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The relationship between the Atlantic Multidecadal Oscillation and temperature variability in China during the last millennium

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ABSTRACT: Using a large number of temperature-sensitive proxy records, we investigated the relationship between the Atlantic Multidecadal Oscillation (AMO) and temperature variability in China during the last millennium. The results indicate a relatively homogeneous pattern of cold/warm anomalies in East, West and the whole of China (EC, WC and WOC). The six major AMO cold phases coincided with cold conditions over EC, WC and WOC, while warm conditions across China occurred during the two major AMO warm phases. This close similarity between the AMO and multi-decadal temperature variability in China is supported by climate model simulations and emphasizes the critical role of surface heating over the Asian continent in linking the AMO and the Indian summer monsoon. The mid-latitude westerly anomalies and the propagation of Rossby waves related to the AMO may be two channels linking sea surface temperature anomalies in the North Atlantic and temperature variability over East Asia. Additionally, the Atlantic Meridional Overturning Circulation may play an important role in transmitting the AMO signal over the globe. We recommend further climate model studies on the mechanisms responsible for the connection between the AMO and regional to global climate changes.

KEYWORDS: Atlantic multidecadal oscillation; China; last millennium; multidecadal time-scales; temperature variability.

Introduction

The Atlantic Multidecadal Oscillation (AMO) is characterized by multidecadal co-variability in North Atlantic sea surface temperature (SST) with a periodicity of about 70 years (Kerr, 2000; Enfield *et al.*, 2001). It affects air temperature and precipitation over much of the Northern Hemisphere (Dima and Lohmann, 2007; Wyatt *et al.*, 2011; Tung and Zhou, 2013), in particular in North America (Hu and Feng, 2008; Feng *et al.*, 2010; Oglesby *et al.*, 2012) and Europe (Sutton and Hodson, 2005).

In the past decade, a growing body of evidence from both instrumental observations and model simulations has demonstrated the important role of the AMO in influencing temperature and precipitation over East Asia (Goswami *et al.*, 2006; Lu *et al.*, 2006; Zhang and Delworth, 2006; Li and Bates, 2007; Feng and Hu, 2008; Li *et al.*, 2008; Luo *et al.*, 2011). The warm (cold) AMO phase has been linked to higher (lower) temperatures for the winter half-year in East China (Li and Bates, 2007) and for all seasons over the whole of East Asia (Wang *et al.*, 2009). Also, the warm (cold) AMO phase appears to be associated with increasing (decreasing) Indian summer monsoon rainfall (Goswami *et al.*, 2006; Lu *et al.*, 2006; Zhang and Delworth, 2006; Li *et al.*, 2008). Furthermore, a large number of studies have suggested that these linkages between the AMO and Indian summer monsoon rainfall may extend back through past millennia and even the entire Holocene (Fleitmann *et al.*, 2003; Feng and Hu, 2008; Berkelhammer *et al.*, 2010).

The critical question is how the AMO may be linked to Indian summer monsoon precipitation. It has been suggested that the AMO can affect the temperature over the Asian continent, changing the meridional temperature gradient between the Asian continent and the tropical Indian Ocean (Goswami *et al.*, 2006; Feng and Hu, 2008; Li *et al.*, 2008), which then influences the intensity of the Indian summer monsoon. However, due to the limited length of instrumental data series, we lack knowledge of whether the AMO affects Asia temperatures on centennial to millennial time-scales, as has been suggested by evidence from model simulations and observations over the instrumental period (Goswami *et al.*, 2006; Li *et al.*, 2008; Wang *et al.*, 2009). In this study, we investigated the relationships between the AMO and temperatures over the last millennium in China, using a large number of temperature proxy records from West, East and the whole of China (WC, EC and WOC). In addition, we compared the AMO index with previously published temperature reconstructions in Europe to investigate the role of the AMO in temperature variability over the Eurasian continent. The results presented here may contribute to a better understanding of climate variability and potential forcings of climate over East Asia.

