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Decadal modulation of the ENSO–East Asian winter monsoon relationship by the Atlantic Multidecadal Oscillation

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Abstract This work investigates the decadal modulation of the El Niño-Southern Oscillation (ENSO)–East Asian winter monsoon (EAWM) relationship by the Atlantic Multidecadal Oscillation (AMO). A stable ENSO–EAWM relationship is found during the positive AMO phase but not during the negative phase. While the impact of El Niño events on the EAWM does not depend on the AMO phase, a different picture is observed for La Niña events. The La Niña boreal winter season coincides with a strengthened EAWM during a positive AMO phase and a weakened EAWM during a negative AMO phase. We suggest that the AMO's modulating effect mainly comprises two pathways that influence ENSO's impact on the EAWM. On one hand, when La Niña coincides with a positive AMO, the warm SST anomalies over the western North Pacific (WNP) are amplified both in intensity and spatial extent, which favors strengthened WNP cyclonic anomalies and an enhanced EAWM. During La Niña with a negative AMO, only very weak SST anomalies occur over the WNP with reduced WNP cyclonic anomalies that are confined to the tropics, thus having little effect on the EAWM. On the other hand, an eastward-propagating Rossby wavetrain across the mid-high latitudes of Eurasia during a warm AMO phase strengthens the Siberian high and thus leads to a strengthened EAWM, while during a cold AMO phase the Siberian high is weakened, leading to a reduced EAWM. In contrast, El Niño and its associated atmospheric responses are relatively strong and stable, independent of the AMO phase. These results carry important implications to the seasonal-to-interannual predictability associated with ENSO.

Keywords Atlantic Multidecadal Oscillation · Decadal modulation · El Niño-Southern Oscillation · East Asian winter monsoon

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1 Introduction

The East Asian winter monsoon (EAWM), featuring conspicuous cold and dry conditions in East Asia, is one of the most prominent climate phenomena during the boreal winter season (e.g., Lau and Li 1984; Huang et al. 2012). The EAWM exhibits remarkable interannual variability, frequently accompanied by freezing rain and snow disasters with catastrophic consequences (e.g., Boyle and Chen 1987; Wang et al. 2011). A large number of efforts have been made to understand the predictability of the EAWM interannual variability (e.g., Chen et al. 2000; Gong et al. 2001; Wu et al. 2009, 2015; Wang et al. 2010; Chen et al. 2014b; Li and Wang 2014). Especially, the possible influence of the El Niño-Southern Oscillation (ENSO) on the EAWM has been extensively studied (e.g., Zhang et al. 1996; Chen 2002; Wang et al. 2000; Chang et al. 2006; Wu and Zhang 2015), since ENSO provides the dominant source for skillful predictability on the seasonal-to-interannual timescale.

ENSO exerts its influence on the East Asian climate mostly through modifying the atmospheric circulation over the western North Pacific (WNP) region (Zhang et al. 1996; Wang et al. 2000; Yang et al. 2007; Xie et al. 2009; Zhang et al. 2011). During the ENSO warm phase (i.e., El Niño), pronounced anticyclonic anomalies are evident over the WNP, which can propagate more moist and warm water vapor towards East Asia. The anomalous WNP anticyclone, possibly associated with local sea surface temperature (SST) cooling (Wang et al. 2000), the El Niño-induced Indian Ocean basin warming (Watanabe and Jin, 2002; Yang et al. 2007; Xie et al. 2009), and/or the ENSO combination mode (Stuecker et al. 2013, 2015, 2016; Zhang et al. 2015, 2016), usually starts developing during the El Niño autumn season and persists into boreal summer of the following calendar year (e.g. Stuecker et al. 2015). Thus, East Asia often experiences a weaker than normal EAWM with a precipitation surplus during El Niño winters (Li. 1990; Zhang et al. 1996; Chen et al. 2000). During La Niña events, the anomalous atmospheric circulations and climate impacts over East Asia are approximately opposite to those during the El Niño phase, but with non-negligible asymmetric characteristics in their intensity and location (Zhang et al. 1996; Hoerling et al. 1997; Chen 2002; Wu et al. 2010).

However, this ENSO–EAWM interannual relationship can only be clearly observed in some decades (Kim et al. 2016). It has been pointed out by many studies that their connection exhibits decadal fluctuations (e.g., Zhou et al. 2007; Li and Ma 2012). This non-stationary behavior might be explained by some modulating factors. For instance, it has been suggested that the ENSO-related winter climate over East Asia varies over the 11-year solar cycle with a more robust connection during periods of lower than normal solar activity (Zhou et al. 2013). The Pacific Decadal Oscillation (PDO) of SST variability in the North Pacific was proposed as another important factor that could modulate the ENSO–EAWM relationship (Wang et al. 2008; Kim et al. 2014, 2016). One study argued that ENSO has significant impacts on the EAWM only during the negative phase of the PDO (Wang et al. 2008). Nevertheless, this point is challenged by another study, which proposed that the negative ENSO–EAWM relationship is significantly strengthened when ENSO and PDO are in-phase (i.e., El Niño/positive PDO phase or La Niña/negative PDO phase) (Kim et al. 2014). Thus, it seems that the modulation of PDO on the ENSO–EAWM connection is not well understood. Furthermore, the low-frequency decadal variability in the Pacific could also be partly caused by ENSO variability (e.g., Jin et al. 2003; Newman et al. 2016).

Another major interdecadal mode, the Atlantic Multidecadal Oscillation (AMO), receives much attention since it was identified as an important driver of Northern Hemisphere climate variability (Delworth and Mann 2000; Kerr. 2000; Enfield et al. 2001; Sutton and Hodson 2005; Sun et al. 2011; Sutton and Dong 2012; Zhou and Wu 2016). Some observations show that the AMO signal can also be detected in the EAWM variability (Li and Bates 2007; Wang et al. 2009; Sun et al. 2011; Wang et al. 2013b). The warm phase of the AMO is favorable for the occurrence of a milder EAWM through a weakening of the Mongolian cold high (Li and Bates 2007), and/or by northern westerlies transporting warm anomalies from the North Atlantic to the east (Sun et al. 2011). In addition, the AMO can modify the tropical Pacific SST background climate state and thus affect ENSO variability (e.g., Dong and Sutton 2002; Dong et al. 2006), which then could also further influence the EAWM. Many studies argued that a positive AMO tends to weaken ENSO variability based on the "atmospheric bridge" mechanism (Dong et al. 2006; Dong and Sutton 2007; Zhang and Delworth 2005; Timmermann et al. 2007; Kang et al. 2014). A positive AMO could result in enhanced trade winds in the western and central tropical Pacific and a deeper thermocline propagating eastward, which could reduce vertical stratification in the eastern equatorial Pacific Ocean and thus suppress the ENSO activity (Dong et al. 2006). These studies suggested that the ENSO-related circulation anomalies over East Asia are possibly modulated by the phase of the AMO through either direct (e.g., Li and Bates 2007) or indirect processes (e.g., Zhang and Delworth 2005). The conclusions have been partly supported by some previous studies, which proposed that ENSO impacts on the South Asian summer monsoon and the WNP summer monsoon are influenced by the AMO phase (Lu et al. 2008; Chen et al. 2010, 2014a).

