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Weakening relationship between East Asian winter monsoon and ENSO after mid-1970s

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The East Asian winter monsoon (EAWM) is characterized by the frequent cold surges and associated closely with the Siberia High, East Asian Trough, and high-level westerly jet stream. The ENSO cycle can modulate the EAWM since it has co-variability with the sea surface temperature over the Indo-Western-Pacific which can tune the land-sea thermal contrast for the EAWM. This paper, by analyzing the EAWM, ENSO, and associated atmosphere-ocean variability, documents the weakening of the EAWM-ENSO relationship after the 1970s. The significant out-of-phase inter-relationship is found to be diminished after the 1970s. Further study in this work suggests that the weakened co-variability of the tropical Indo-Western-Pacific climate associated with ENSO after the 1970s is partly responsible for the weakened inter-relationship. Meanwhile, the reduced EAWM interannual variability and northward retreat of the EAWM-associated climate variability are favorable to the weakened ENSO-EAWM connection.

East Asian winter monsoon, ENSO, interdecadal variability, interannual variability

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The East Asian winter monsoon (EAWM) is characterized by the frequent cold surges in the lower atmosphere and has broad impact on the climate of Asia and tropical Indo-Pacific [1]. The EAWM is closely associated with the Siberia High in low atmosphere, the East Asian Trough in middle troposphere, and the westerly jet stream in high troposphere. In the past years, there has been increased disasters in China resulted by anomalous East Asian winter monsoon and associated snowstorms [2–4].

There is remarkable interannual and interdecadal variability of EAWM [5–9]. The out-of-phase relationship between ENSO and EAWM variation was documented by Webster and Yang [10], Zhang et al. [11], and Lau and Nath [12]. Gong et al. [13] indicated the connection between variability of the Arctic Oscillation and EAWM. Thus the EAWM is mainly regulated by the ENSO cycle and the Arctic Oscillation in the interannual variability. Recently, Liu et al. [14] indicated that the Arctic sea ice content has substantial impact on the EAWM, winter temperature and snowstorm activity.

However, both the EAWM and ENSO have the decadal and interdecadal fluctuations, accompanied by complex variation of the climate regimes [15–17]. The inter-relationship between the East Asian summer monsoon and ENSO is not stable from decades to decades [18]. The instable linkage of the summer monsoon to ENSO leads to low ENSO-induced climate predictability in East Asia. Thus the long-term variation of the EAWM-ENSO connection is important, but has not been well recognized so far.

In this paper, we will first verify the moving correlation coefficient between the EAWM and ENSO index and then analyze the associated atmospheric and oceanic climate variability in the two typical periods with high and low inter-relationships respectively. Since our concern in this paper is

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the inter-decadal variability, we adopted 23-years sliding window for analyzing the moving correlation.

The data sets employed in this research include the National Centers for Environmental Prediction (NCEP) 2.5°× 2.5° resolution reanalysis for 1948–2010 [19], and the sea surface temperature (SST) data with 2.0°×2.0° resolution from the National Oceanic and Atmospheric Administration (NOAA) [20]. The East Asian winter monsoon index (EAWMI) is defined as the mean geopotential height at 500 hPa in the area of（25°–45°N, 110°–145°E）to describe the East Asian trough that closely associated with the EAWM and cold surge activity. Since the Aleutian low pressure system is a dominant mode in North Pacific, we will also investigate its relationship to ENSO. The sea-level pressure averaged in the region of (155°E–130°W, 30°–70°N) is defined as the index of Aleutian Low (ALI). In this paper, the December-January-February (DJF) mean is taken to stand for the boreal winter. The Niño3.4 index is computed as the mean SST in the tropical eastern Pacific (170°–120°W, 5°N–5°S) to describe the phase of ENSO.

1 The weakening relationship between EAWM and ENSO after the 1970s

We first plotted the temporal variation of the EAWMI and Niño3.4 in Figure 1. Clearly, the EAWM becomes much weakened after mid-1980s. Meanwhile the interannual

