

# Two major modes of variability of the East Asian summer monsoon

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## Introduction

The East Asian Summer Monsoon (EASM) is a major feature of June/July/August (JJA) global atmospheric circulation, and lots of indices have been defined to measure the variability of the East Asian Summer Monsoon (EASM), but they are not consistent with each other (Wang *et al.* 2008). Wang *et al.* (2008) carry out a multivariate Empirical Orthogonal Function (MV-EOF) analysis on a set of six meteorological fields (precipitation, the zonal and meridional winds at 850hPa and 200hPa, and sea-level pressure) in JJA for the 1979–2006 period and get two modes of EASM.

Wang *et al.* (2008) recommend that the EASM strength can be represented by the PC of the first EOF, which has unique advantages and provides a unified index for the majority of the existing indices. They also recommend Wang and Fan index (1999) as a more simple index to measure and monitor the EASM. In the same spirit, we show in the present paper that the second EOF is closely related to the variability in the intensity of the South Asian High (SAH) at 100hPa, providing a second simple index to monitor another independent aspect of the EASM's variability.

Hoskins and Rodwell (1995) show that the mean JJA circulation associated with the EASM, including SAH, is captured by a nonlinear dry, dynamical model driven by diabatic heating diagnosed from ECMWF analyses. These results inspire us to understand the dynamics of the variability of EASM by running a dry, linear dynamical baroclinic model (LBM, Watanabe and Kimoto, 2000, 2001), linearized about the mean JJA circulation and driven by the diabatic heating (DBQ) anomalies associated with the first two MV-EOF modes.

Wang *et al.* (2008) associate the first EOF with the decaying phase of ENSO events and the second EOF with the developing phase. Regarding the first EOF, the link with ENSO has not been robust throughout the 44 years of our analysis and has only been significant during the years since 1979 studied by Wang *et al.* (2008). A change in the relationship between ENSO and East Asian climate after the mid-1970s has also been noted by Xie *et al.* (2010), attributed to the SST anomalies in the Indian Ocean.