Since ENSO and EAWM are both possibly influenced by the AMO, does their relationship vary with different phases of the AMO? And if the relationship does vary, by which mechanism(s) can the AMO modulate this relationship? A previous study proposed that the fluctuation of the ENSO–EAWM relationship is possibly attributable to the combined effect of the PDO and AMO (He and Wang 2013). However, the question of how the AMO modulates the ENSO–EAWM relationship has not been sufficiently elucidated. The purpose of this study is to explore the low-frequency (decadal) modulation of the ENSO–EAWM relationship by the AMO. We found that the unstable relationship is primarily modulated by AMO and the modulation exhibits asymmetric features for the ENSO warm (i.e., El Niño) and cold phases (i.e., La Niña). In the remainder of this paper, Sect. 2 describes the utilized datasets and methodologies. The unstable features of the ENSO–EAWM relationship, as well as the decadal modulation by the AMO, are illustrated in Sect. 3. Furthermore, in Sect. 4 we explore possible mechanisms that can explain this modulation based on both observations and the Atmospheric Model Intercomparison Project (AMIP)-style simulations. The major conclusions are summarized and discussed in Sect. 5.

Table 1 El Niño and La Niña events for the 1951–2013 period

El Niño events	La Niña events
1957, 1963, 1965, 1968, 1969, 1972, 1977, 1982, 1986, 1987, 1991, 1994, 1997, 2002, 2004, 2006, 2009	1954, 1955, 1962, 1964, 1967, 1970, 1971, 1973, 1974, 1975, 1984, 1988, 1995, 1998, 1999, 2000, 2005, 2007, 2008, 2010, 2011

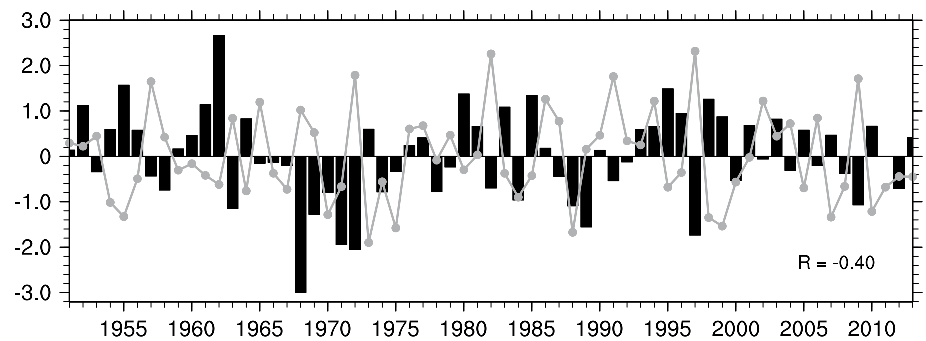

Fig. 1 Time evolution of the DJF EAWM (*bar*) and Niño3.4 indices (*dotted curve*) during 1951–2013. Note the ERSST v3b data are used when calculating the Niño3.4 indice. The intensity of the EAWM (EAWMI) is measured by the negative area-averaged 850 hPa meridional wind anomalies within the domain of 20°–40°N and 100°–140°E

2 Data and methodology

The monthly datasets (1951–2014) used in this work include the global SST derived from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST analysis, version 3 (ERSST, Smith et al. 2008). Atmospheric circulations are examined based on the National Centers for the Environmental Prediction/National Center for the Atmospheric Research (NCEP/NCAR) reanalysis data (Kalnay et al. 1996). The precipitation anomalies are investigated using the NOAA's precipitation reconstruction dataset (PREC) (Chen et al. 2002).

Several climatic indices are used to facilitate the analysis. The intensity of the EAWM (EAWMI) is measured by the negative area-averaged boreal winter 850 hPa meridional wind anomalies (e.g., a negative EAWMI is associated with anomalous southerly wind) within the domain of 20°–40°N and 100°–140°E (Yang et al. 2002). Wang and Chen (2010) pointed out the performance of this index is relatively better than the others in capturing the interannual ENSO–EAWM relationship. The Niño3.4 index is used to describe the ENSO intensity, which is defined as the area-averaged SST anomalies in the Niño3.4 region (5°S–5°N, 120°–170°W). The AMO index is calculated as the area-averaged boreal winter SST anomalies within the domain of 0°–60°N and 0°–80°W (Trenberth and Shea 2006). The PDO index, defined as the leading principal component of monthly SST variability in the North Pacific (poleward of 20°N), is provided by the University of Washington (http://jisao.washington.edu/data_sets/pdo/). All the above indices are normalized before our analysis. All datasets are analyzed for the boreal winter season (December–February: DJF), and the winter of 1951 refers to the 1951/1952 winter. Anomalies for all variables are defined as the deviation from the long-term climatological mean (1951–2013). A threshold of ±0.5 standard deviations of the Niño3.4 index during the DJF season defines ENSO winters. With this method we identify 17 El Niño and 21 La Niña winters (Table 1). The linear trend was removed from all anomalies to avoid possible influences associated with the long-term trend. All statistical significance tests were performed based on the two-tailed Student's *t* test.

3 Results: Decadal modulation of the ENSO–EAWM relationship by the AMO

3.1 Unstable ENSO–EAWM relationship

Figure 1 shows the time evolution of the DJF Niño3.4 index and EAWMI from 1951 to 2013. Conspicuous interannual variability is displayed in these two indices with an approximate out of phase inter-relationship (e.g., El Niño winters are associated with a negative EAWMI, meaning anomalous southerly atmospheric flow and enhanced precipitation over East Asia), which has been mentioned by previous studies (Li. 1990; Zhang et al. 1996; Chen et al. 2000). The temporal correlation coefficient between the two indices is −0.4, which exceeds the 99% confidence level. However, this negative correlation seems to be caused by the El Niño events rather than the La Niña events. The La Niña events exhibit a highly unstable relationship with the EAWM. Some La Niña winters (e.g., 1973 and 1995) coincide with a strengthened EAWM, while other some La Niña winters (e.g., 1984 and 1988) are accompanied by a weakened EAWM.