Data description

The instrumental observations of annual mean surface air temperature in China extend back to AD 1880 (Wang and Gong, 2000; Wang *et al.*, 2001). Using a combination of long instrumental series and proxy records (tree-ring width, ice-core $\delta^{18}O$ and historical documentary data), Wang and Gong (2000) developed 10 regional annual mean temperature series covering the whole land area of China. In this study, the EC, WC and WOC temperature series were calculated from the 10 regional series (Wang and Gong, 2000; Wang *et al.*, 2007). In addition, the CRU TS 3.1 (land) $0.5 \times 0.5^\circ$ gridded dataset (Mitchell and Jones, 2005) was also used to investigate the relationships between AMO index and temperatures over China. Spatial correlation analyses were

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performed using the KNMI Climate Explorer (www.knmi.nl; Trouet and van Oldenborgh, 2013).

The tree-ring width-based temperature series for the Eastern Tibetan Plateau (Liang *et al.*, 2008; Wang *et al.*, 2013), west Tien Shan (Esper *et al.*, 2003) and Nepal (Cook *et al.*, 2003) were used in the present study to represent WC temperature variability. In EC, there are abundant and continuous historical documentary records. Many scholars have reconstructed the temperature history for this region using a variety of documentary data (for a review, see Ge *et al.*, 2008). In this study, the decadal winter half-year temperature reconstruction for the middle and lower reaches of the Yellow River and Yangtze River (Ge *et al.*, 2003) and temperature reconstructions with decadal resolution for Huabei and Huadong regions (Wang *et al.*, 1998) were used to represent EC temperature conditions. In addition, three millennium-long multi-proxy temperature reconstructions for WOC (Yang *et al.*, 2002; Wang *et al.*, 2007; Shi *et al.*, 2012) were used in this study. Tree-ring-based temperature reconstructions for central (Büntgen *et al.*, 2011a) and northern Europe (Esper *et al.*, 2012; Melvin *et al.*, 2013) were also used for comparison with Chinese temperature series to assess the similarity between the influences of the AMO on temperature in Europe and China.

The observational (Kaplan *et al.*, 1998) and reconstructed (Gray *et al.*, 2004; Mann *et al.*, 2009) AMO index series were used to examine North Atlantic SST variations and were compared with EC, WC and WOC temperature series. The records for total solar irradiance (TSI) (Bard *et al.*, 2000; Mann *et al.*, 2005) and volcanic eruptions (Gao *et al.*, 2008) were used to assess the role played by external forcings in influencing temperature variations over the Eurasian continent.

Results

The connection between the AMO and temperatures in China during the last 130 years

We calculated the spatial correlation of the instrumental AMO index (Kaplan *et al.*, 1998) with the gridded CRU TS 3.1 land surface air temperature dataset (Mitchell and Jones, 2005) during the period AD 1950–2009 (Fig. 1). A close relationship was seen between the AMO index and temperature anomalies in China, with correlations of $r > 0.50$ covering most of the area of interest. Figure 2(a) shows comparisons between annual mean AMO index (Kaplan *et al.*, 1998) and temperature series for EC, WC and WOC (Wang and Gong, 2000) over the last 130 years. We found that the AMO index exhibits interannual fluctuations coherent with temperature anomalies in EC, WC and WOC. The AMO index correlated significantly ($P < 0.01$) with temperature series from EC, WC and WOC, with correlation coefficients of 0.44, 0.40 and 0.44, respectively. The positive temperature anomalies over China during *c.* 1930–1950 and *c.* 1990–2010 both occurred synchronously with an AMO warm phase, while negative temperature anomalies during *c.* 1895–1915 and *c.* 1965–1985 both occurred synchronously with an AMO cold phase (Fig. 2b).

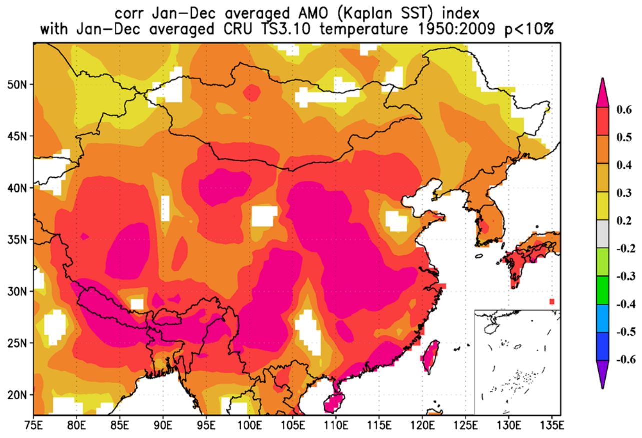

Figure 1. Spatial correlation pattern of annual mean (January–December) AMO index (Kaplan *et al.*, 1998) with the concurrent CRU TS 3.1 (land) 0.5 × 0.5° gridded air temperature dataset during the period 1950–2009. This figure is available in colour online at wileyonlinelibrary.com.