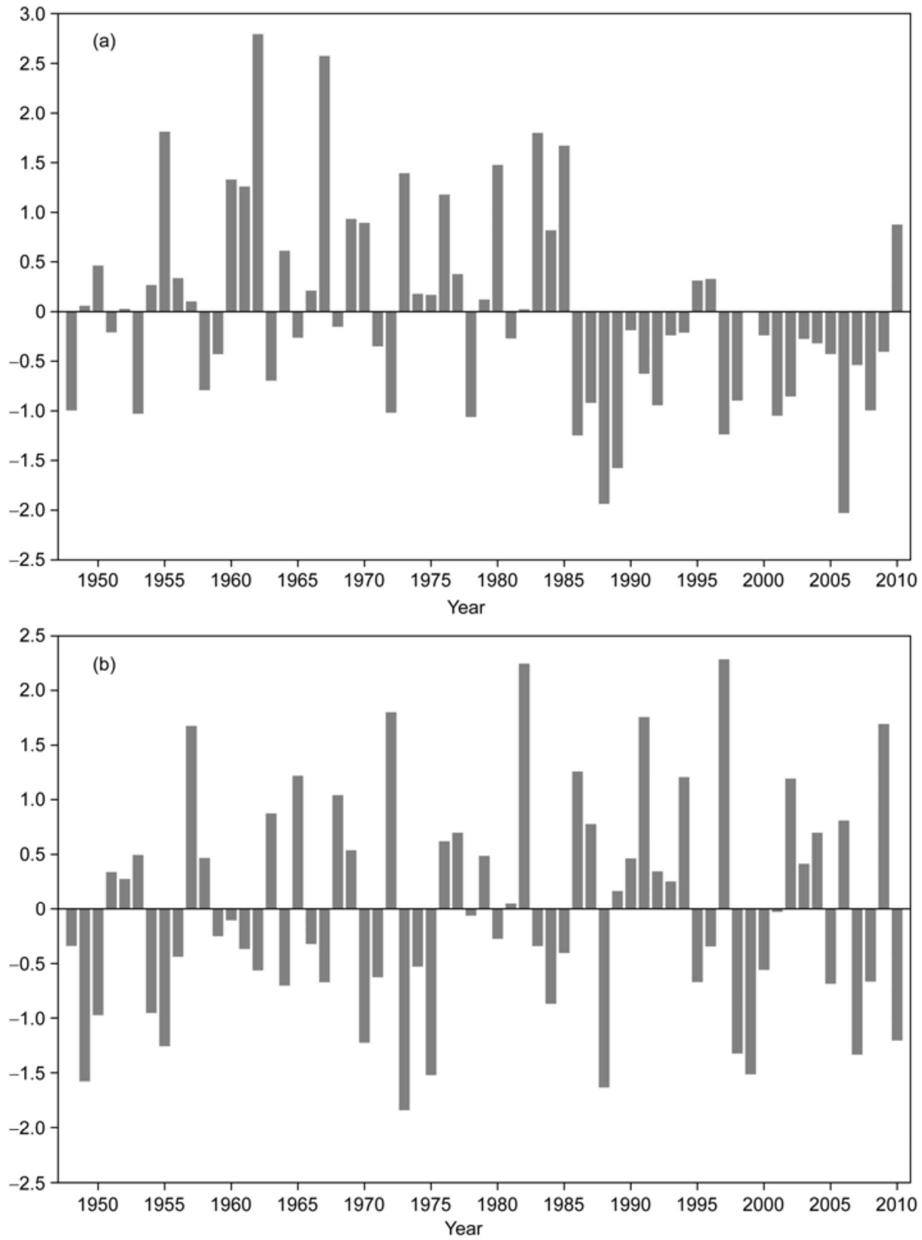

Figure 1 The interannual variation of the DJF mean EAWMI (a) and Niño3.4 SSTA index (b) during 1948–2010.

variability is also reduced in the latter period. Comparatively, there is no significant long-term change in Niño3.4 for both the mean strength and interannual variability. We then computed the sliding correlation coefficient between the EAWMI (ALI) and Niño3.4 during 1948–2010, with 23 years moving window. Figure 2 indicates that Niño3.4-EAWMI out-of-phase correlation was quite significant before mid-1970s, but insignificant thereafter. In contrast, the out-of-phase relationship between Niño3.4 and ALI experienced a reverse process, from insignificant to significant correlations.

