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Role of seasonal transitions and the westerlies in the interannual variability of the East Asian summer monsoon precipitation

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Abstract

A recent hypothesis holds that changes to the East Asian summer rainfall are characterized by changes in the timing and duration of its intraseasonal stages, controlled by the meridional position of the westerlies relative to the Tibetan Plateau. This hypothesis is examined in the context of the leading mode of East Asian summer (July–August) rainfall. One phase of this “tripole” mode—characterized by less rainfall over central eastern China and increased rainfall over northeastern and southeastern China—is tied to an earlier termination of Meiyu that results in a significantly shorter Meiyu and longer Midsummer stage. This phase also exhibits an earlier northward transition of the westerlies to the north of the Plateau, essentially mirroring the changes to precipitation seasonality. The reverse does not hold true for the opposite phase. Our results show direct observational evidence for the meridional position of the westerlies to control East Asian summer monsoon seasonality.

1 Introduction

The dominant mode of interannual rainfall variability of the East Asian summer monsoon (EASM) is an out-of-phase relationship between rainfall over central and eastern China and Japan, with rainfall over northeastern and southeastern China, typically referred to as the “tripole” pattern [*Hsu and Lin*, 2007; *Hsu and Liu*, 2003] (Figure 1). A number of forcings have been implicated in causing this EASM variability, notably the Pacific-Japan pattern associated with anomalous convective heating over the Philippine Sea [*Kosaka and Nakamura*, 2006; *Nitta*, 1987] and variations to Tibetan Plateau sensible heating [*Hsu and Liu*, 2003]. The causes and consequences of this summertime precipitation change have been well studied both for understanding its dynamics and societal consequences.