As suggested by evidence from model simulations (Li and Bates, 2007; Wang *et al.*, 2009), our results indicate that positive (negative) temperature anomalies over China are associated with warm (cool) phases of the AMO (Fig. 2a,b). However, this relationship may be disrupted in some periods, e.g. the 1950s, perhaps due to the major negative phase of the Pacific Decadal Oscillation (PDO) and the NINO 3.4 index. [The NINO 3.4 index is one of El Niño/Southern Oscillation (ENSO) indicators, defined as the average of SST anomalies in the region 5°N–5°S and 170°W–120°W.] The above results imply that temperature variability in China is also related to changes in the Pacific climate on multidecadal time-scales (Li and Xian, 2003; Wu *et al.*, 2010). Nevertheless, we find weak, non-stationary relationships with PDO and ENSO (Fig. 2b,c). Additionally, the weak and non-stationary relationship between the North Atlantic Oscillation (NAO) and temperature variability in China is also seen on multi-decadal time-scales. Overall, our results suggest that the AMO shows a closer relationship with temperature anomalies over China in comparison with other atmospheric oscillations (e.g. NAO, ENSO and PDO), and that this relationship has been relatively robust and stable over the past 130 years.

Note that in Fig. 2(b) the AMO lags changes in Chinese temperature and not the other way around. This may be partly explained by a small window size used in data smoothing (20 years), and the short length of the observational data, which covers fewer than two cycles of the AMO. Subsequently, we will investigate their relationship on centennial to millennial time-scales and further assess whether such lags were existent over the past 1000 years.

The relationship between the AMO and temperature variability in China during the last millennium

To examine the relationship between the AMO and temperature variability in China over the past millennium, we compared two reconstructed AMO index series with 10 temperature-sensitive proxy records in China. Figure 3 shows the comparison of AMO index series (Gray *et al.*, 2004; Mann *et al.*, 2009) with temperature records for EC (Wang *et al.*, 1998; Ge *et al.*, 2003), WC (Cook *et al.*, 2003; Esper *et al.*, 2003; Liang *et al.*, 2008; Wang *et al.*, 2013) and WOC (Yang *et al.*, 2002; Wang *et al.*, 2007; Shi *et al.*, 2012). We found that the cold events during the 1960s–1980s and the 1890s–1910s were just two of several such cold periods on multidecadal time-scales that were seen in China in the context of the past millennium. Additionally, the warm/cold fluctuations on decadal to multidecadal time-scales in EC, WC and WOC temperature series varied simultaneously. As indicated by the vertical bars in Fig. 3, there were six major AMO cold phases during the 1330s–1350s, 1440s–1460s, 1600s–1650s, 1810s–1830s, 1890s–1910s and 1960s–1980s, each corresponding to a cold period over EC, WC and WOC.