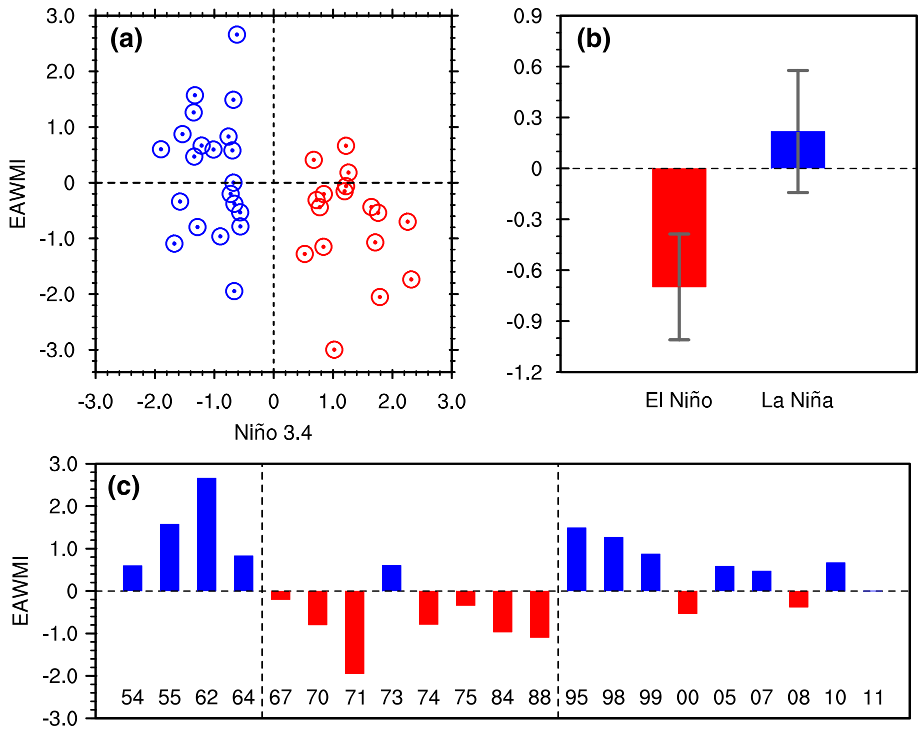

Fig. 2 **a** Scatterplot of the EAWMI as a function of the Niño3.4 index for El Niño (*red circle*) and La Niña (*blue circle*) boreal winter seasons. **b** Composite EAWMI during El Niño (*red bar*) and La Niña (*blue bar*) boreal winters. The *error bars* represent 1 standard deviation error estimates for El Niño and La Niña winters, respectively. **c** The EAWM indices of all La Niña winters for 1951–2013 in chronological order (note only La Niña events are shown and the *red*/*blue bars* represent weakened/strengthened EAWM)

This strongly asymmetric response of the EAWM to ENSO warm and cold phases is clearly displayed in Fig. 2a. On one hand, most (14 of 17; over 82%) of El Niño winters are accompanied by a weakened EAWM. On the other hand, no simple linear relationship is observed between the EAWM and Niño3.4 indices during La Niña winters. Around half the La Niña events correspond to a strengthened EAWM, while the other half are associated with a weakened EAWM. The composite plot shown in Fig. 2b can further confirm this asymmetry. El Niño events are robustly associated with a weakened EAWM with relatively small standard deviation. In contrast, the La Niña composite EAWMI shows a small positive value, albeit with large standard deviation, indicating that the La Niña–EAWM relationship might be more complex. Interestingly, if the EAWM indices of all La Niña winters are presented in chronological order, pronounced decadal variability can be found in the La Niña–EAWM relationship (Fig. 2c). Most La Niña winters experienced an intensified EAWM before the mid-1960s and after the mid-1990s, and a weakened EAWM during the interim period. This non-stationary character might be induced by a decadal signal modulation, which will be explored in this paper.

3.2 Decadal modulation by the AMO

Figure 3 shows the 17-year sliding window correlation between Niño3.4 and EAWMI (colored solid line), the 9-year running averaged PDO index (gray dashed line), and the AMO index (bar). As the PDO and AMO are the dominant decadal to multidecadal signals in the Northern Hemisphere, we investigate their potential modulating impact on the unstable ENSO–EAWM relationship. Here, a moving 17-year window is used to detect the correlation changes between the ENSO and EAWM on decadal to multidecadal time scales. The qualitative conclusions remain unchanged if we use other moving windows, such as 15- and 19-year. Our results (Fig. 3) clearly show that, at the 90% confidence level, ENSO and EAWMI are significantly correlated before the late 1960s and after the mid-1990s, while a non-significant relationship is found during the interim period. This robust multidecadal modulation is similar to that displayed in Fig. 2c and was mentioned by an earlier study (Li and Ma 2012, see their Fig. 9), which reports a similar decadal fluctuation of the relationship between ENSO and the winter rainfall over southeastern China. The PDO phase switches from negative to positive in the mid-1970s and again back to a negative phase around 2001, which is also displayed in the study of Kim et al. (2014). The PDO does not vary consistently with the sliding window correlation between the Niño3.4 index and the EAWMI. In contrast, the AMO exhibits an approximate inverse temporal evolution with the positive phase before the late 1960s and after the middle 1990s, and the negative phase during the interim period. This result suggests that the ENSO–EAWM relationship is likely modulated by the AMO. During the positive AMO phase, ENSO exerts a robust influence on

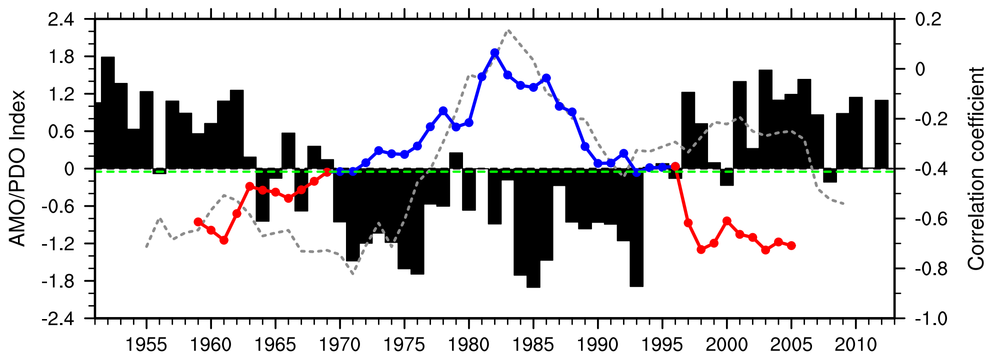

Fig. 3 The raw AMO index (*bar*), 9-year running averaged PDO index (*gray dashed curve*) and the 17-year sliding correlation between the Niño3.4 index and EAWMI (*colored solid curve*) during 1951–2013. The *horizontal green dashed line* indicates the 90% significance level for the correlation (note the *red/blue color* in the *solid curve* means the correlation above/below the 90% confidence level)

