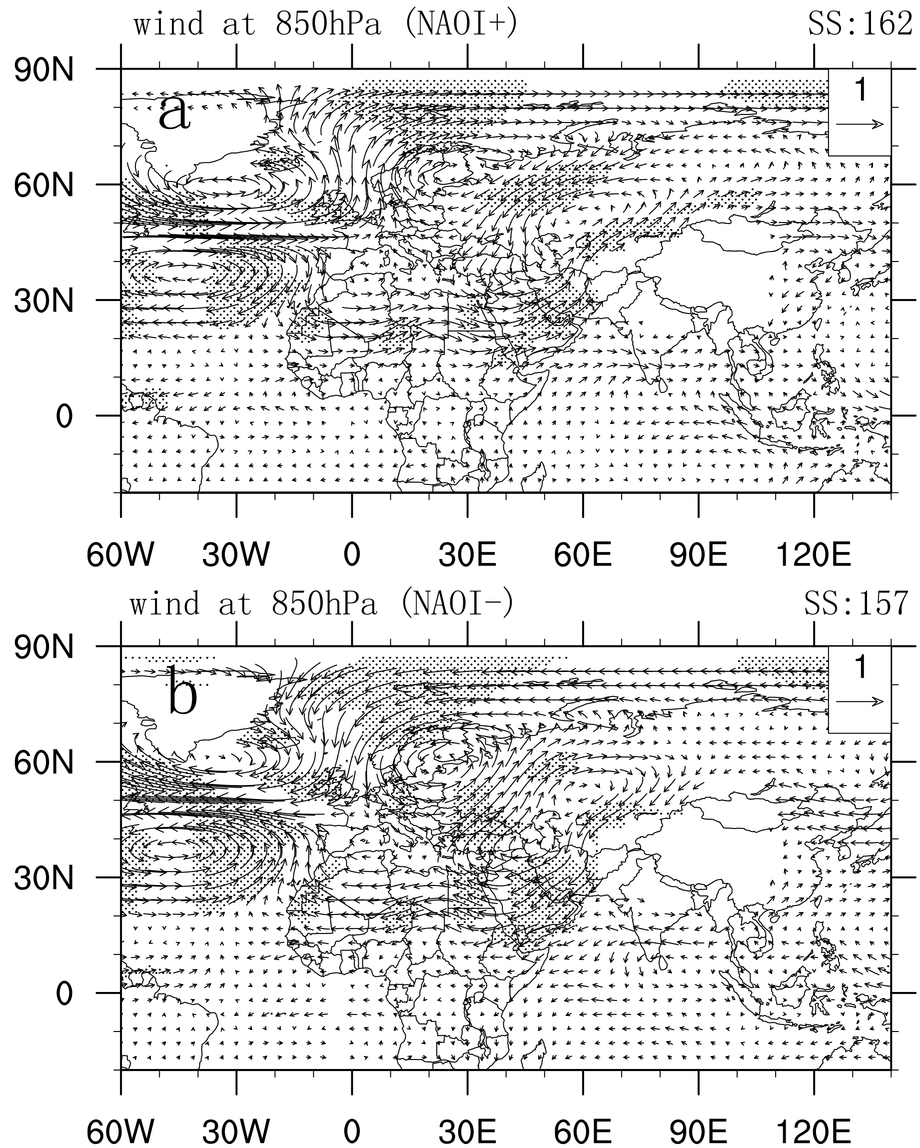

Figure 3. Same as Figure 2 but for the composites of JJA wind (m s^{-1}) at 850 hPa for the (a) positive and (b) negative NAOI. The wind vectors are missing over western China and around where the simulated 850-hPa surface is below the ground.

precipitation due to the anomalous ascent of air is dominant over the anomalous cyclonic circulation locations. Thus, we conclude that the NAO variation contributes to the simulated anomalous summer precipitation patterns, as shown in Figures 1a and 1b, via the five-core wave train pattern, as shown in Figure 2.

4. Conclusions and Discussion

We use a 1,000-year simulation performed with the CCSM2.0.1 to characterize the interannual teleconnections between the summer NAO and summer precipitation in eastern China during the last millennium. The result of the composite analysis reveals that the positive (negative) NAOI is associated with negative (positive) precipitation anomalies at approximately north of 30°N and positive (negative) precipitation south of this latitude. These NAO impacts over eastern China agree with the MADA and observation data. The influence of NAO on summer precipitation in eastern China is chiefly via the “North Atlantic-Eurasian teleconnection pattern.” A positive NAOI is indicative of anomalously high SLP and 500-hPa geopotential heights over the subtropical North Atlantic Ocean, Eastern Europe, and Mongolia-north China and low SLP and geopotential heights over the high-latitude North Atlantic Ocean and Urals, and vice versa. The positive anomaly centers in the pressure field of the wave train correspond to the centers of the anomalous anticyclone in the 850-hPa wind anomalies and hence causes deficient precipitation in the regions where they are located and vice versa. Thus, during the positive phase of NAOI, deficient precipitation regions occur over the subtropical North Atlantic Ocean, Eastern Europe, and Mongolia-north China, and positive precipitation anomaly regions occur in the northeastern North Atlantic Ocean and Urals. In each of these regions, the precipitation anomalies exhibit opposite signs associated with the negative NAOI. Our simulated results show that the interannual teleconnection pattern between the simulated summer NAO and precipitation in eastern China may be the eastern end of the regional climate response linked to the wave train along its pathway through northern Eurasia. However, the questions that arise are whether the teleconnection influences and mechanism due to the NAO in summer over the last millennium as a whole revealed by CCSM2.0.1 are robust during those periods with distinct climatic characteristics and across different model experiments? Answering these questions may lead to a better understanding of the interannual teleconnection between the summer NAO and summer precipitation in eastern China during the last millennium.

There are three distinct climate intervals during the last millennium: the Medieval Climate Anomaly (AD 1000–1300), the Little Ice Age (AD 1300–1850), and the Current Warm Period (AD 1850 to present). The changes in climate during the Medieval Climate Anomaly and Little Ice Age are controlled mainly by natural forcing, while anthropogenic factors play a large role in the climate changes during the Current Warm Period. A comparison of the interannual teleconnection between the summer NAO and summer precipitation in eastern China among the three climate intervals shows that the teleconnection influences and mechanism during those periods are all similar to those during the last millennium as a whole (Figures S2 and S3). This comparison indicates that the simulated results identified a robust climatic impact due to the NAO in summer during the last millennium.

The results of a model intercomparison based on four simulations from the CMIP5/PMIP3 archive show that the five-pole precipitation anomaly pattern due to the NAO in summer revealed by CCSM2.0.1 can also be observed in different model experiments, except for CCSM4 (Figures S4 and S5); this finding supports the conclusion that the influence of the NAO on summer precipitation over northern Eurasia is chiefly via the "North Atlantic-Eurasian teleconnection pattern." However, the models differ in their teleconnection influences in eastern China, and the causes of these differences among these atmosphere-ocean general circulation models is another associated topic that remains to be explored.

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