Weaker connection between the Atlantic Multidecadal Oscillation and Indian summer rainfall since the mid-1990s

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ABSTRACT
Previous studies have shown that the Atlantic Multidecadal Oscillation (AMO) can play an important role in modulating the variability of Indian summer monsoon rainfall (ISMR) over a 50–60-yr timescale. A significant positive correlation between the AMO and ISMR is found both in observations and models. However, instrumental records show that the relationship becomes non-significant or even of opposite sign after the mid-1990s, suggesting a weakening of the AMO–ISMR connection. The mechanism for the breakdown of the AMO–ISMR connection is investigated in the present work, and the results suggest that a substantial warming in the Indian–tropical western Pacific Ocean plays a role. The warming weakens the meridional gradient of tropospheric temperature between Eurasia and the Indian Ocean, and reduces the meridional sea level pressure gradient between the Indian Subcontinent and Indian Ocean, weakening the Indian summer monsoon. Thus, warming in the Indian–tropical western Pacific Ocean seems responsible for the weakened connection between the AMO and ISM.

1. Introduction
The Indian summer monsoon rainfall (ISMR) has been observed to have multidecadal variability, with less rainfall during the periods 1901–1930 and 1961–1990, and more rainfall during 1871–1900 and 1931–1960 (Parthasarathy, Munot, and Kothawale 1994; Krishnamurthy and Krishnamurthy 2013; Ding et al. 2013; Shi, Li, and Wilson 2014). This multidecadal variability, with a period of approximately 60 years, is in-phase with the Atlantic Multidecadal Oscillation (AMO) (Zhang and Delworth 2005b; Goswami et al. 2006; Li et al. 2008).

The AMO is a leading pattern of decadal variation in sea surface temperatures (SSTs) in the North Atlantic, characterized by an alternating basin-scale warming and cooling with a regular periodicity of 65–80 years and an amplitude of 0.4 °C (e.g. Enfield, Mestas-Nunez, and Trimble 2001). The AMO has been considered to be an internal climate variability associated with the Atlantic Meridional Overturning Circulation (AMOC), and even described as its observable fingerprint (e.g. Delworth and Mann 2000; Knight et al. 2005; Zhang and Delworth 2005a; Yu et al. 2009; Drinkwater et al. 2014; McCarthy et al. 2015).

Several paleoclimate studies have implied a positive correlation between North Atlantic SSTs and ISMR (Chauhan et al. 2000; Burns et al. 2003; Gupta, Anderson, and Overpeck 2003; Wang et al. 2013), and modeling studies have suggested that a positive-phase (negative-phase) AMO can give rise to enhanced (weakened) ISMR (e.g. Lu, Dong, and Ding 2006; Li et al. 2008; Wang, Li, and Luo 2009).
The physical mechanisms for the connection can be classified into two types: air–sea interactions (Zhang and Delworth 2005a; Lu, Dong, and Ding 2006; Zhou et al. 2015), and atmospheric teleconnections alone (Goswami et al. 2006; Feng and Hu 2008; Li et al. 2008; Wang, Li, and Luo 2009; Luo, Li, and Furevik 2011). Zhang and Delworth (2005a), based on a fully coupled ocean–atmosphere model (GFDL CM2.1), indicated that a large reduction in the AMOC (corresponding to a negative AMO) can lead to a southward shift of the ITCZ over the Atlantic and Pacific. This shift weakens the surface trade winds over the Pacific, and induces an El Niño–like (La Niña–like) pattern in the southeastern (northeastern) tropical Pacific, which results in a weakened (stronger) Walker circulation and then weaker ISMR. Zhou et al. (2015) suggested that a positive-phase AMO can lead to an Indo-Pacific warm SST response, and then enhanced easterlies in the equatorial western Pacific, and finally an intensification of ISMR. On the other hand, Li et al. (2008) and Wang, Li, and Luo (2009) proposed that a positive AMO causes tropospheric warming over Europe and western Asia, and increases the meridional temperature gradient between Eurasia and the Indian Ocean, thus strengthening the ISMR. Their results were based on AGCM sensitivity experiments with positive AMO–related SST anomalies (SSTAs). Additionally, Luo, Li, and Furevik (2011) analyzed a 600-yr simulation with the Bergen Climate Model and suggested that a positive AMO can excite a Rossby wave train from the North Atlantic across South Asia, which can increase the meridional temperature gradient between Eurasia and the Indian Ocean and intensify the ISMR.