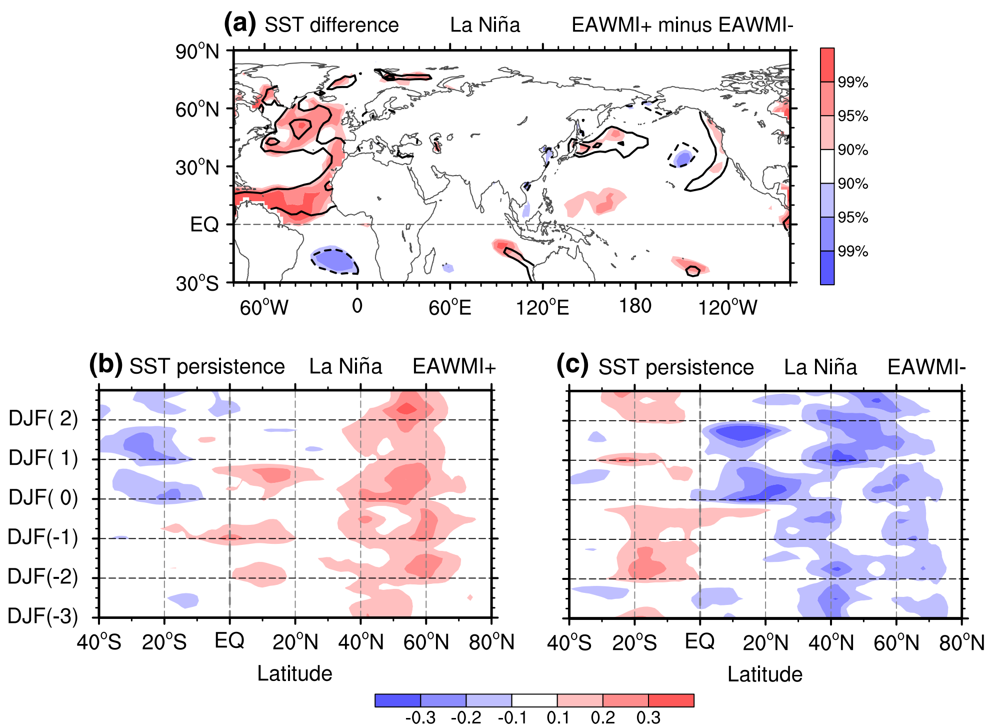

Fig. 4 **a** Composite SST difference (°C) between the La Niña years with positive EAWMI and the ones with negative EAWMI. **b** SST persistence for the La Niña years with positive EAWMI in the Atlantic Ocean (0°–80°W). **c** As **b**, but for the La Niña years with negative EAWMI. The contour interval in **a** is 0.3 °C and the zero isoline is omitted. *Shadings* represent values above the 90, 95, and 99% confidence levels, respectively

the EAWM, which is not the case for the negative AMO phase. However, the decadal modulation by the AMO seems to be active only on the La Niña–EAWM relationship, since El Niño events show stable (independent of the AMO phase) impacts on the EAWM. Thus, the AMO exhibits asymmetric effects on the ENSO–EAWM relationship. The results are qualitatively the same if instead we use the East Asian trough index (Sun and Li 1997) to characterize the EAWM (not shown).

Figure 4 displays the SST anomaly difference between La Niña winters with a positive EAWMI and La Niña winters with a negative EAWMI to examine the mechanism that might explain the possible modulation imposed by the AMO. Almost no significant SST difference (at the 95% confidence level) can be observed across the entire Pacific (Fig. 4a), thereby confirming that the PDO is possibly not the primary decadal modulator of the ENSO–EAWM relationship. In contrast, a pronounced warm SST anomaly

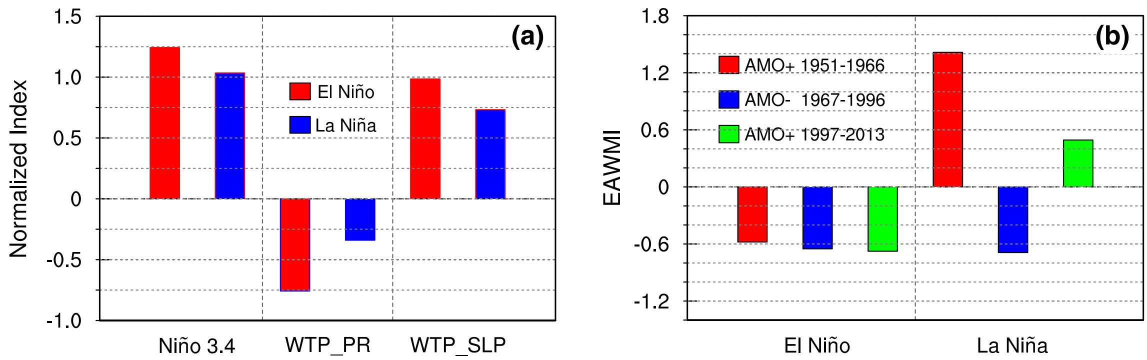

Fig. 5 **a** Composite Niño3.4, WTP_PR, and WTP_SLP indices during El Niño (*red bar*) and La Niña (*blue bar*) winters. The WTP_PR and the WTP_SLP indices are defined as the DJF precipitation and SLP anomalies averaged over the region of 5°–20°N, 140°–170°E. Note the signs of the indices for La Niña winters were reversed for the sake of comparison. **b** Composite EAWMI of the El Niño and La Niña winters during three periods according to the AMO phase

difference (at the 95% confidence level) is evident in almost the entire North Atlantic, which resembles the SST anomaly pattern associated with the AMO. The SST persistence in the North Atlantic is further explored to see whether the observed signal occurs on either decadal or interannual time scales. The SST anomalies, both during La Niña winters with positive and negative EAWMI, are maintained for at least six years in the North Atlantic (Fig. 4b, c). In addition, the ENSO–EAWM linear correlation coefficient over the 17-year sliding window reaches a value of −0.66 with the AMO time series, which increases to −0.84 after a 9-year running mean is performed the unfiltered AMO index. Thus, we demonstrated that the AMO has a strong modulating effect on the La Niña–EAWM relationship.

4 Possible modulation mechanisms by the AMO

4.1 Stable El Niño–EAWM relationship

We first explore the stable impact of El Niño on the EAWM. Figure 5a shows the composite Niño3.4 index and the ENSO-related atmospheric responses over the WNP region for El Niño and La Niña events, respectively. Considering that the WNP acts as a bridge for the ENSO–EAWM connection (e.g., Zhang et al. 1996; Wang et al. 2000), we calculate indices for precipitation and sea level pressure (SLP) anomalies over this region. A strong asymmetry is displayed in the response as a function of the ENSO phase (Fig. 5a), that is, the SST anomalies during La Niña events are weaker than those during El Niño events (e.g., Jin et al. 2003). An even stronger asymmetry is evident for the ENSO-associated atmospheric responses, possibly due to a nonlinear feedback of the atmosphere to the background SST (Wu et al. 2010). The more stable El Niño–EAWM relationship might be explained by the larger amplitude of the ENSO warm phase (positive skewness for ENSO intensity) as well as the inherent nonlinear atmospheric feedback to SST. In contrast, a weaker signal is present in the WNP during La Niña events. As a result, EAWM is more easily dominated by other remote forcings, such as the AMO. Next, we show the composite EAWMI as a function of El Niño and La Niña for three different time periods based on the different AMO phases (Fig. 5b). A weaker than normal EAWM (negative EAWMI) occurs during El Niño events in all three time periods, thereby confirming a stable El Niño–EAWM connection independent of the AMO phase. In contrast, the EAWMI during La Niña winters is clearly dependent on the AMO phase. For La Niña events during a positive AMO phase we observe a positive EAWMI, while a negative AMO is associated with a negative EAWMI.