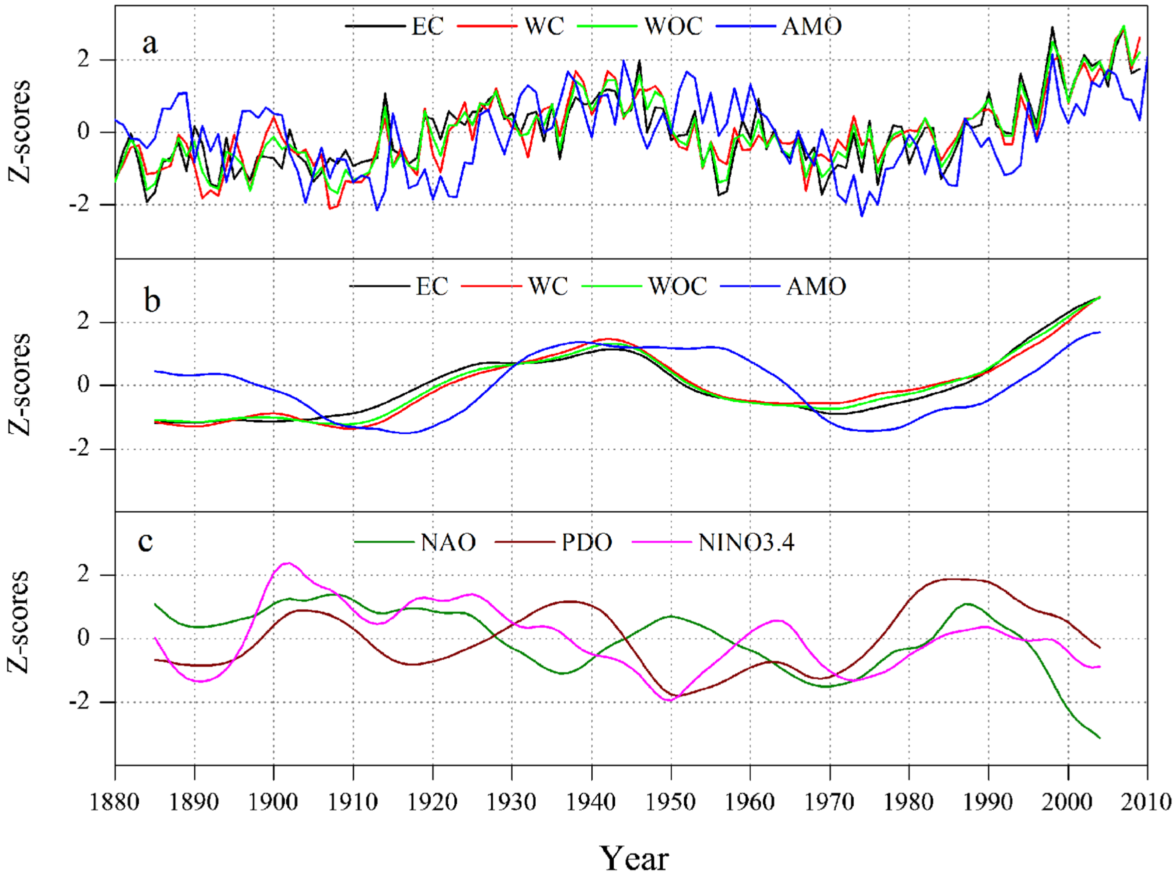

Figure 2. (a) Comparisons of the instrumental AMO index with temperature series for EC, WC and WOC during the past 130 years. (b) As in (a) but for 20-year low-pass filtered data. (c) 20-year low-pass filtered NAO, NINO 3.4 and PDO indexes. This figure is available in colour online at wileyonlinelibrary.com.

It is also evident that the two major AMO warm phases in the 1030s–1090s and the 1220s–1270s were associated with a positive temperature anomaly over EC, WC and WOC. These findings, in general, indicate that multi-decadal temperature variability over East Asia was related to the AMO during the last millennium.

We also investigated the relationship between the AMO and temperature variability in northern (Esper *et al.*, 2012; Melvin *et al.*, 2013) and central Europe (Büntgen *et al.*, 2011a). As shown in Fig. 3, similar patterns of warm/cold fluctuations were seen in China and Europe on multi-decadal time-scales. The warm (cold) AMO phases were followed by warm (cold) periods over Europe.

Additionally, we identified those time intervals during which the low-pass filtered and standardized AMO index series from Mann *et al.* (2009) exceeded ± 1.5 standard deviations (SD). These intervals could be regarded as the warm/cold phases of the AMO. The periods 1008–1096 and 1932–1952 were identified as two warm phases of the AMO, while the period 1602–1622 was regarded as one cold phase of the AMO. We calculated mean temperature departure within the warm/cold phases of the AMO for EC, WC, WOC and Europe based on the 31-year low-pass filtered and standardized temperature series (the series for each region used here are the same as those shown in Fig. 3). As expected, two warm phases of the AMO during 1008–1096 and 1932–1952 were associated with positive temperature departures in EC, WC, WOC and Europe, while one cold phase of the AMO during 1602–1622 was coincident with positive departures in each region (Fig. 4). Additionally, there were some regional differences in temperatures over China. For example, the EC temperature series was weakly related to the AMO during AD 1008–1096, whereas the WC series was weakly associated with the AMO during AD 1602–1622 (Fig. 4). These regional differences in the climate history of China may be related to other atmospheric oscillations, as discussed above.