Although the above studies have shown that the AMO has a substantial impact on ISMR, the connection between the two cannot be observed in the last 20 years, as manifested in the temporal evolutions of the AMO and ISMR indices (Figure 1). Until the mid-1990s, they vary in-phase, having a correlation coefficient of 0.60. However, in the last 20 years, the connection weakens significantly, or is even opposite (Sankar et al. 2016). For example, during the periods of the 1900s–1930s and 1960s–1990s, a negative AMO corresponds roughly to dry ISMR; whereas, during the 1930s–1960s, a positive AMO corresponds to a wet ISMR phase. However, since the mid-1990s, when the AMO turned into a positive phase, ISMR has remained in a dry phase, in contrast to previous findings and perceptions (Figure 1). In this study, we address whether the change in the AMO–ISMR connection is due to multidecadal variability of SST beyond the Atlantic Ocean.

### 2. Datasets

Two sets of observational SST are used. One is from the Kaplan Extended monthly SST data-set (Kaplan et al. 1998), on a 5° × 5° grid, and the other is the Met Office Hadley Centre’s monthly SST data-set (HadISST) (Rayner et al. 2003), gridded to 1.0° latitude by 1.0° longitude. Also, two sets of observational precipitation are employed – one from the Climate Research Unit (CRU) TS 3.1 data-set (Mitchell and Jones 2005), on a 0.5° × 0.5° grid, and the other from the Global Precipitation Climatology Centre (GPCC) (Rudolf et al. 2005), on a 1.0° × 1.0° grid. In addition, the sea level pressure (SLP), horizontal wind component (U and V) and air temperature (T\textsubscript{a}) are from the twentieth Century Reanalysis (V2) data-set, on a 2.0° × 2.0° grid (Compo et al. 2011). The study period is 1901–2010, which is the period during which all the datasets overlap.

The AMO index series is from the NOAA PSD website (https://www.esrl.noaa.gov/psd/data/timeseries/AMO/), while the Pacific Decadal Oscillation (PDO) index series is from JISAO, University of Washington (http://research.jisao.washington.edu/pdo/PDO.latest.txt). A total of three ISMR index series are used. The first is from observations at more than 300 stations in Indian subcontinent (Sankar et al. 2016), referred to as ‘ISMR(station).’ The two others are calculated as the seasonal (June–September) averaged land precipitation over India (10°–30°N, 60°–90°E) based on the CRU and GPCC datasets (Goswami et al. 2006; Li et al. 2008), referred to as ‘ISMR(CRU)’ and ‘ISMR(GPCC),’ respectively. All these datasets are linearly detrended to reduce the anthropogenic forcing signal.

### 3. Results

The AMO has one and a half cycles during 1901–2010 (Figure 1). Considering the uncertainty in the data quality in the earlier period, three AMO extreme periods after 1920 that fall outside the range of ±0.5 standard deviations of the AMO index are selected for composite analysis. There is one cold period from 1967 to 1993 (referred to as ‘N1’), and two warm periods from 1930 to 1959 (referred to as ‘P1’) and from 1997 to 2010 (referred to as ‘P2’).
Figure 2 shows the composite precipitation anomaly for the three AMO periods. In the first two periods, it can be clearly seen that P1 corresponds to increased precipitation, and N1 to decreased precipitation, over the Indian subcontinent. Specifically, P1 yields a dipole pattern, with more precipitation in central-northern India and less precipitation to the south (Figure 2(a) and (d)), while N1 is characterized by less precipitation in much of India (Figure 2(b) and (e)). P1 has positive values of 7.3 and 4.1 mm/month, and N1 negative values of −2.0 and −1.4 mm/month, for CRU and GPCC, respectively. The above analyses agree with previous studies showing that a positive (negative) AMO favors more (less) summer precipitation in India (e.g. Li et al. 2008; Wang, Li, and Luo 2009). However, P2 is characterized by decreased precipitation in India, particularly in northern India, showing negative values of −7.0 and −5.3 mm/month (Figure 2(c) and (f)). As mentioned in the introduction, the positive correlation between the AMO and ISMR has weakened, and even become negative in the last two decades.

Figure 3 displays the SSTA composites for the three periods. The North Atlantic SSTA shows an overall basin-scale
warming and cooling for the warm and cold periods, respectively. Relative to P1 and N1, the most significant difference can be found in the Indian–tropical western Pacific Ocean (In+WesP) (30°S–20°N, 50°–150°E), with the substantial warm anomalies in P2 (Figure 3). Next, we compare the temporal series of the averaged SSTA in the In+WesP with the ISMR indices. Considering the important role of the PDO in modulating the ISMR (Krishnamurthy and Krishnamurthy 2014; Zhu et al. 2015; Zhu, Wang, and Ma 2016), a comparison between the PDO and the ISMR indices is also conducted. As previous studies suggest, there is a negative correlation between the In+WesP SSTA and ISMR, as well as the PDO (Krishnamurthy and Krishnamurthy 2014, 2015). Hence, it can be speculated that the variability of ISMR results from the joint action of the three SSTA factors. For example, the ISMR is in its positive phase in P1 but with weaker amplitude during 1930–1945 (first half of P1) relative to 1945–1960 (second half of P1). The reason can be ascribed to the change of the In+WesP and PDO (Figure 1). In+WesP SSTSs begin to increase around the mid-1980s. The PDO turns into a positive phase in the early 1980s, and enters a negative phase in the late 1990s (Figure 1). Therefore, the dry phase after 1995 results from the impact of the In+WesP SSTA alone.