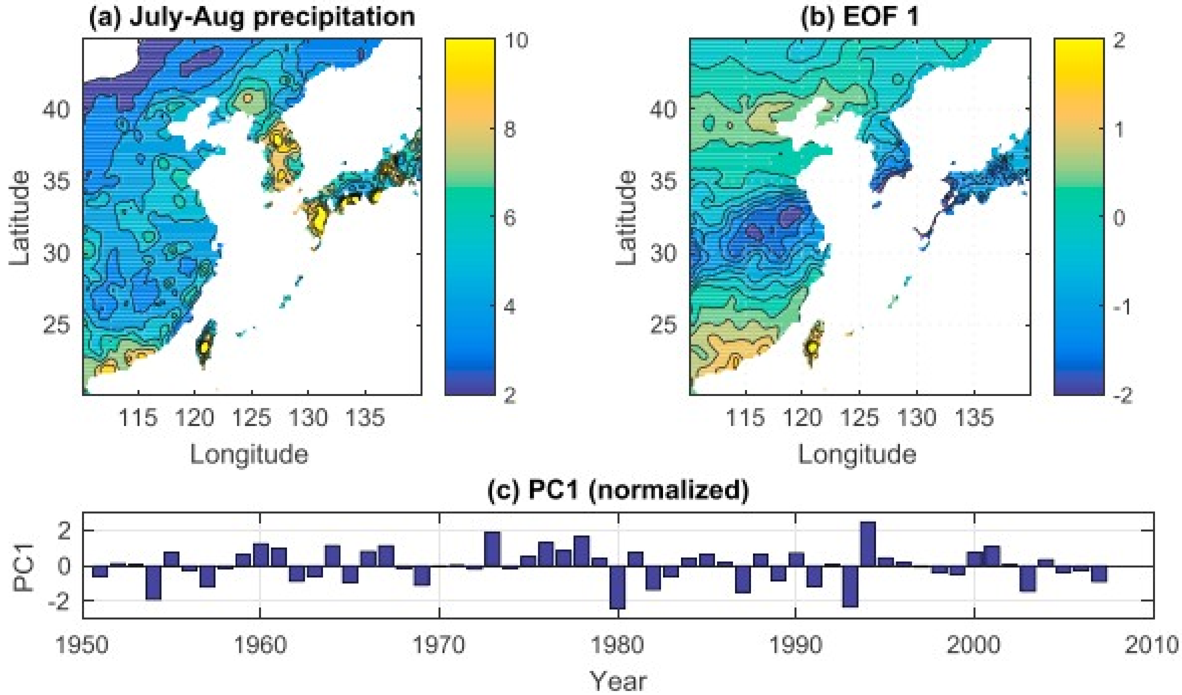

Figure 1. (a) July–August precipitation climatology (in mm/d). The (b) first EOF and (c) principal component of July–August mean precipitation over East Asia 100°–145°E longitude and 20°–45°N latitude. The spatial pattern is the regression of the normalized PC1 onto the July–August rainfall anomaly (units are mm/d per standard deviation). The first mode is the well-known tripole mode with reduced rainfall over central eastern China and Japan and increased rainfall over northeastern and southeastern China. We use the APHRODITE data set spanning 1951–2007. The mode explains 17.7% of the total variance.

The rainfall climatology over East Asia is also known to undergo a complex intraseasonal evolution, with several quasi-stationary stages and abrupt transitions in between [*Ding and Chan*, 2005] (Figure 2). There is a persistent spring rainfall stage over southern China that gives way to a pre-Meiyu stage around mid-May characterized by the onset of significant convection over the South China Sea. Beginning mid-June, the Meiyu rainband migrates northward to central China, and in mid-July the rainfall jumps to northeastern China to start the Midsummer stage; this rainfall stage terminates around mid-August (in this manuscript, we refer to these stages as spring, pre-Meiyu, Meiyu, and Midsummer). Persistent rainfall in southeastern China also occurs during the Midsummer stage, giving rise to a tripole structure in rainfall.

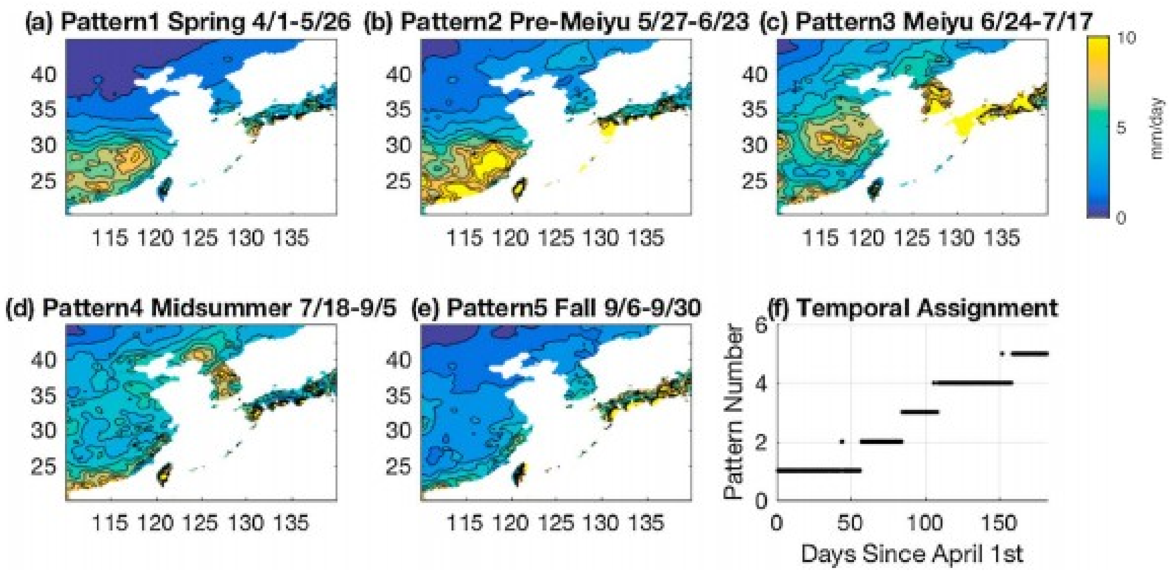

Figure 2. SOM analysis of East Asian rainfall. (a–e) The spatial patterns in SOM analysis of the APHRODITE data set. Pattern 1 denotes the "spring persistent rainfall" (1 April to 26 May) (Figure 2a); pattern 2 denotes the pre-Meiyu (27 May to 23 June) (Figure 2b); pattern 3 denotes the Meiyu (24 June to 17 July) (Figure 2c); pattern 4 denotes the "Midsummer" (18 July to 5 September) (Figure 2d); pattern 5 corresponding to fall (6–30 September) (Figure 2e); and the corresponding temporal assignment for the five patterns (Figure 2f).