Thus it seems that ENSO impact on Asia-Pacific sector

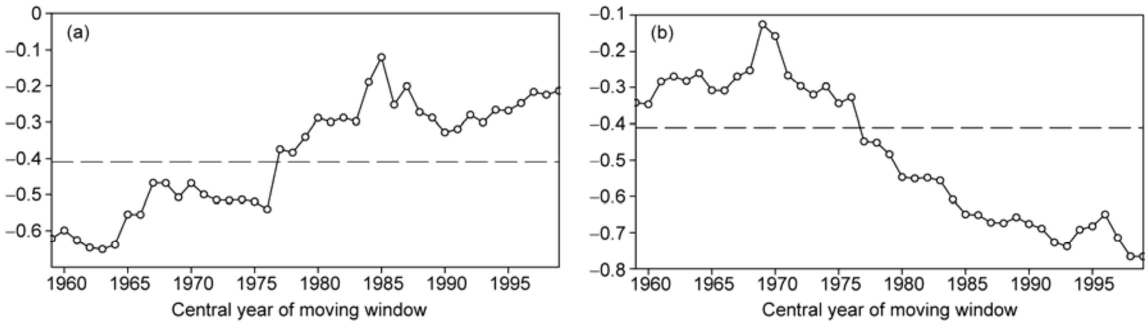

Figure 2 The 23-year-sliding correlation coefficient between Niño3.4 SSTA index and EAWMI (a), Aleutian low index ALI (b) for DJF during 1948–2010. The dashed line indicates the standard for 95% significance, estimated by the Student's *t*-test.

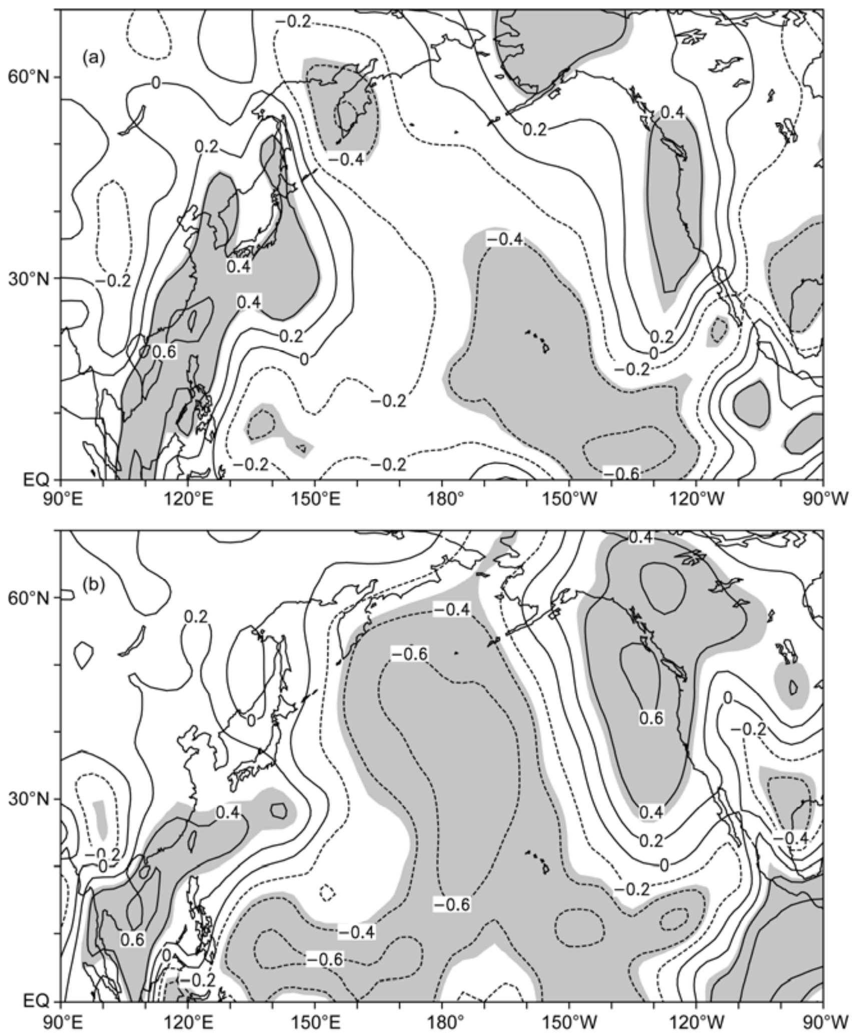

Figure 3 The correlation coefficients between Niño3.4 SSTA index and meridional wind at 850 hPa during 1948–1976 (a) and 1977–2010 (b). Shaded area indicates significant correlation at 95% level, estimated by the Student's *t*-test.