4.2 Unstable La Niña–EAWM relationship

We now turn to discuss the possible mechanisms responsible for the unstable La Niña–EAWM relationship. We categorize La Niña events into two types according to the AMO phase, that is, La Niña events during a positive AMO phase (AMO+/La Niña) and La Niña events during a negative AMO phase (AMO−/La Niña) (see Table 2). Figure 6 shows the composites of anomalous winter SST, SLP and 850 hPa horizontal winds for these two cases. We observe strong positive SST anomalies (~0.3 °C) to the east of the Philippines for the AMO+/La Niña composite (Fig. 6a). In contrast, no pronounced positive SST anomalies occur in this region for the AMO−/La Niña composite (Fig. 6b). Accordingly, the spatial structures of anomalous atmospheric circulations are expected to be different for the two categories of La Niña events. Pronounced low-level cyclonic circulation anomalies cover both the

Table 2 Category of La Niña events for 1951–2013 period according to the AMO phase

AMO+/La Niña	AMO−/La Niña
1954, 1955, 1962, 1964, 1998, 1999, 2000, 2005, 2007, 2008, 2010, 2011	1967, 1970, 1971, 1973, 1974, 1975, 1984, 1988, 1995

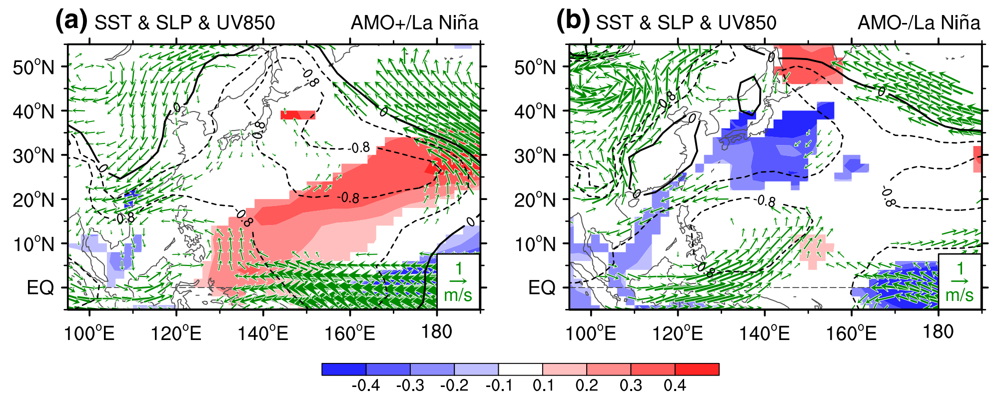

Fig. 6 Composites of anomalous SST (*shading* in °C), SLP (contours in hPa, from −0.8 to 0 by 0.4) and 850 hPa horizontal wind (*vector* in m/s) for the cases of **a** AMO+/La Niña and **b** AMO−/La Niña. The SST and wind anomalies are only displayed when they are significant at the 90% confidence level

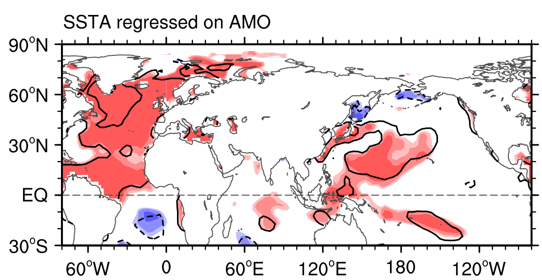

Fig. 7 Regressed SST anomalies (*contour* in °C, from −0.1 to 0.3 by 0.2) with respect to the AMO index. *Shading* represents the values above the 90, 95, and 99% confidence levels, respectively

WNP and East Asia expanding from the tropics to 50°N for the AMO+/La Niña composite (Fig. 6a). Being part of the well-developed anomalous cyclone, northerly wind anomalies are evident over East Asia and hence the EAWM is strengthened. In contrast, the amplitude of the WNP cyclonic anomalies is strongly reduced and their expansion is drastically confined to the tropics for the AMO−/La Niña composite (Fig. 6b). Therefore, the cyclonic circulation anomalies seem to have no strong effect on the EAWM.

Evidently, the distinct differences of SST and related atmospheric circulation anomalies over the WNP between the AMO+/La Niña and AMO−/La Niña composite could be closely linked to the different AMO phases. To understand the role of the AMO in the development and maintenance of the associated climate anomalies, we display in Fig. 7 the regressed SST anomalies upon the AMO index. The spatial SST pattern associated with the positive AMO phase (Fig. 7) shows very similar positive SST anomalies in the WNP region as the AMO+/La Niña composite (Fig. 6a). This result is in line with many previous studies (e.g., Kucharski et al. 2011; Hong et al. 2013), which pointed out that the Atlantic warming could increase the zonal SST gradient in the tropical Pacific via a modification of the Walker circulation involving low-level wind anomalies in the central-western Pacific (e.g., Kucharski et al. 2011; McGregor et al. 2014). This process may be further amplified by the local moisture feedback since the WNP is the mean moisture convergence region resulting from the surface wind field and high SSTs (Hong et al. 2013). We also utilize the partial regression method here to linearly remove the impact of simultaneous PDO, and the result remains unchanged (Figures not shown). Thus, if a La Niña event occurs during a positive AMO phase, the warm SST anomalies in the WNP will be amplified, while being reduced during a negative AMO phase. As a result of a Gill–Matsuno-type response (Matsuno 1966; Gill 1980), the local atmospheric cyclonic circulation anomalies will be enhanced during a positive AMO phase (reduced during a negative AMO phase), both in intensity and spatial extent.

It now seems easy to understand the strengthened EAWM for the AMO+/La Niña case. The scientific question that remains to be answered is what is the external forcing for the significantly weakened EAWM in the AMO−/La Niña case since it is not possibly attributable to

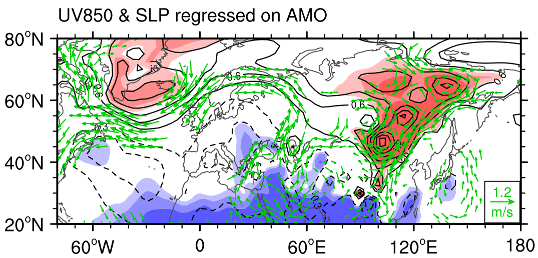

Fig. 8 Regressed anomaly patterns of SLP (*contour* in hPa) and 850 hPa horizontal winds (*vector* in m/s) with respect to the AMO index. *Contour* interval is 0.3 hPa and the zero isoline is omitted. *Shading* represents the SLP values exceeding the 90, 95, and 99% confidence levels, respectively. The wind anomalies are shown only when the zonal or meridional wind anomalies are significant at the 90% confidence level

the tropical Pacific anomalies. We note that the two composite patterns feature prominent anticyclonic and cyclonic circulation anomalies over the Lake Baikal region, respectively (Fig. 6). This suggests that the AMO signal may also impose a mid-high latitudinal pathway to influence the ENSO–EAWM relationship. To detect the possible teleconnection pathway over the mid-latitudes of Eurasia, we display in Fig. 8 the regressed anomalous 850 hPa winds and SLP with respect to the AMO index. Over the North Atlantic, an anomalous low-level anticyclone and cyclone appear north and south of about 50 N, respectively. This anomalous atmospheric circulation pattern resembles the negative phase of the North Atlantic Oscillation (NAO), as demonstrated by earlier studies (Grossmann and Klotzbach 2009; Gastineau and Frankignoul 2015). The pattern is characterized by a prominent wavetrain of two alternating positive and negative polarity centers extending eastward from the North Atlantic to East Asia (Fig. 8). East Siberia and Japan are controlled by high and low pressure anomalies (i.e., anticyclonic and cyclonic circulation anomalies), respectively. The associated anomalous northerlies prevailing over East Asia are then favorable for a stronger EAWM. Correspondingly, the aforementioned anomalies in the mid-high latitudes of Eurasia are basically reversed during a negative AMO phase. Figure 9 demonstrates the vertical structure of the wavetrain pattern and its associated wave activity flux (WAF). The WAF is calculated following the study of Takaya and Nakamura (2001), and defines the tendency of wave energy propagation. For both AMO+/La Niña and AMO−/La Niña composites, the wave energy is clearly propagating eastward from the extratropical North Atlantic to East Asia across the mid-high latitudes of the