It has been long known that Meiyu onset is linked to the seasonal northward migration of the westerlies across the Tibetan Plateau [*Yeh et al.*, 1959], and recent studies have suggested that the westerlies act to dynamically control the intraseasonal stages of East Asian rainfall. In particular, *Molnar et al.* [2010] proposed that the seasonal migration of the maximal westerlies from south of the plateau to the north marked the transition from pre-Meiyu to Meiyu, and the migration of westerlies away from the northern edge of the plateau marked the transition from Meiyu to Midsummer.

The juxtaposition of the interannual and intraseasonal behavior of the East Asian monsoon begs the question of how the two are related. *Chiang et al.* [2015] hypothesized that (i) EASM paleoclimate changes were caused by changes to the timing and duration of the distinct intraseasonal stages and that (ii) they in turn were controlled by changes to the meridional position of the westerlies relative to the plateau. Specifically, a northward shift of the westerlies would lead to earlier timing of the pre-Meiyu to Meiyu or Meiyu to Midsummer transitions (the so-called “Jet Transition Hypothesis”). A subsequent study by *Kong et al.* [2017] found that EASM changes across the Holocene as simulated by an atmospheric general circulation model exhibited precisely the behavior postulated by this hypothesis.

An outstanding question however is whether this hypothesis is supported in the *observed* EASM variability. There are relatively few studies that address the issue of timing and duration from modern data; indeed, most variability studies use monthly or seasonal averages to interrogate the data, but by construction they can discern neither timing nor duration. There are more studies that relate the meridional position of the westerlies to EASM interannual variability; in particular, *Hsu and Lin* [2007] found that the tripole pattern is tied to a meridional shift of the westerlies straddling the plateau region. However, the mechanism linking this shift in the westerlies to changes in the timing of the EASM intraseasonal stages remains largely unexplored.

The purpose of the study is to rigorously test the *Chiang et al.* [2015] hypothesis from observed interannual variability, using the dominant tripole mode as a target. We use an objective method—the self-organizing map (SOM) applied to precipitation data—to identify the timing and duration of the intraseasonal stages and also to examine the meridional positions of the westerlies corresponding to the identified intraseasonal stages. We will show that one phase of the tripole mode is characterized by a significantly earlier termination of Meiyu, resulting in a shorter Meiyu stage and longer Midsummer stage consistent with an observed pattern of increased rainfall over northeastern China and reduced rainfall over central eastern China.

The paper proceeds as follows. Section 2 lays out the data and methodology, in particular, demonstrating that the SOM objectively extracts the timing and duration of the observed intraseasonal stages. The SOM analysis is then used to examine the timing and duration of intraseasonal stages in precipitation for opposite phases of the tripole pattern (section 3). In section 4, we show that the timing of the intraseasonal evolution of the westerlies significantly differs between opposite phases of the tripole pattern and in accordance with changes to timing of the precipitation intraseasonal stages. We conclude and discuss our results in section 5.

2 Data and Methods

2.1 Data

The Asian Precipitation—Highly-Resolved Observational Data Integration Towards Evaluation (APHRODITE) gridded rainfall data set for “Monsoon-Asia” [APHRO_MA_025deg_V1003R1; *Yatagai et al.*, 2012] covering the period 1951–2007 is the primary observed rainfall data set used for this analysis. A distinct feature of this data set is the high density of spatial coverage and quality of the station network used. For zonal and meridional winds, we use the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research reanalysis 1 [*Kalnay et al.*, 1996] spanning the same period as the APHRODITE data set. We use the daily averaged data in all cases and discard leap days when forming daily climatologies.