Despite some regional differences, overall the similarities between the EC and WC temperature series suggest generally coherent patterns in temperature variability over China (Fig. 3). Additionally, Fig. 4 indicates that multidecadal temperature variability across the Eurasian continent is sensitive to the AMO (Fig. 4).

Discussion and conclusions

Observations of temperature anomalies in recent decades indicate that the warm phases of the AMO are related to high temperature anomalies across Europe in all seasons, although opposite trends were found for summer precipitation between northern and southern Europe (Sutton and Dong, 2012). Such a connection between the AMO and temperature variability over Europe can also be seen in climate model simulations (Sutton and Hodson, 2005; Knight *et al.*, 2005). We suggest further that the influence of the AMO on temperature variability across Europe extends at least throughout the last millennium. Moreover, the signal of the AMO was also recorded by tree-ring width records in central eastern Siberia and north-east China during the past five centuries (Wang *et al.*, 2011). Consistent with the above evidence from the mid and high latitudes of the Eurasian continent, our results further suggest that the AMO can influence temperature variability in East Asia. The warm AMO phases are characterized by elevated winter temperatures in EC (Li and Bates, 2007). A similar influence of the AMO on temperatures is also apparent in all seasons over East Asia (Wang *et al.*, 2009).

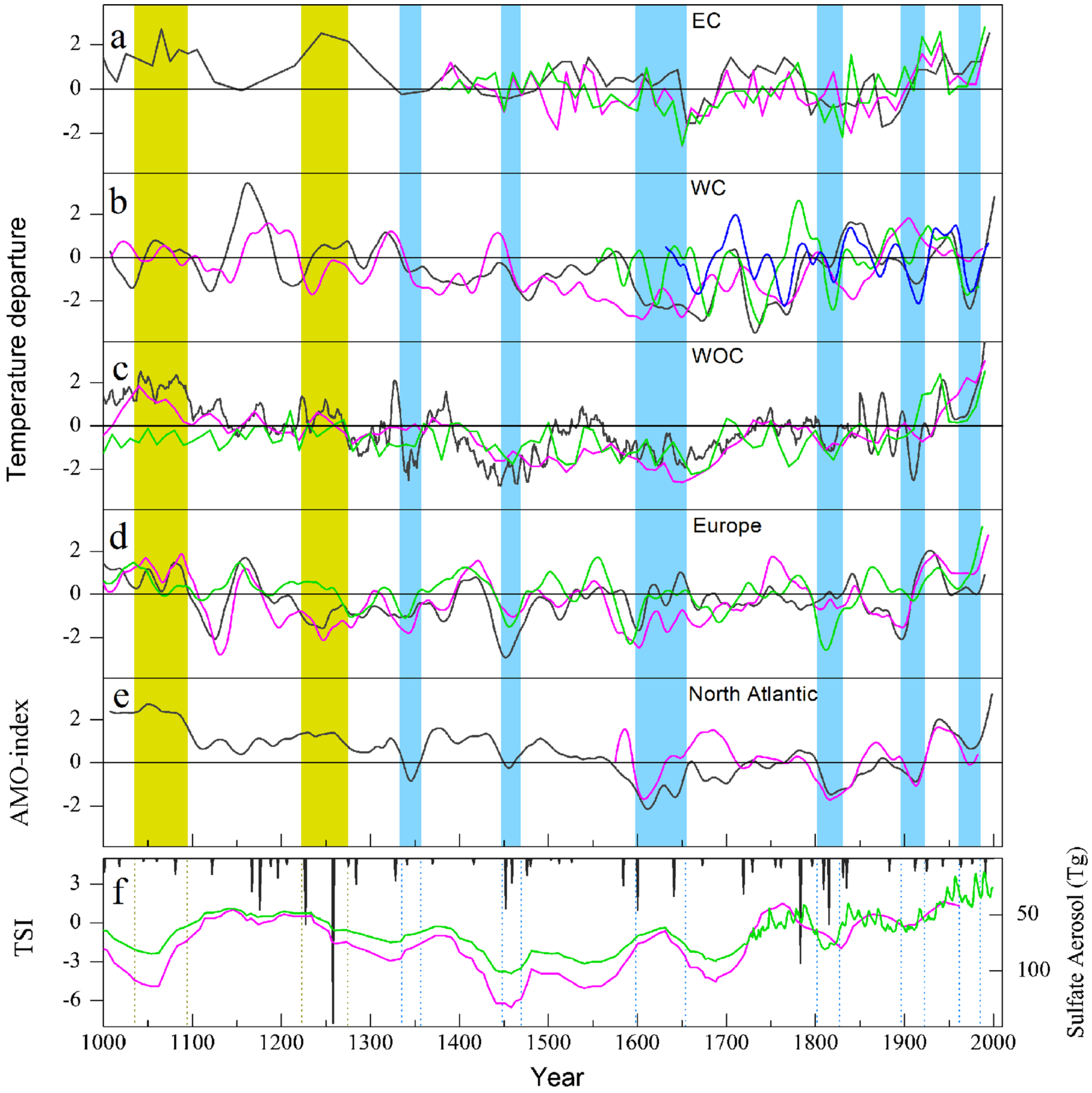

Figure 3. Comparisons of the reconstructed AMO index series (e) with temperature records in EC (a), WC (b), WOC (c), Europe (d) and the records for external forcings (f) during the last millennium. (a) Black (Ge *et al.*, 2003), red (Wang *et al.*, 1998) and green (Wang *et al.*, 1998) lines are historical documentary data-based temperature reconstructions for the middle and lower reaches of the Yellow River and Yangtze River, Huabei, and Huadong, respectively. (b) Black (Wang *et al.*, 2013), red (Esper *et al.*, 2003), green (Cook *et al.*, 2003) and blue (Liang *et al.*, 2008) lines are tree-ring width-based temperature reconstructions for Qamdo, West Tien-shan, Nepal and Nangqian, respectively. (c) Black (Shi *et al.