Figure 4 shows mid- and upper-tropospheric heating anomalies composites. In P1, there is significant heating from the North Atlantic to northern Africa and the Eurasian continent, with a heating center over the south of the Caspian Sea, which tends to increase the meridional thermal contrast between the continent and the Indian Ocean (0.29 °C) and thus intensify the ISMR (Figure 4(a)). This agrees with previous model-based studies (Li et al. 2008; Wang, Li, and Luo 2009). However, the heating belt in P2 moves toward the south relative to P1, leading to an opposite meridional thermal contrast (−0.29 °C) and ISMR. The southern shift of the heating belt may be related to a warming in the tropical Ocean, especially in the Indian Ocean (0.29 °C) and thus intensify the ISMR (Figure 4(a)). This agrees with previous model-based studies (Li et al. 2008; Wang, Li, and Luo 2009). However, the heating belt in P2 moves toward the south relative to P1, leading to an opposite meridional thermal contrast (−0.29 °C) and ISMR. The southern shift of the heating belt may be related to a warming in the tropical Ocean, especially in the Indian Ocean (Figure 4(c)) and western tropical Pacific. In addition, N1 mainly shows weak cooling signals in the middle and upper troposphere, with a negative meridional gradient of −0.07 °C (Figure 4(b)).

Next, we look at the atmospheric circulation (Figure 5). A Gill pattern can be seen over the In+WesP in P2, showing low-pressure anomalies over the equator and
high-pressure anomalies off the equator. The Gill pattern is associated with basin-scale warming in the In+WesP. In terms of the horizontal winds at 850 hPa, there are easterly anomalies from the Bay of Bengal to the Arabian Sea and Indian Ocean, which tend to abate the climatological southwesterly winds and then reduce the amount of moisture transported from the Indian Ocean (Figure 5(c)). In P1, low-pressure anomalies mainly exist over the Arabian Sea, which correspond to southwesterly anomalies over coastal Africa and the Arabian Sea, bringing moisture into the Indian subcontinent (Figure 5(a)). Low-pressure anomalies in N1 are found over the Indian subcontinent. Hence, northerly anomalies along the western rim of the anomalous low-pressure system may obstruct moisture from the Indian Ocean (Figure 5(b)), thus reducing the ISMR.

4. Summary and discussion

In this study we employ composite analysis to compare the climatic patterns in different AMO phases to investigate how decadal SST variability can influence the AMO–ISMR connection. The substantial warming in the In+WesP may play a role in weakening the connection between the AMO and ISMR in the last two decades. This warming tends to diminish the meridional gradient of tropospheric temperature between Eurasia and the Indian Ocean, and reduce the meridional SLP gradient between the Indian subcontinent and the Indian Ocean, thus weakening the ISMR. Hence, warming may affect the physical processes involved in the AMO’s modulation of the ISMR.

It is important to note that this study is subject to limitations with respect to the length and quality of the instrumental data in the earlier period, thus making it difficult to identify the nature of the relationships between the decadal SST variability and ISMR. If this result is reasonable, it should be more significant under stronger warming scenarios simulated within the CMIP5 framework — an aspect we intend to analyze in the next step of our research. Besides, the AMO and ISMR could also be influenced by solar, volcanic, and anthropogenic aerosol forcings (Otterå et al. 2010; Bollasina, Ming, and Ramaswamy 2011; Chylek et al. 2011; Booth et al. 2012). To better understand the
roles played by these various forcing mechanism, we plan to conduct a comprehensive analysis using dedicated AGCM experiments and the simulations available from the range of coupled models in CMIP5.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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**Figure 5.** The SLP (shading) and 850-hPa horizontal wind (vector) composite in three different AMO phases. The dots indicate statistical significance at the greater than 95% confidence level. For the SLP, black dots indicate statistical significance at the 0.05 level. For the wind, only regions where the wind is statistically significant at the 0.05 level are shown. The reference wind speed is given in the lower-right corner. Units: hPa and m s$^{-1}$. 
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