2.2 Tripole Pattern

To obtain an index representing the dominant mode of East Asian summer rainfall interannual variability, we apply an empirical orthogonal function (EOF) analysis [e.g., *Weare*, 1977] on APHRODITE rainfall averaged during July–August. The analysis is taken over East Asia across the domain bounded by 100°–145°E longitude and 20°–45°N latitude. The data were weighted by the square root of the cosine of the latitude prior to computing the EOF. The first EOF, explaining 17.7% of the variance, is shown in Figure 1; it is well separated from EOF2 which explains 12.5% (not shown). As expected, the spatial pattern corresponds to the well-known tripole pattern in rainfall with central eastern China and Japan having the same sign and northeastern and southeastern China possessing the opposite. The principal component of the first mode (PC1) (Figure 1c) shows large year-to-year variation in the amplitude and sign, indicative of significant interannual variability. For the remainder of this paper, we will use PC1, normalized by its standard deviation, as our index for the tripole pattern.

2.3 Self-Organizing Map

Following *Kong et al.* [2017], we use a clustering method—the self-organizing map (SOM)—to objectively identify and extract the intraseasonal stages of the EASM from the APHRODITE data set. The method is ideally suited given the discreteness of the intraseasonal stages and abrupt transitions evident in the EASM. The SOM method is a neural network-based cluster analysis that classifies a high-dimensional data set into representative patterns, using a neighborhood function to topologically order the high-dimensional input and group similar clusters together [*Kohonen*, 1998]. The SOM has recently been used to extract patterns of climate variation such as the El Niño–Southern Oscillation [*Johnson*, 2013] and Northern and Southern Hemisphere teleconnection patterns [*Chang and Johnson*, 2015; *Johnson et al.*, 2008]. In addition, *Chattopadhyay et al.* [2008] employed SOM analysis to characterize intraseasonal oscillation of the Indian summer monsoon, and *Chu et al.* [2012] used it to extract intraseasonal modes of the East Asian-western North Pacific summer monsoon.

We apply the SOM analysis to the APHRODITE daily climatology during 1951–2007, using the region bounded by ($20^{\circ}-45^{\circ}$N, $110^{\circ}-140^{\circ}$E) following *Wang and LinHo* [2002] (APHRODITE contains data only over land). The data were then area weighted by multiplying each grid point by the square root of the cosine of the latitude. We calculated the 9 day running mean of the daily climatology and chose one half year spanning the summer season (1 April to 30 September) for the SOM analysis. Following *Johnson* [2013], we use the Epanechicov neighborhood function and the batch training algorithm. A statistical distinguishability test was done following *Johnson* [2013], and we specified the number of nodes (K) to be 5 × 1 to match the number of expected rainfall patterns.

The result (as first reported in *Kong et al.* [2017]) shows that the SOM is able to objectively extract the intraseasonal stages of the EASM rainfall. Our result differs slightly from *Kong et al.* [2017] because they used a 5 day smoothing period instead of 9 day. The SOM patterns match the intraseasonal stages and transitions of the EASM, with spatial and temporal characteristics largely in agreement with those described in *Ding and*

Chan [2005]. Figures 2a–2e show these spatial patterns in sequence: "spring" (pattern 1), "pre-Meiyu" (pattern 2), "Meiyu" (pattern 3), "Midsummer" (pattern 4), and "fall" (pattern 5). Figure 2f shows the temporal assignment of each pattern. We note that the onset timing of pre-Meiyu and Meiyu from our SOM analysis is slightly delayed compared to *Ding and Chan* [2005]: instead of early May and mid-June, the pre-Meiyu starts in late May and Meiyu starts in late June in our SOM analysis. This difference may be due to the precipitation data and the time range used in our SOM analysis being different from *Ding and Chan* [2005], and that they focus on eastern China, whereas our SOM analysis extends out into Korea and Japan.