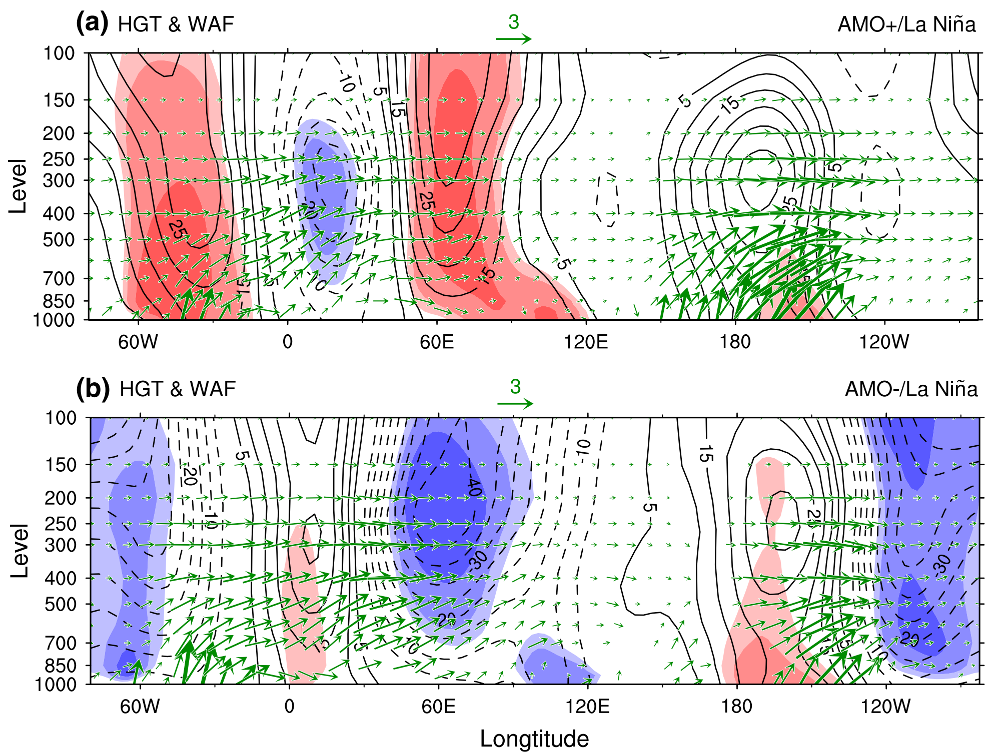

Fig. 9 Meridional mean (40°–65°N) anomalies of the wave activity flux (*vector* in m^2/s^2) and geopotential height (*contour* in gpm) for the cases of **a** AMO+/La Niña and **b** AMO−/La Niña. The contour interval is 5 gpm and the zero isoline is omitted. *Shading* represents the values for geopotential height anomalies above the 90, 95, and 99% confidence levels, respectively. The *vertical* component of the wave activity flux is multiplied by a factor of 100 for better visualization

Eurasian continent, thus suggesting an important modulating effect on East Asian climate by the AMO. The signal of the wavetrain is also clearly detected in the geopotential height anomalies, but with an approximately opposite zonal structure for the two cases (Fig. 9). Thus, robust high pressure anomalies occurring over the area between 60° and 120°E are favorable for the occurrence of a stronger than normal EAWM for La Niña events during a positive AMO phase, while low pressure anomalies are occurring in the same region, which are favorable for a reduced EAWM for La Niña events during a negative AMO phase. Therefore, if La Niña coincides with a positive AMO, the EAWM will be intensified owing to the superimposed local (cyclonic circulation anomalies over the WNP) and remote (a Rossby wavetrain across the mid-high latitudes of Eurasia) effects. In contrast, if La Niña coincides with a negative AMO, the weakened EAWM seems to be mainly attributable to the mid-high latitudinal signal associated with the AMO (remote effect).

4.3 AMIP-style simulations

We further explore our hypotheses based on the observational analyses using numerical modeling experiments. The atmospheric general circulation model (AGCM) developed by the Geophysical Fluid Dynamics Laboratory (GFDL AM3) is utilized to examine whether the asymmetric modulation of the ENSO–EAWM relationship by the AMO can be simulated. The AM3 model is the atmospheric component of the new GFDL coupled atmosphere–ocean GCM CM3 with a horizontal resolution of 2.0° × 2.5° and 48 vertical levels. This model has an implemented prognostic representation of aerosol–cloud interactions, and interactive gas-phase chemistry and aerosol chemistry (see Donner et al. (2011) for more details). The simulations are forced with Atmospheric Model Intercomparison Project (AMIP)-style SST boundary conditions from 1979 to 2008, which covers the latest phase transition of the AMO in the observations. We utilize an ensemble average of five simulations with perturbed initial conditions for better reliability. Although some biases exist in the simulated atmospheric responses to ENSO, such as a stronger anomalous Aleutian low and a relatively localized anomalous WNP anticyclone (see Figs. 6, 11c, d), which may be caused by the overestimated SST forcing and the absent Pacific air–sea coupling processes in AGCMs (Wu et al. 2006), the AM3 model possesses a good ability to simulate East Asian atmospheric responses associated with ENSO (Wang et al. 2013a).

The composite EAWMI and the associated atmospheric circulations for different combinations of ENSO and AMO

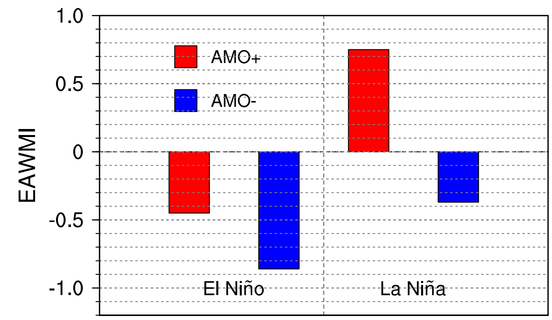

Fig. 10 Composites of simulated EAWMI for the El Niño and La Niña winters during the positive and negative AMO phases. The *red* and *blue bars* represent the positive and negative AMO phase, respectively

phases simulated by the AM3 model are shown in Figs. 10 and 11, respectively. The asymmetric AMO modulation on the ENSO–EAWM connection is well captured by the AM3 simulations. During El Niño events, East Asia experiences a reduced winter monsoon, independent of the AMO phase (Fig. 10). The strong modulation of the La Niña–EAWMI relationship by the AMO (i.e., strengthened EAWM in the AMO+ and weakened EAWM in the AMO− phases), is also realistically simulated (Fig. 10). Next, the simulated spatial patterns of the anomalous atmospheric responses for the four phase combinations of ENSO and AMO are examined (Fig. 11). Regardless of the AMO phase (positive or negative), El Niño events tend to result in a large-scale anomalous low-level anticyclonic circulation over the WNP, thereby causing a weaker than normal EAWM. As discussed before, it seems that the WNP atmospheric responses to El Niño are too large in amplitude to be apparently disturbed by other low frequency signals, as seen in the observations (Fig. 5). In contrast, the condition of the EAWM associated with La Niña events clearly dependents on the AMO phase also in the simulations (Fig. 11). Pronounced low-level cyclonic circulation anomalies (i.e., low pressure anomalies) cover both the tropics and mid-latitudes for the AMO+/La Niña composite, resulting in a strengthening of the EAWM. In contrast, the cyclonic anomalies for the AMO−/La Niña composite are confined to the tropics (~20°N) while to the north an anomalous anticyclone is present. The model simulated zonal cross sections of the geopotential height anomalies for the AMO+/La Niña and AMO−/La Niña combinations are shown in Fig. 12 to explore the mid-high latitudinal atmospheric responses forced by SST associated with the AMO. Similar to the observations shown in Fig. 9, the AMIP-style experiments reproduce a wavetrain extending eastward from the North Atlantic to East Asia with approximately opposite