## Results

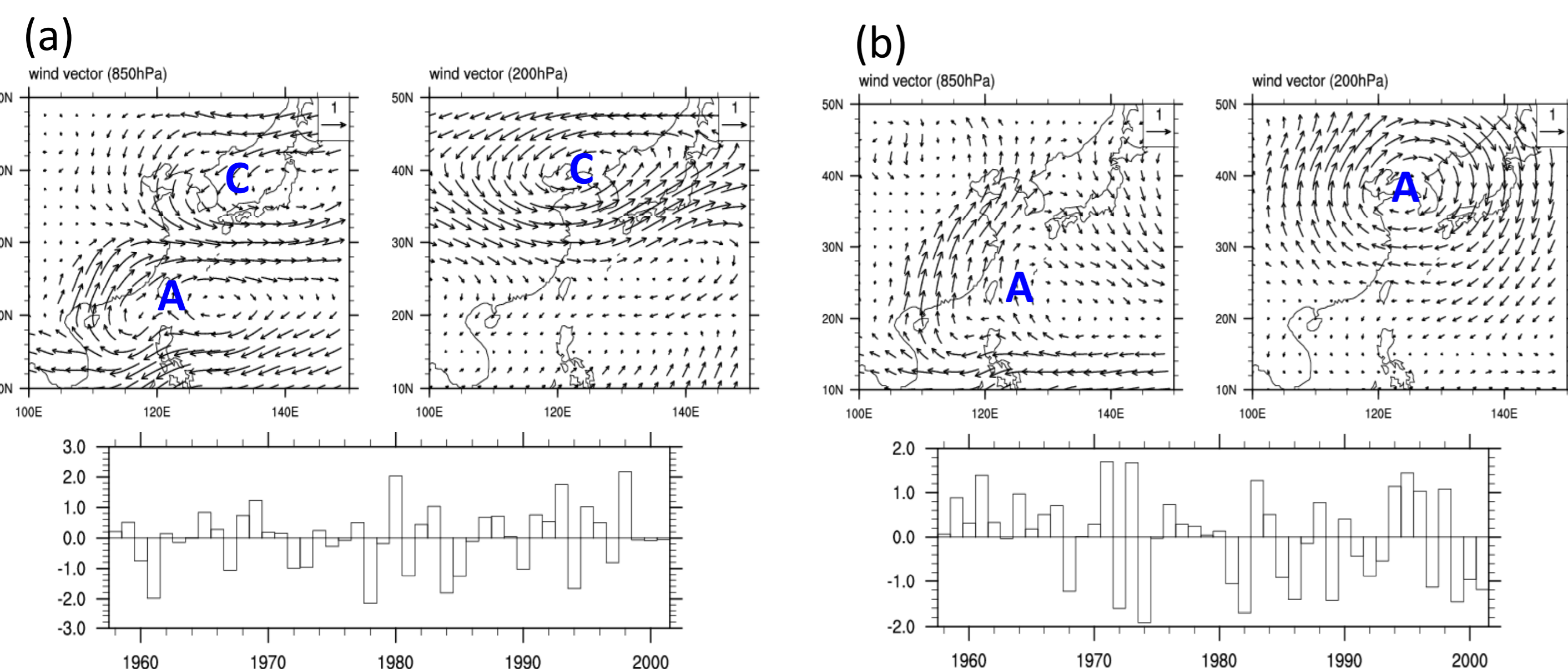


Figure 1. Spatial patterns and time series of (a) the first and (b) the second MV-EOF mode of the East Asian summer 850hPa winds (vector in the left panels) and 200hPa winds (vector in the right panels) over the domain bounded by 10°–50°N and 100°–150°E for the years 1958–2001 with ECMWF reanalysis data. The first and second MV-EOF modes explain 20.2% and 11.6% of total variance, respectively. The reference arrow in the top right corner corresponds to 1m s<sup>-1</sup>.