3 Intraseasonal Analysis of the Tripole Pattern

We ask whether the tripole pattern (Figure 1) can be interpreted in terms of changes in rainfall seasonality. The July–August period on which the tripole index (PC1 in Figure 1c) is based overlaps with two intraseasonal stages, namely, a portion of the Meiyu and most of the Midsummer. We pick "high" ("low") years from PC1 by using values exceeding +0.75 (below −0.75) standard deviation; a total of 13 high PC1 years and 13 low PC1 years were obtained. To obtain the timings of the intraseasonal stages for each category, we apply a 9 day running mean to the daily rainfall climatologies for each of the high and low composites. We then match each day from high and low daily climatologies to the nearest APHRODITE SOM pattern (Figure 2) based on the minimum Euclidean distance.

The result is shown in Figure 3a and Table 1. The most pronounced differences are in the variation of the Meiyu and Midsummer stages of high years: the Meiyu stage terminates almost 3 weeks earlier in the high years (30 June) compared to normal (17 July), meaning that the Midsummer stage likewise starts earlier. On the other hand, the start of the Meiyu and end of the Midsummer stages are not significantly different; as a consequence, high years have a considerably shorter Meiyu stage (9 days versus 24 days normally) and longer Midsummer stage (67 days versus 50 days normally) (Table 1). We tested the significance of the change in onset and duration using a bootstrapping method: we computed onset and duration statistics from 13 year climatologies randomly sampled (with replacement) from the observational data, repeating this 1000 times to obtain probability distributions. The results confirmed that the high composite statistics for the Meiyu and Midsummer durations and Midsummer onset are significant at the 95% level. For low years the Meiyu duration is slightly longer than normal (2 days) and the Midsummer duration is somewhat shorter (9 days), but neither is significant; the only significant statistic for low years is a delayed onset of Midsummer (23 July compared to 18 July). In short, it is the high years that are anomalous.

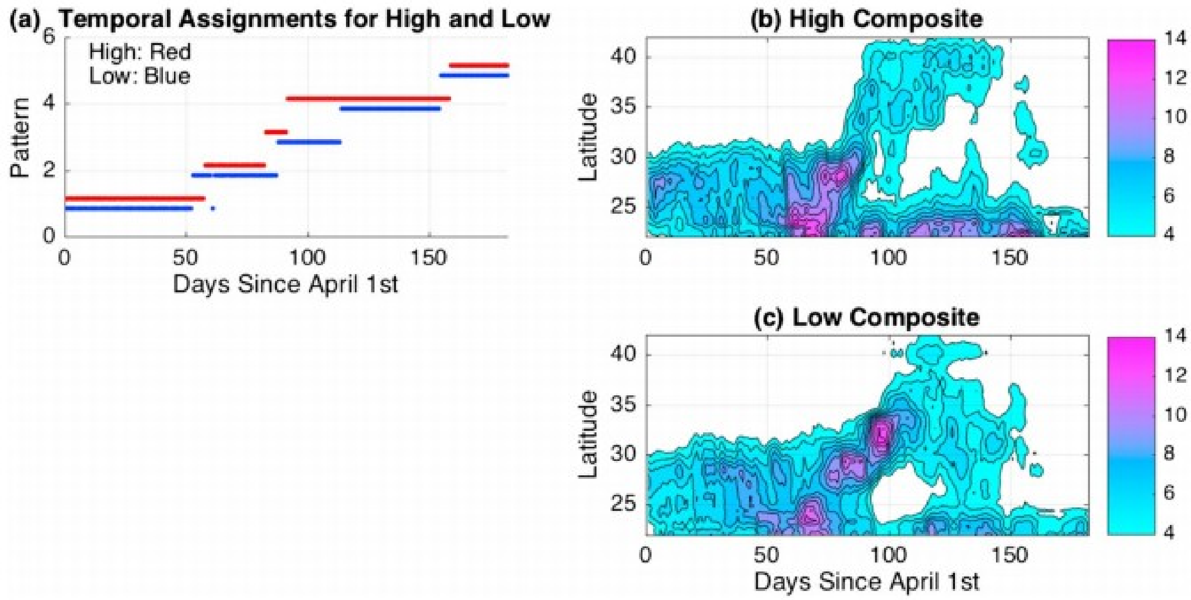

Figure 3. (a) Timing of the intraseasonal stages for high and low PC1 composites, derived from matching the daily field to the closest climatological SOM pattern shown in Figure 2. (b and c) Hovmöller plot of East Asian rainfall zonally averaged over eastern China 110°E–125°E, for high (Figure 3ab) and low (Figure 3ac) composites, showing the shorter Meiyu and longer Midsummer stage duration for the former as compared to the latter. The color scale is in mm/d.