*, 2012), red (Yang *et al.*, 2002) and green (Wang *et al.*, 2007) lines are multi-proxy temperature reconstructions for China. (d) Black (Esper *et al.*, 2012, MXD), red (Melvin *et al.*, 2013, MXD) and green (Büntgen *et al.*, 2011a; TRW) lines are tree-ring-based temperature reconstructions for northern and central Europe. (e) Black (Mann *et al.*, 2009) and red (Gray *et al.*, 2004) lines are reconstructed AMO index series. (f) Black (Gao *et al.*, 2008), red (Bard *et al.*, 2000) and green (Mann *et al.*, 2005) lines are series for NH stratospheric sulphate aerosol and total solar irradiance (TSI). The yellow (blue) bars highlight simultaneous warm (cold) AMO phases and temperatures over EC, WC and WOC. In (b), (d) and (e), each series has been smoothed with a 30-year low-pass filter. Each series has been standardized with respect to the period AD 1800–1960. This figure is available in colour online at wileyonlinelibrary.com.

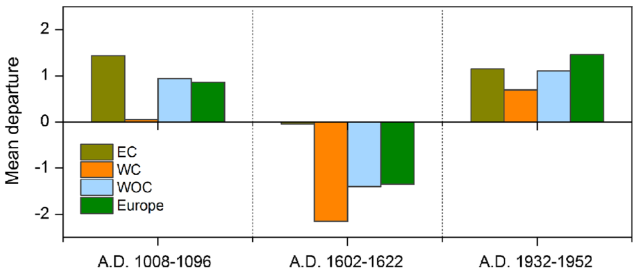

Figure 4. Mean departure of temperature for EC, WC, WOC and Europe during two warm intervals of the AMO (AD 1008–1096 and 1932–1952, index > + 1.5 SD) and one cold interval of the AMO (AD 1602–1622, index <–1.5 SD). Mean departures were calculated for each region using temperature series as in Fig. 3. This figure is available in colour online at wileyonlinelibrary.com.

In light of these observations for AMO climate teleconnections across the Eurasian continent extending back through the last millennium, we now consider two important questions that arise. First, what causes the AMO variability? Based on climate model simulations, it has been suggested that the AMO variability is internally driven by the Atlantic Meridional Overturning Circulation (AMOC) (Knight *et al.*, 2005; Sutton and Hodson, 2005). Nevertheless, recent evidence from Otterå *et al.* (2010) showed that the AMO can also be influenced by external forcings, such as TSI variations and volcanic eruptions. Thus, it can be argued whether the consistent patterns in AMO and the temperature variations over China are caused by a common set of external forcings (e.g. the TSI suggested by Soon, 2009). In this case, the AMO and the temperature in