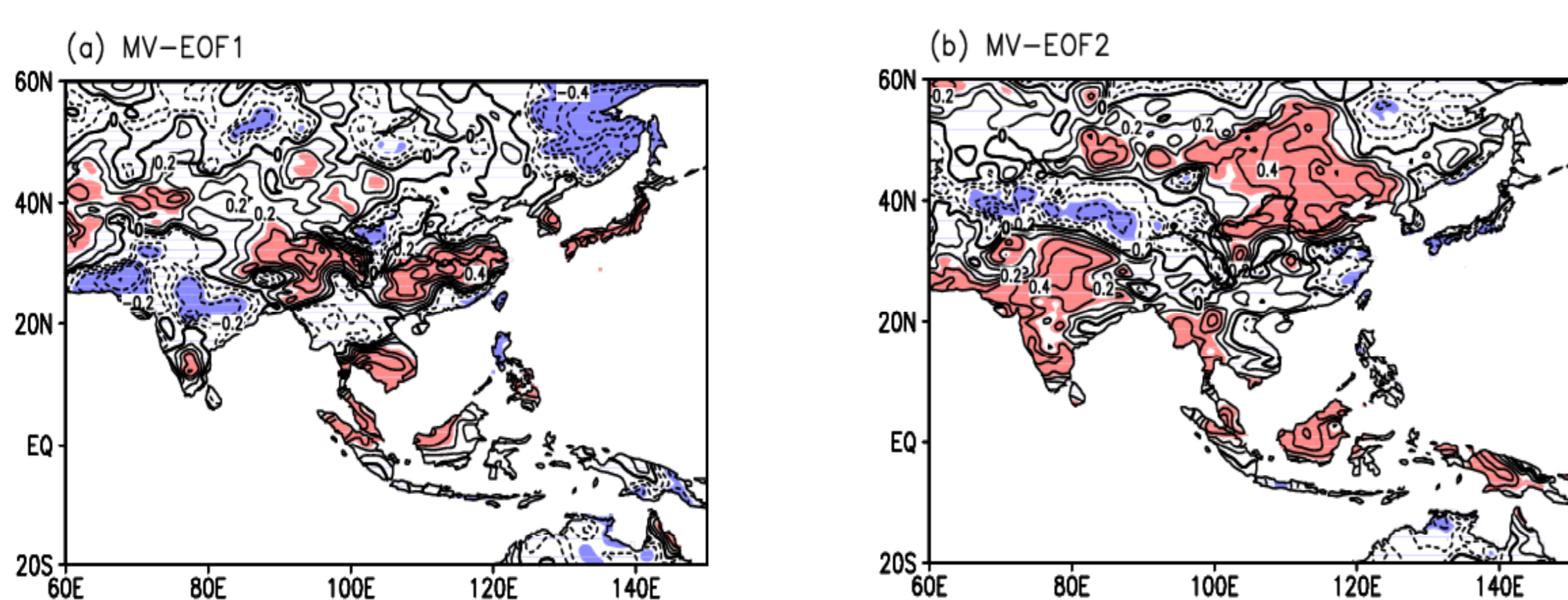


Figure 2. Correlation of JJA precipitation of CRU TS 2.1 with (a) PC1 and (b) PC2 of the MV-EOFs shown in Figure 1. Shaded areas indicate correlation above the 90% significance level.