Table 1. Table of Onset/Termination Dates and Duration Days for the Climatology, High and Low Years Based on the SOM Calculations on Aphrodite Precipitation Data[a]

	57 Year Climatology	PC1 High Years	PC1 Low Years
Pre-Meiyu onset	27 May	28 May	23 May
Meiyu onset	25 June	22 June	*27 June*
Midsummer onset	18 July	**1 July**	**23 July**
Midsummer termination	5 September	5 September	1 September
Pre-Meiyu duration	28	25	35
Meiyu duration	24	**9**	26
Midsummer duration	50	**67**	41

[a]Bold face indicates significance at the 95% level and italics at the 85% level.

Our results and interpretation above are readily visible in a Hovmöller plot of rainfall zonally averaged over 110°–120°E (eastern China) for each of the high (Figure 3b) and low (Figure 3c) composites. In the high composite, the northward displacement of the rainband during the Meiyu stage is evident, and the rainfall stays over northern China for longer for the Midsummer stage. There is also increased rainfall over southeastern China during this period. For the low composite, the northward migration during the Meiyu is slower, and the rainfall stays over northern China for a relatively brief period before migrating back toward the south.

In the previous analysis, the high and low climatologies are projected onto the full 57 year SOM patterns. We apply another test where we apply the SOM to the high composite and derive their SOM patterns, and likewise for the low composite. The results (not shown) confirm our previous findings—that for high as compared to low composites, the Meiyu is shorter and terminates earlier, whereas the Midsummer starts earlier and has longer duration. An additional finding is that the Meiyu spatial pattern derived for the low composite have considerably stronger rainfall over central eastern China than for the high composite; this can also be seen in the rainfall Hovmöller plots in Figure 3b (high) and Figure 3c (low). Thus, increased rainfall over central eastern China during PC1 low years is a consequence of both a longer Meiyu stage, and more intense Meiyu rainfall.

4 Behavior of the Westerlies

The second part of the hypothesis posed by *Chiang et al.* [2015] is the association of the tripole precipitation pattern with westerly winds across Asia. In this section, we show evidence that the westerlies act as a causal influence on the precipitation seasonality.

First, we show the spatial structure of the westerly changes associated with changes to the timing of Meiyu termination, by comparing high and low composites averaged between 1 July and 22 July, the time period where high years are already in Midsummer stage, whereas low years are still in Meiyu. The upper tropospheric zonal winds (Figures a and S1c) show a northward displacement of the peak westerlies across Asia and the western North Pacific in high years relative to low years. Notably, the peak westerlies in the high composite have cleared the northern base of the plateau (~40°N), whereas that for the low composite has not (Figure S1c). The westerly changes are accompanied by large-scale changes to the upper tropospheric meridional temperature gradient across Asia (Figures S1b and S1d). The results are consistent with the hypothesis that high years have earlier Meiyu termination relative to low years because of an earlier northward migration of the westerlies across the Plateau.

We examine in greater detail the vertical structure of zonal winds averaged across 60–125°E—across the Tibetan Plateau and into East Asia—and meridional winds over East Asia averaged over 105–125°E. The physical rationale for choosing these longitude ranges is that we are assessing the extent to which the westerlies is perturbed by the plateau—i.e., we seek measures of the state of the stationary eddy circulation. In particular, there is substantial stationary meridional flow just downstream of the plateau, and previous studies have suggested a link between the evolution of the meridional flow with specific stages in the EASM [*Chen and Bordoni*, 2014; *Park et al.*, 2012]. Figures 4a–4j shows daily climatologies of the zonal (U) and meridional (V) wind averaged over each of the intraseasonal stages using the timings derived from the precipitation SOM (see Table 1). Figure 4k shows the best match among the five wind “patterns” for any given day, chosen based on the minimum Euclidean distance between that day's combined U and V wind fields with each of the five patterns. The results show an evolution of wind field that is more or less in sync with the precipitation timing.