East Asia can vary simultaneously without a direct effect of AMO on temperature in East Asia. In the present study, we also investigated the effects of TSI (Bard *et al.*, 2000; Mann *et al.*, 2005) and volcanic eruptions (Gao *et al.*, 2008) (Fig. 3f) on the AMO and temperature variations over China and Europe. Our results revealed only weak responses of the AMO and temperatures over the Eurasian continent to natural external forcings. This is consistent with the study by Büntgen *et al.* (2011b), who suggested that internal climate dynamics (mainly represented by the AMO) played a more important role than external forcings in determining past temperatures in northern Europe. However, it should be noted that simple correlations and comparisons do not by themselves demonstrate causation. As suggested by Muller *et al.* (2013), the association between the AMO and temperature variations over the Eurasian continent may also be a result of common external natural forcings; however, it is equally possible that temperature variations over the Eurasian continent can be direct responses to the AMO. Further climate model studies are needed to examine whether it is natural external forcing or internal climate dynamics that plays the primary role for the coherent temperature fluctuations in the North Atlantic and over the Eurasian continent.

Secondly, what internal climate mechanism may be connecting the AMO with East Asia temperature? One possibility involves mid-latitude westerly anomalies and the propagation of Rossby waves (Li and Bates, 2007; Li *et al.*, 2008). The warm AMO phase is linked to enhanced mid-latitude westerlies (Grossmann and Klotzbach, 2009), which induce negative surface air pressure anomalies over the North Atlantic extending to mid-latitude Eurasia (Knight *et al.*, 2005; Li and Bates, 2007). The surface low-pressure air over the mid-latitude Eurasian continent weakens the Siberian–Mongolian high-pressure system, and reduces the strength of the East Asian winter monsoon (Li and Bates, 2007; Wang *et al.*, 2009). By contrast, Li *et al.* (2008) and Luo *et al.* (2011) conducted diagnostic simulations and found a propagating Rossby wave train in the middle and upper troposphere extending from the Atlantic across Asia during the warm AMO phase, implying that high Atlantic SST can directly warm the middle or upper troposphere of the Asian continent.

This study focuses on the influence of the AMO on multidecadal temperature variability in China over the past millennium. The tropical and North Pacific SST anomalies can also influence temperature variability in China on interdecadal time-scales (Li and Xian, 2003; Wu *et al.*, 2010). However, our results suggest that the relationship between temperature variability in China and the ENSO and PDO are both unstable on multidecadal time-scales (Fig. 2b,c), and these relationships are possibly different (even opposite) in different intervals (Wu *et al.*, 2010). As suggested by Sun *et al.* (2008), the linkage between the NAO and temperature variability in China varies with time on multidecadal time-scales. In addition, the NAO is a large-scale seesaw in atmospheric pressure between the western mid-latitude and high-latitude North Atlantic (Hurrell, 1995), rather different from the co-variability in North Atlantic SST described by the AMO (Kerr, 2000). Feng and Hu (2008) suggested the significant association of the AMO rather than the NAO with temperatures in China (see Feng and Hu, 2008; Fig. 2). Likewise, Muller *et al.* (2013) recently revealed that the AMO plays a more important role than other atmospheric oscillations in influencing decadal temperature variations over the globe, and the AMOC may be responsible for a worldwide signal of the AMO.

Admittedly, there is a need for further work to improve our understanding of the physical mechanisms responsible for the connection between the AMO and climate variability in East Asia. In the present study, the results to a great extent demonstrate a possible relationship between the AMO and temperature variations in East Asia on multi-decadal time-scales throughout the last millennium, and provide strong support for those studies (Goswami *et al.*, 2006; Feng and Hu, 2008; Li *et al.*, 2008) that have emphasized the critical role of surface heating over the Asian continent in linking the AMO and the Indian summer monsoon. These findings can be used to better understand climate variability and potential forcings of the climate in East Asia.

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Abbreviations. AMO, Atlantic Multidecadal Oscillation; AMOC, Atlantic Meridional Overturning Circulation; EC, East China; ENSO, El Niño/Southern Oscillation; NAO, North Atlantic Oscillation; PDO, Pacific Decadal Oscillation; SST, sea surface temperature; TSI, total solar irradiance; WC, West China; WOC, whole of China

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