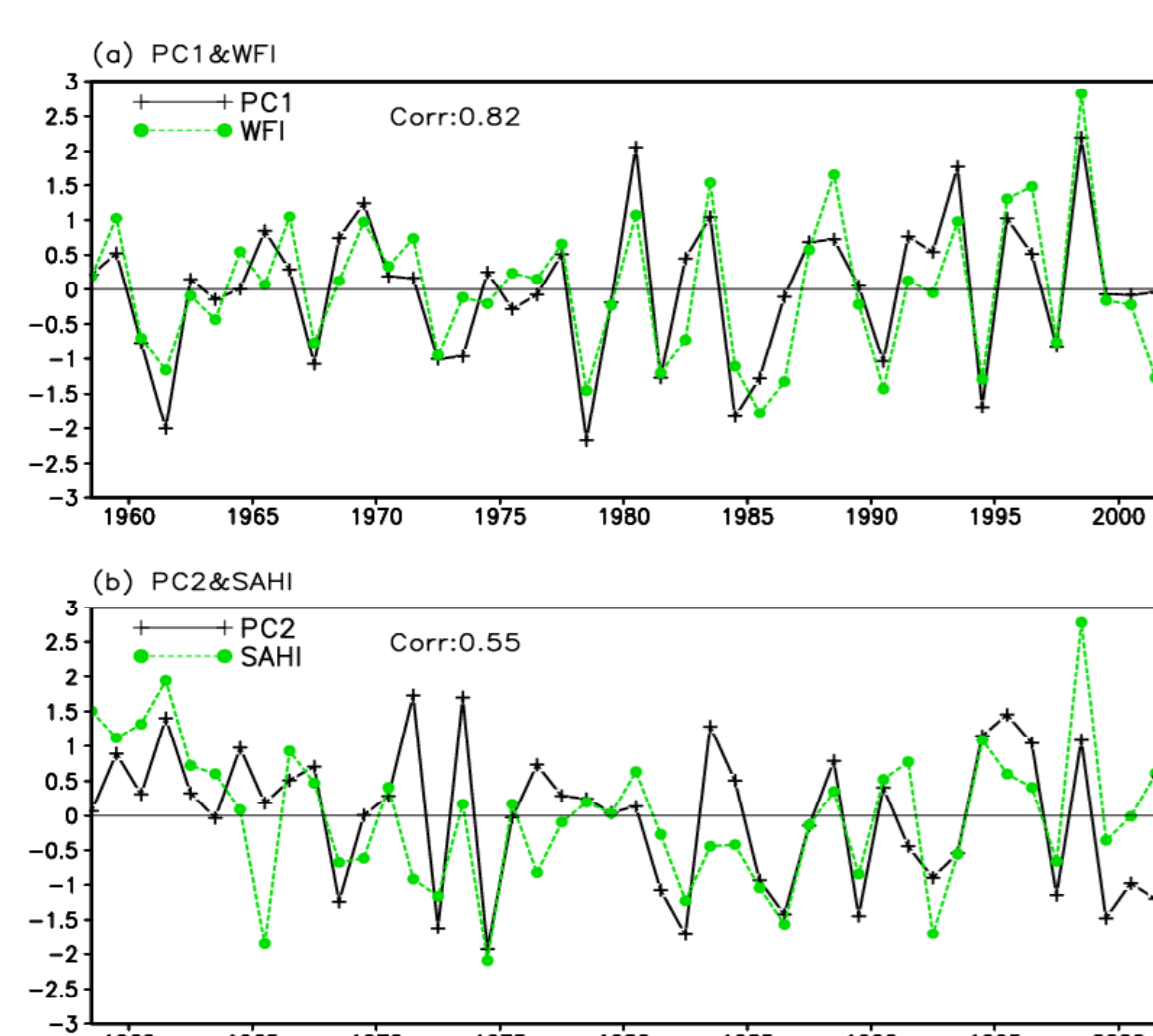


Figure 3. Time series for (a) the Wang and Fan index (WFI, dotted line), PC1 (solid line), (b) South Asian High index (SAHI, dotted line) and PC2 (solid line). The correlation coefficient between WFI and PC1 is 0.82, and 0.55 between SAHI and PC2, significantly different from zero at the 99% confidence level. The