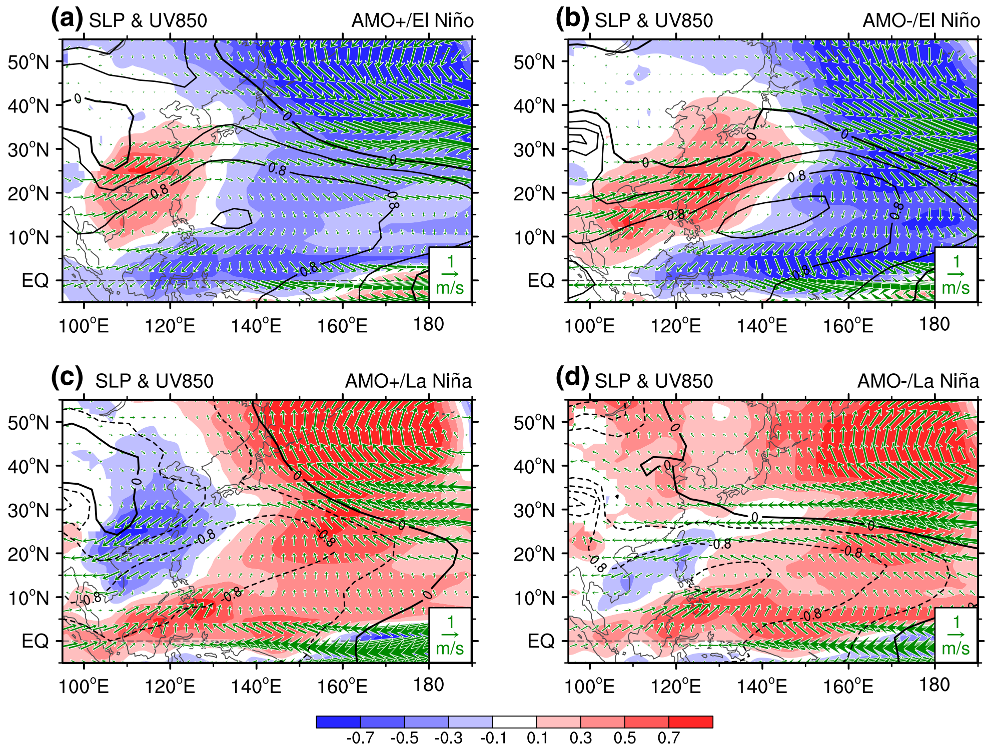

Fig. 11 Model simulated composites of anomalous 850 hPa meridional wind (*shading* in m/s), SLP (*contours* in hPa) and 850 hPa *horizontal* wind (*vectors* in m/s) for the cases of **a** AMO+/El Niño, **b** AMO−/El Niño, **c** AMO+/La Niña and **d** AMO−/La Niña. The *contours* are from 0 to 1.2 by 0.4 for **a** and **b**, and from −1.2 to 0 by 0.4 for **c** and **d**

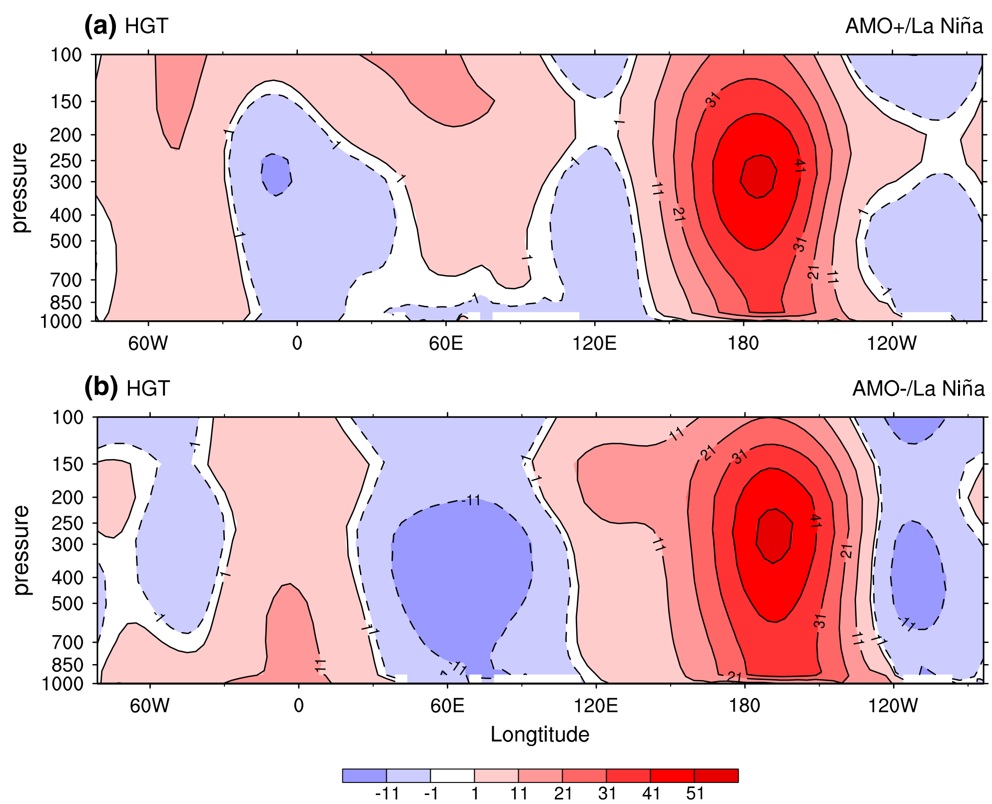

Fig. 12 Model simulated zonal cross section of the composite anomalous geopotential height (*contour* and *shading* in gpm) averaged over 30°–60°N for the cases of **a** AMO+/La Niña and **b** AMO−/La Niña