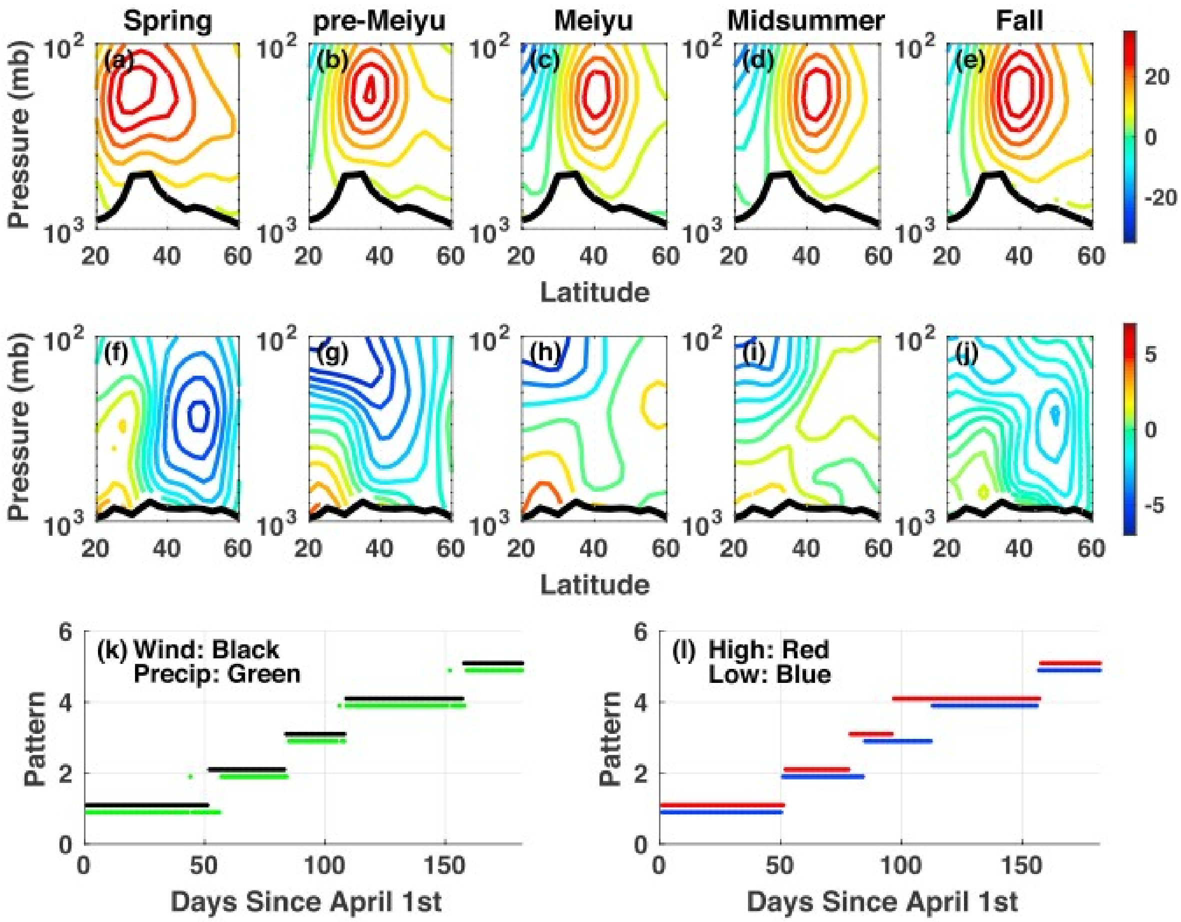

Figure 4. Tropospheric wind structures associated with the EASM intraseasonal stages, and how they change during high and low composites. (a-e) Zonal wind averaged over 60–125°E for each of the five intraseasonal stages; the timings are taken from Table 1 (spring starts on 1 April and fall ends on 30 September). (f-j) Same as Figures 4a–4e but for meridional wind averaged over 105–125°E. (k) The closest pattern match to each day in the wind climatology (in black); note that a 9 day running mean is used prior to the pattern matching. For reference, the precipitation pattern match is also shown (in green). (l) Same as Figure 4k but using high (red) and low (blue) composites.