WFI is defined as the zonal wind at 850hPa in the region (5°–15°N, 90°–130°E) minus that in the region (22.5°–32.5°N, 110°–140°E). The SAHI is the time series of anomalies in the JJA mean 100hPa geopotential height averaged over the region (25°–40°N, 30°–110°E).

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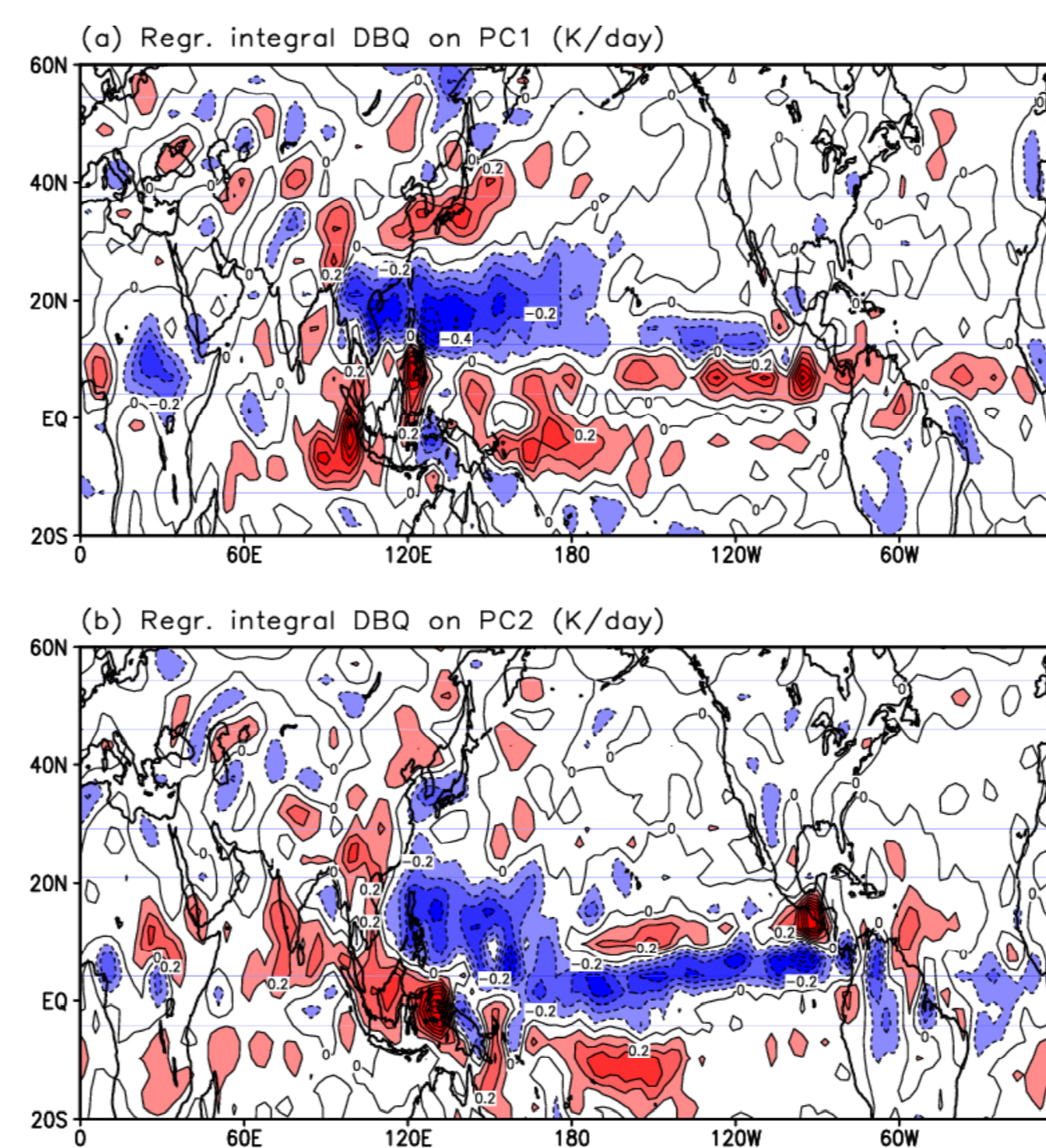