retreated southward and eastward after mid-1970s. Thus we test this retreat of ENSO impact by analyzing the correlation coefficient between 850 hPa meridional winds and Niño3.4 index for the two periods 1948–1976 (P1) and 1977–2010 (P2). We do find that the ENSO signal in northwestern Pacific and northeastern Asia, with differences between P1 and P2. During P1, positive phase of Niño3.4 corresponds to positive meridional wind anomalies over the South China Sea, eastern China and Northeast Asia (weak East Asia winter monsoon), and negative meridional wind anomalies over the Kansas Peninsula region and northern tropical eastern Pacific, and vice versa. In the latter period (P2), the positive correlation over Asia retreated to the South China Sea and Southeast Asia. There was no significant correlation in eastern China and the Korea-Japan region. Meanwhile the negative correlation over the Kansas Peninsula retreated southeastwards, with the major area of negative correlation coefficient in the Aleutian region and middle-latitudes Pacific. Hence the Niño3.4-ALI negative correlation is intensified in P2. It is interesting to note that the ENSO signal in North America differs as well between P1 and P2.

The above mentioned southward retreat of the ENSO signals is demonstrated by the surface air temperature fields (Figure 4). In the first period (P1), positive correlation coefficient between the 2 m air temperature and Niño3.4 appears in large area including India, Southeast Asia, South China, the tropical-northern Indian Ocean and South China Sea and Eastern China Sea. However, such positive correlation coefficient exists only in the tropical Indian Ocean and part of South China Sea during P2. Meanwhile, the tropical western North Pacific is covered with negative correlation in P2, which does not exist in P1. In addition, we find that the ENSO signal in North America is intensified in P2 than P1.

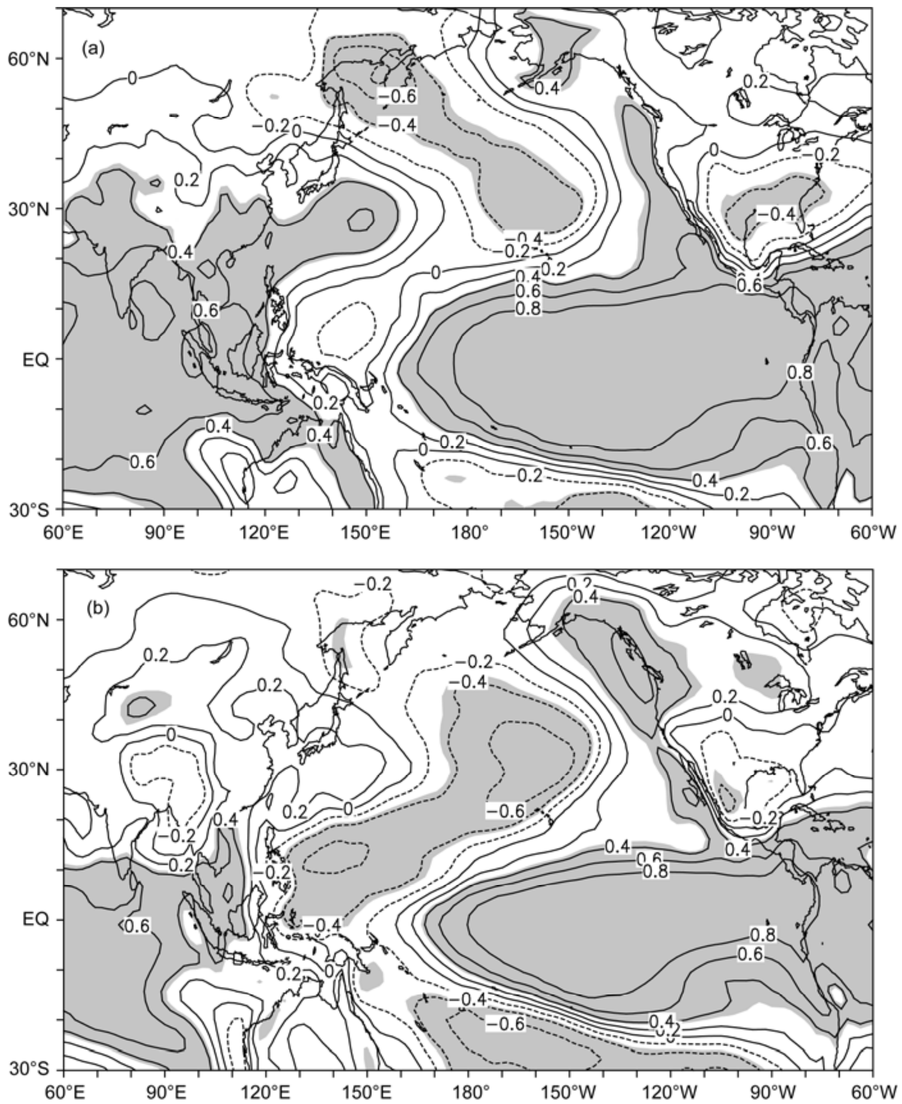

Figure 4 The correlation coefficients between Niño3.4 SSTA index and air temperature at 2 m during 1948–1976 (a) and 1977–2010 (b) periods. Shaded area indicates significant correlation at 95% level, estimated by the Student's *t*-test.