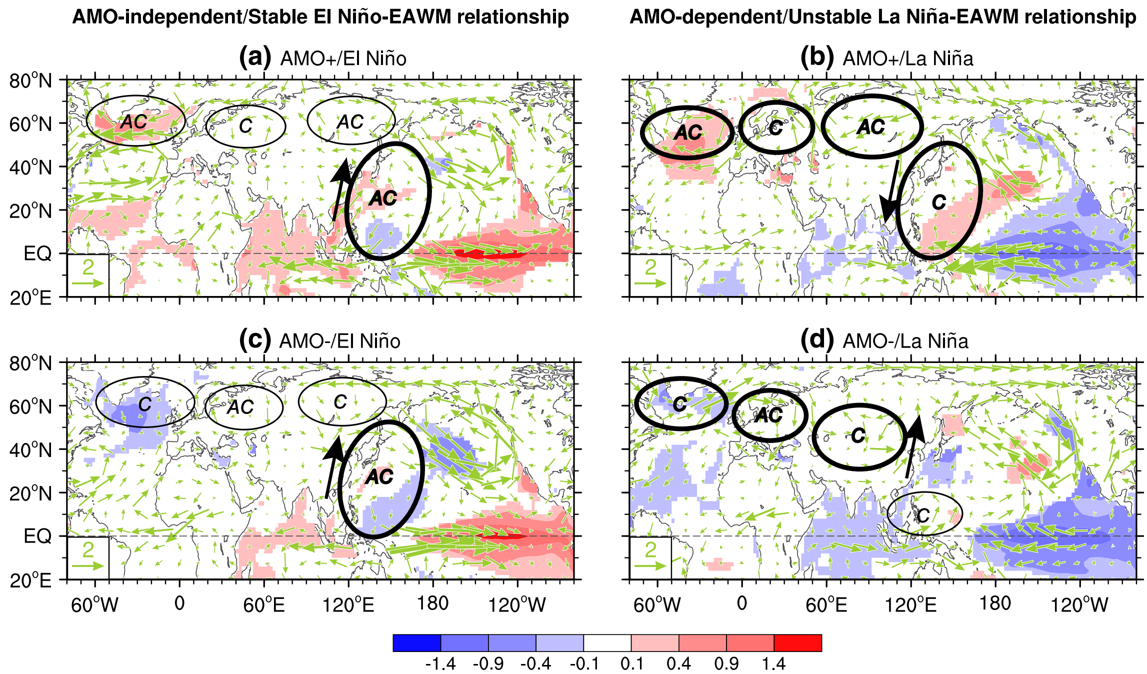

Fig. 13 Schematic for the decadal modulation of the AMO on the ENSO–EAWM relationship for the cases of **a** AMO+/El Niño, **b** AMO+/La Niña, **c** AMO−/El Niño and **d** AMO−/La Niña. The DJF SST and 850 hPa wind anomalies are displayed by *shadings* and *green vectors*, respectively. The SST anomalies that are not significant at 90% confidence level are not shown and the anomalous low-level anticyclones (AC) and cyclones (C) are indicated by *ellipses*, note that the *thick ellipses* mean the teleconnections play a significant role in determining the ENSO–EAWM relationship while the impacts of the *thin ellipses* are negligible. The *black arrows* qualitatively denote the prevailing wind fields for the four cases, respectively

anomalies over the Eurasian continent for the AMO+/La Niña and AMO−/La Niña cases. The consistency between the observations and simulations increases our confidence for the aforementioned mechanisms responsible for the asymmetric modulation of the ENSO–EAWM relationship by the AMO.

5 Conclusions and discussion

The present study demonstrates the asymmetric decadal modulation of the ENSO–EAWM relationship by the AMO and its associated mechanisms based on both observational analyses and AMIP-style simulations. The 17-year sliding window ENSO–EAWM correlation varies consistently with the AMO phase rather than the PDO phase. During a positive AMO phase, a significant negative correlation ($R = -0.67$, 99% confidence level) is found between ENSO and EAWMI, while this correlation breaks down for the negative AMO phase. The decadal variability of the ENSO–EAWM relationship is mainly attributable to the unstable impacts of La Niña on the EAWM. Almost all El Niño winters (except 3 events) are accompanied by a weaker than normal EAWM since El Niño-related low-level anticyclonic anomalies are present over the WNP tend to transport more warm and moist water vapor towards East Asia. This relationship is independent of the AMO phase likely because of the larger amplitude of El Niño SST anomalies and their associated nonlinear atmospheric impacts. In contrast, the La Niña–EAWM relationship depends crucially on the AMO phase. La Niña boreal winter seasons coincide with a strengthened EAWM during a positive AMO phase and a weakened EAWM during a negative AMO. In comparison with El Niño, the tropical SST anomalies and their associated atmospheric responses during La Niña events are usually weaker (Wu et al. 2010). Hence, La Niña impacts on the EAWM are more easily influenced by a remote AMO signal.

We suggest that the AMO influences the La Niña–EAWM relationship via two different pathways. On one hand, the AMO phase could modify the anomalous SST over the WNP through a modulation of the Walker circulation (e.g., Kucharski et al. 2011; McGregor et al. 2014) and the moisture feedback in the WNP (Hong et al. 2013), which are closely associated with La Niña's impacts on the EAWM. During La Niña events coinciding with a positive AMO phase, strong and large-scale positive SST anomalies occur over the WNP, which tend to enhance the circulation anomalies via coupled air–sea feedbacks (e.g., Wang et al. 2000; Stuecker et al. 2015). As a result, East Asia tends to experience low-level northerly wind anomalies and a strengthened EAWM. In contrast, no pronounced SST anomalies are evident over the WNP during La Niña winters coinciding with a negative AMO. Furthermore, the corresponding low-level cyclonic anomalies over the WNP are drastically confined to the tropics, thus exerting no strong effect on the EAWM.

On the other hand, the AMO could modify the atmospheric anomalies over Siberia via downstream energy propagation at the mid-high latitudes over Eurasia and thus further impact the EAWM. The atmospheric circulation anomalies associated with the AMO manifest a distinct Rossby wavetrain extending eastward to East Asia. During AMO positive phase, high pressure and anticyclonic anomalies are evident over East Siberia, which are favorable for an enhanced EAWM. During a negative AMO phase, the aforementioned situation over Eurasia is largely reversed and the EAWM is weakened. The observed features are well captured by the AM3 model in an AMIP-style simulation. These modeling results further strengthen our possible mechanisms explaining the asymmetric decadal modulation of the ENSO–EAWM by the AMO. As a summary, a schematic (Fig. 13) for the decadal AMO modulation of the ENSO–EAWM relationship is provided. Note that the different AMO spatial structures between Fig. 13a and b (or Fig. 13c, d) could be the results of an ENSO modulation since ENSO also influences the Atlantic SST variability on interannual timesacle (e.g., Saravanan and Chang 2000).

In the present study, we emphasize an Atlantic multidecadal modulation signal (i.e., AMO) in the ENSO–EAWM relationship. It should be noted that the EAWM might also be influenced by interannual SST variability in North Atlantic (Han et al. 2011; Liu et al. 2014), which may partly account for the existing uncertainty of AMO modulation on the La Niña–EAWM inter-relationship (i.e., the 2000 and 2008 events in Fig. 2c are in a positive AMO phase but feature intensified EAWMs). In addition, many other external factors, such as, Eurasian snow depth (Li and Wang 2014), Arctic SST and sea ice concentration (Wu et al. 2011; Li and Wu 2012; Chen et al. 2014b), solar cycle activity (Zhou et al. 2013), and the warming in the northern Indian Ocean (Watanabe and Jin 2002), may also impact the winter monsoon circulations.

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