Figure 4. Regression patterns of the DBQ anomalies associated with (a) EOF-1 and (b) EOF-2 integrated over the depth of the troposphere from 925hPa to 150hPa. Shaded areas in red and blue colors indicate the regression value above 0.1K/day and below -0.1K/day, respectively. Positive/negative values indicate anomalous heating/cooling associated with the positive phase of each EOF. DBQ is diagnosed from 6-hourly ERA-40 data as a residual in the thermodynamic equation.

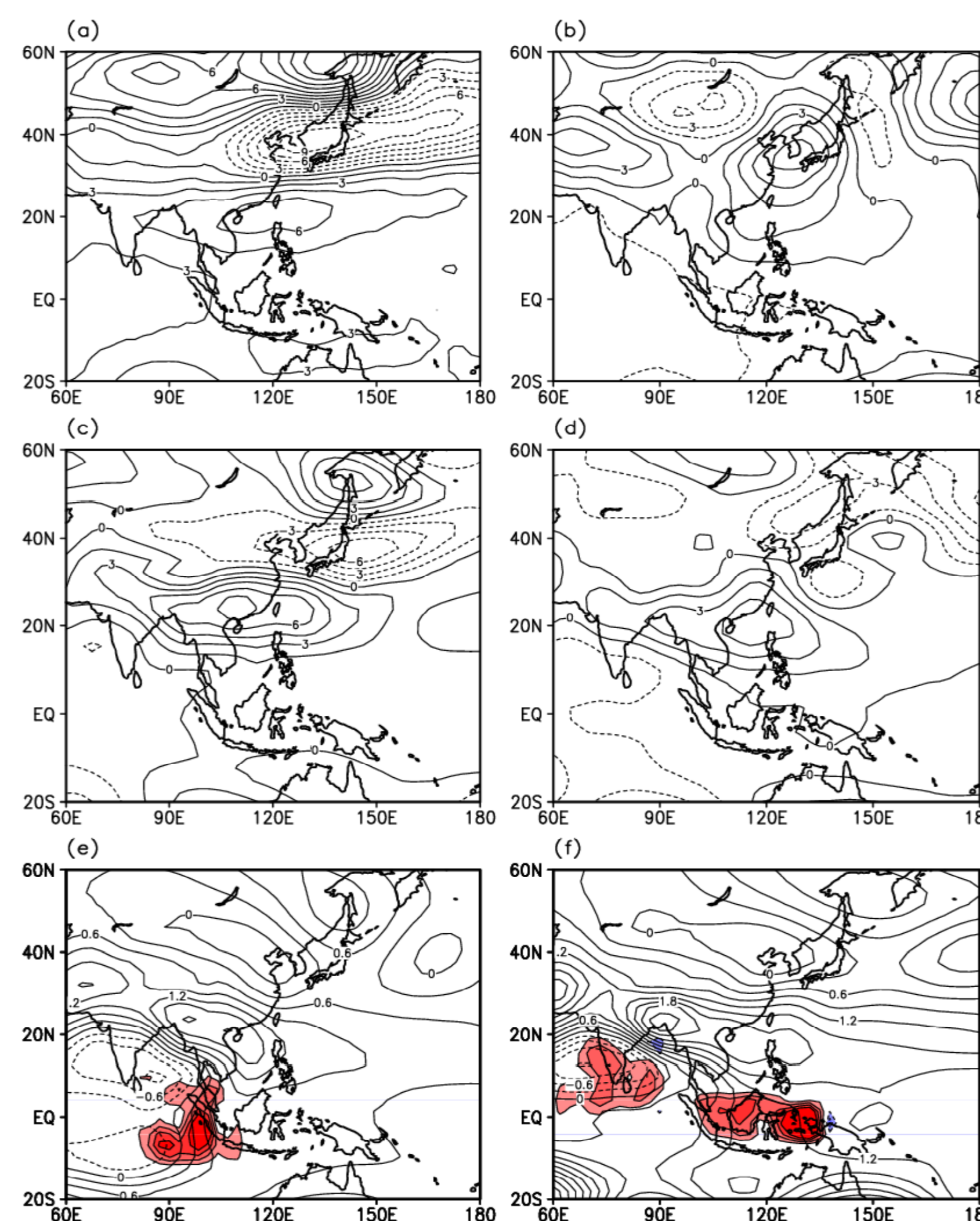


Figure 5. Regression patterns of geopotential height and wind field associated with (a) EOF-1 and (b) EOF-2 at 850hPa in the ERA-40 reanalysis data, and the geopotential height and wind field response in the LBM model to the global 3-D DBQ regressed on (c) PC1 and (d) PC2 of the MV-EOFs. Contour lines indicate geopotential height, and vectors indicate the wind field. Contour interval is 2m. The reference arrow in the top right of each panel corresponds to 3 m s<sup>-1</sup>.

Figure 6. 500hPa geopotential height in the ERA-40 reanalysis data regressed against (a) PC1 and (b) PC2, and the response of the LBM model to the (c), (d) global and (e), (f) Indian Ocean/maritime continent 3-D DBQ (shaded area, shading as in Figure 4) regressed on PC1 (left column) and PC2 (right column). Contour interval for geopotential height in (a–d) is 1.5m, and 0.3m in (e), (f), contour interval for DBQ in (e) and (f) is 0.1 K/day.

Figure 7. Lead-lag correlation between the Niño-3 sea surface temperature (SST) index and the two PC time series, the WF-index and the South Asian High Index (SAHI) from JJA(-1) to JJA(1). The two horizontal black solid lines represent the 90% confidence level based on Student's t test. "JJA(0)" indicates the summer simultaneous with the MV-EOF analysis, "-1" indicates the preceding year and "1" the following year.

## Summary

We study the two major modes of variability of the EASM as identified using a MV-EOF analysis. The second mode is shown to be related to changes in intensity of the SAH while, consistent with previous work, the first mode is associated with the WFI. DBQ anomalies associated with each mode, can reproduce many of the anomalous circulation features, and those over the tropical Indian Ocean is very important in the dynamics of both modes, especially EOF-1. At the same time, we also note a link to the variability of the Indian Summer Monsoon in the case of EOF-2. The second EOF is consistently linked to both the decaying and the onset phase of ENSO events throughout the study period (1958–2001), and a feature of the presence of zonal wind anomalies along the Equator in the Western Pacific helps initiate ENSO events. On the other hand, a link between the first EOF and ENSO is found only in the post-1979 period.

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