Why the EAWM-Niño3.4 index relationship became weakened after mid-1970s? We now display the result of EOF (Empirical Orthogonal Function) decomposition on the SST. Figure 5 indicates that tropical eastern Pacific SST has a decreased linkage with the tropical Indian-western Pacific SST in P2 than P1. We find that the positive value of the EOF1 in 90°–150°E sector of Indo-Pacific (the ENSO mode) is quantitatively larger and spatially broader in P1 than in P2. The SST anomalies in this sector are closely associated with EAWM, because they can change the land- sea thermal contrast which is the fundamental driving force for the winter monsoon.

From the atmospheric perspective, the interannual variability of EAWM was also weakened during the latter period. The correlation between 2 m air temperature and EAWMI (Figure 6) demonstrates this feature. The out-of-phase relationship between EMWMI and surface air temperature over East Asia retreated northward spatially and the magnitude of the correlation coefficient was smaller in P2 than in P1. The significant correlation in the northern Indian Ocean, South China Sea and Southeast Asia does not exist anymore in P2.

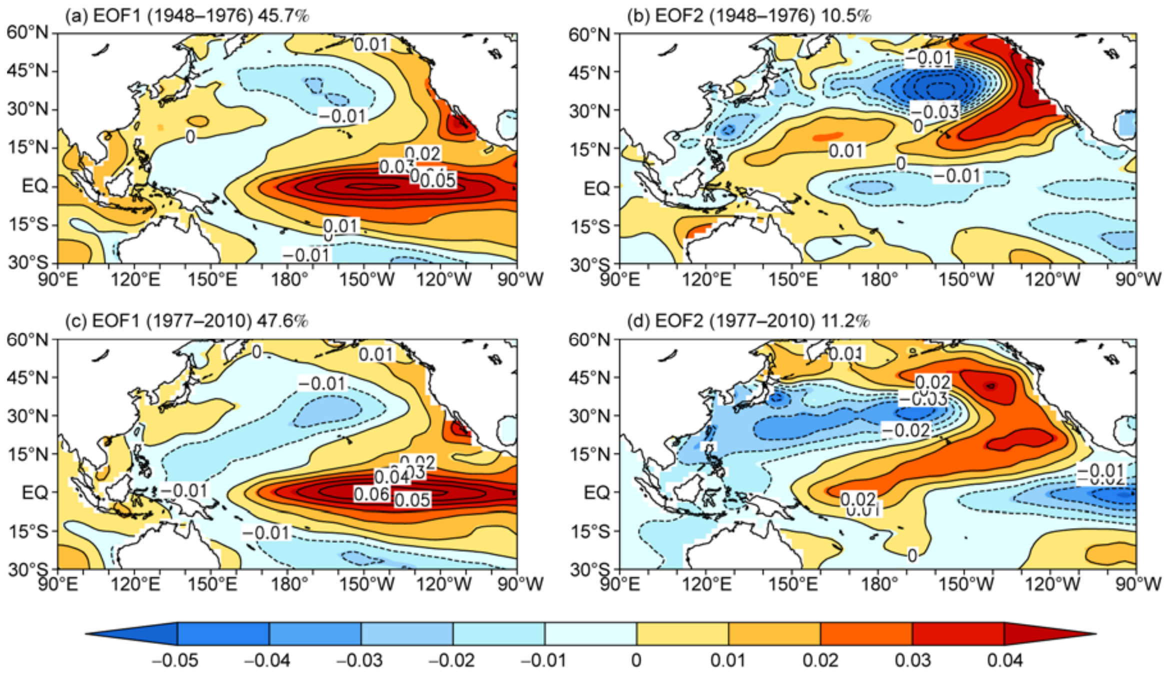

Figure 5 The first and second principle mode of DJF SST EOF analysis performed for 1948–1976 and 1977–2010 respectively. The explained variance of the principle mode is indicated by the percentage.