Figures 4a–4e show the climatological progression of the maximal westerlies northward across the plateau during the spring and pre-Meiyu. By the Meiyu stage, the maximal westerlies shift to the northern edge of the plateau then shift off the plateau by Midsummer. This behavior is in accordance with previous studies [*Chiang et al.*, 2015; *Schiemann et al.*, 2009]. On the other hand, the meridional wind patterns show a progressive decrease in the amplitude of the tropospheric northerlies around 40–50°N from spring to Meiyu, and an increase in the lower tropospheric southerlies over 20–30°N during this period. The former is consistent with a gradual reduction in the stationary eddy influence and the latter an increase in the low-level monsoonal flow with the progression of the seasons. By the Midsummer stage, the northerlies disappear and the monsoonal southerlies penetrate into northeastern China. The fall stage is marked by the southward movement of the maximal westerlies back toward the plateau and reemergence of the northerlies over 40–60°N.

We now test if the timings of the wind for high and low composites reflect similar changes as for the precipitation. We do this by finding the stage of the combined U and V wind patterns (shown in Figures 4a–4f) that best matches the wind for any given day in the high and low composite, using a minimum Euclidian distance criterion. This technique is similar to what was done for the precipitation high and low composites with the precipitation SOM patterns. The results (Figure 4l) show that indeed, the wind evolution tells a similar story about the difference between high and low composite years as does the precipitation SOM. In particular, high years exhibit a considerably earlier Meiyu termination and Midsummer onset, whereas the onset of Meiyu and the termination of Meiyu and Midsummer in low years do not differ much from the climatology. Taken together, high composite years are marked by tropospheric winds that indicate a short Meiyu and long Midsummer stage.

5 Conclusions and Discussion

We show from observational analysis that one phase of the leading mode of summer (July–August) rainfall interannual variability over East Asia—the so-called tripole mode—results from a significantly earlier termination of the Meiyu, leading to a shorter Meiyu duration and longer Midsummer stage. Furthermore, these changes to the timing and duration of rainfall are mirrored by corresponding changes to the northward migration of the westerlies across the Tibetan Plateau. Along with the result by *Kong et al.* [2017], we have shown that the hypothesis proposed by *Chiang et al.* [2015] appears to be applicable to at least two situations relating to EASM changes—namely, the observed dominant mode of interannual variability of East Asian summer precipitation and secular changes to the EASM over the Holocene.

We wonder whether EASM changes on other time scales—in particular, decadal and interdecadal variations—are also attributable to changes in seasonality driven by the meridional position of the westerlies. One distinct possibility is the observed secular change over the latter half of the twentieth century associated with the "north drought-south flood" pattern [*Gong and Ho*, 2002]. *Jiang et al.* [2008] suggested that the northward Meiyu migration occurred more rapidly before the late 1970s and had a more northward terminal position over northern China than that over the late twentieth century, and *Yu et al.* [2004] argued that the secular change is tied to tropospheric cooling over East Asia, imposing a southward shift of the westerlies. A preliminary examination using our SOM analysis shows some indication of changes to rainfall seasonality over the latter half of the twentieth century, but the statistical significance of the changes remains to be determined.

Our results provide direct observational evidence that the intraseasonal stages of the East Asian summer monsoon are linked by the meridional position of the westerlies relative to the Tibetan Plateau. This link has previously only been suggested through inference of the observed seasonal cycle or through model simulations [e.g., *Kong et al.*, 2017]. The mechanisms by which the westerlies dynamically control the intraseasonal stages of the EASM, however, remain to be determined; most likely, it is the westerlies that control the intraseasonal stages, though in principle we acknowledge that the reverse may be true.

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