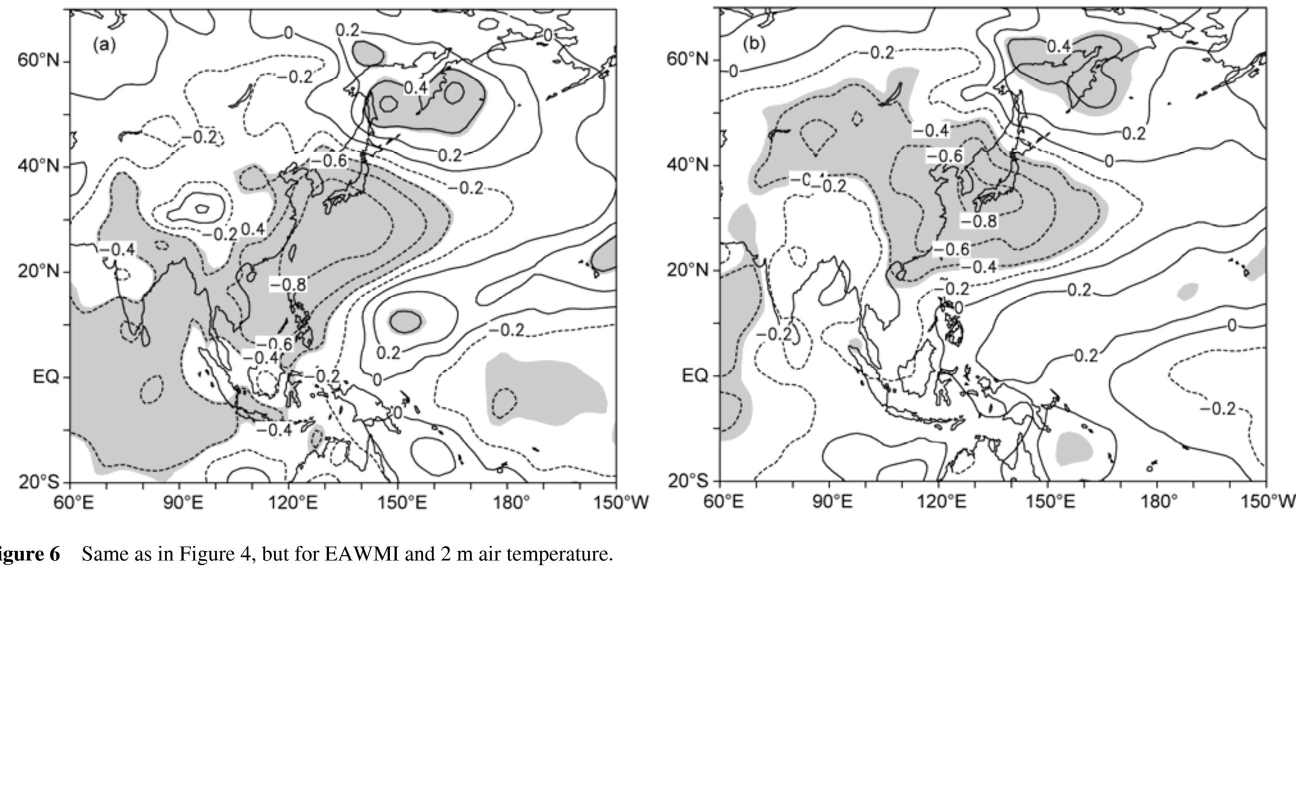

Figure 6 Same as in Figure 4, but for EAWMI and 2 m air temperature.

2 Conclusion

This paper reveals the weakening relationship between EAWM and ENSO cycle after mid-1970s. Their connection was statistical significant during 1948–1976 and insignificant during 1977–2010. We find that the Niño3.4 connections to East Asian winter climate basically retreated southward to low latitudes in the northern Indian Ocean, Asia, and western Pacific region. In the northern Asia-Pacific, the ENSO signals shifted eastward from Northeast Asia to Northwest Pacific after mid-1970s, leading to an intensified ENSO-Aleutian Low connection in P2.

Our further analysis reveals that the ENSO-associated SST variability was suppressed in the latter period in the northern Indian Ocean and tropical western Pacific, thus favorable to a weak linkage between ENSO and EAWM. In addition, the interannual variability of EAWM also experienced a decreasing trend after mid-1970s, leading to the retreat of EAWM signals from the broad tropical to mid-latitudes region of the Indian Ocean, Asia, and western Pacific to only the mid-latitudes. Thus the northward retreated EAWM signals yielded a weaker linkage to the tropical mode-ENSO and an intensified connection to the Arctic Oscillation.

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