Subseasonal Variability of Precipitation in China during Boreal Winter

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ABSTRACT

Using pentad data of the Northern Hemisphere extended winter (November–March) from 1979 to 2012 derived from the daily rainfall of the National Meteorological Information Center of China, subseasonal variability of precipitation in China is analyzed. The two dominant modes of subseasonal variability are identified with an empirical orthogonal function (EOF) analysis. The first EOF mode (EOF1) is characterized by a monopole in South China, whereas the second EOF mode (EOF2) has a meridional dipole structure with opposite precipitation anomalies over the Yangtze River basin and the coastal area of South China. These two modes tend to have a phase shift to each other in both space and time, indicating that part of their variability represents a southward-propagating pattern.

The subseasonal variability is decomposed into two components: one related to the Madden–Julian oscillation (MJO) and the other independent of MJO. It is found that the MJO contributes to about 10% of the precipitation variability in South China. EOF1 is associated with MJO phase 3, corresponding to enhanced equatorial convection in the Indian Ocean and depressed convection in the western Pacific, while EOF2 is related to MJO phase 5 when the enhanced tropical convection moves to the Maritime Continent region. Subseasonal precipitation variability in China that is independent of the MJO is especially affected by processes including tropical convection variability and the “cold surge” phenomenon or the development of a Siberian high and cold-air outbreak in East Asia associated with a wave train from the North Atlantic.

1. Introduction

Wintertime precipitation over the China mainland is mainly associated with the East Asian winter monsoon system, which is characterized by strong northwesterly and northeasterly winds in the lower troposphere originating from Siberian-high surges of cold and dry air. (In this paper, winter refers to the November–March boreal “extended winter.”) Although precipitation is limited in winter compared to summer (and provides beneficial moisture), the most costly and disruptive winter weather hazards are occasional prolonged ice storm events affecting nearly all of southeastern and east-central China (Zhou et al. 2011; Wang et al. 2008; Gao et al. 2008). The precipitation variability on a subseasonal scale, ranging from a week to a season, is closely related to certain characteristic phenomena.

Some previous studies have linked subseasonal wintertime precipitation variability to influences of the Madden–Julian oscillation (MJO; Lin et al. 2010; Liu and Yang 2010; Jia et al. 2011; He et al. 2011). MJO is characterized by a planetary scale of wavenumbers 1–3 and eastward propagation with a period of approximately 30–60 days, its amplitude is larger during the boreal winter and spring than summer (e.g., Madden and Julian 1971, 1994; Lau and Chan 1986; Sperber 2003), and it has been identified as a major subseasonal predictor (e.g., Waliser et al. 1999). For example, the winter rainfall in the Yangtze River basin and southern...
China was found to be related to the position of the MJO convective center (Jia et al. 2011; Liu and Yang 2010). As the convective center of the MJO propagates eastward to the eastern Indian Ocean, enhanced rainfall in the Yangtze River basin moves southward to southern China (Liu and Yang 2010; He et al. 2011). The MJO was also observed to be partly connected to wintertime surface air temperature (SAT) over East Asia (Jeong et al. 2005; He et al. 2011). Although MJO is the dominant mode of tropical subseasonal variability, our preliminary results show that MJO contributes about 10% of the total subseasonal precipitation variability in South China. The main purpose of this study is to investigate the influence of non-MJO tropical intraseasonal variability on winter precipitation in China and its associated processes.

In winter, extratropical systems play significant roles in weather and climate anomalies in China. The cold surge is an important type of wintertime shallow extratropical disturbance, associated with strong winds, sharp rises of surface pressure, and a sudden fall of SAT in the midlatitudes and subtropics (Boyle and Chen 1987). Previous studies indicate that the cold surge can even penetrate into the Southern Hemisphere and induce or reinforce tropical convection (Chang et al. 2003; Wang et al. 2012), possibly contributing to the trigger of the MJO (Liebmann and Hartmann 1984; Matthews and Kiladis 1999; Wang et al. 2012). Another purpose is to examine how the cold surge is related to the subseasonal precipitation variability in China.

The paper is arranged as follows. Section 2 describes data sources and analysis techniques. Section 3 presents the two leading modes of subseasonal wintertime precipitation variability in China through an empirical orthogonal function (EOF) analysis, and sections 4 and 5 investigate impacts of both tropical and extratropical processes on these two modes, respectively. Section 6 summarizes conclusions.

2. Data and methodology

The datasets used in this study cover 1979–2012 and include observed daily precipitation at 756 stations in mainland China from the China National Climate Center, atmospheric fields from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996), and daily averaged satellite-observed outgoing longwave radiation (OLR) data from the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting series of satellites (Liebmann and Smith 1996). Stations with more than 5 days (20%) of missing observations during any single winter month of 1979–2012 are excluded, resulting in 589 stations being used in the analysis here. OLR and atmospheric variables from the NCEP–NCAR reanalysis, including 2-m near-surface air temperature, 500-hPa geopotential height (Z500), horizontal and vertical wind components at standard levels, and sea level pressure (SLP), all are on a 2.5° × 2.5° latitude–longitude grid. According to He et al. (2011), NCEP–NCAR reanalysis data reliably depict subseasonal variability in China.

Wheeler and Hendon (2004, hereafter WH04) developed two real-time multivariate MJO indices (RMM1 and RMM2) to represent the MJO as dimensionless magnitudes of projections onto the two leading EOF patterns of combined anomalies of OLR and zonal winds at 850 and 200 hPa (deseasonalized, adjusted for interannual and longer variations such as ENSO, normalized, and averaged over all latitudes from 15°S to 15°N—a latitude range that captures MJO most effectively while nearly excluding midlatitude effects). The chosen variables and latitude range capture almost all MJO variability including the intraseasonal (30–80 day) spectral peak. The daily values of RMM1 and RMM2 are obtained from the Australian Bureau of Meteorology website (http://www.bom.gov.au/climate/mjo/). The extracted three-dimensional MJO pattern on any day is reconstructed from RMM1 × EOF1 + RMM2 × EOF2. Because RMM1 leads RMM2 by about 10 days, WH04 plot the indices in two-dimensional phase space (RMM1, RMM2) and define eight phases indicating longitudes of enhanced or suppressed convection, where the usual eastward anomaly propagation appears as counterclockwise phase-space movement.

The daily atmospheric fields, station precipitation, OLR, and RMM indices are averaged by pentads in the 33 extended winters from 1979/80 to 2011/12, where each extended winter is the 30 pentads from 2–6 November to 27–31 March (the 24th pentad from 25 February to 1 March is a 6-day average in leap years). RMM indices are already deseasonalized and adjusted for interannual and longer variations. Here, all other time series are equivalently adjusted (but are not normalized, so they retain their original units) by subtracting the seasonal cycle of the 33-yr pentad climatology and then the mean anomaly for each extended winter for each grid point or station. Pentad averaging and the other adjustments allow the analyses to focus on a subseasonal time scale.

EOF analysis is performed on the pentad precipitation anomaly time series to obtain the dominant modes of subseasonal variability of extended winter precipitation in China. Linear regression with various lag times is utilized to study relationships of the two
leading EOF modes with MJO and other atmospheric variables. The statistical significance of regression coefficients and correlation coefficients in the analyses is assessed using the Student’s $t$ statistic. Effective sample sizes in the Student’s $t$ tests to account for autocorrelations are estimated using the relationship outlined in Bretherton et al. (1999).

### 3. Leading modes of subseasonal precipitation variability

Figure 1 shows spatial patterns of the first two leading EOFs of winter subseasonal precipitation variability in China, obtained by linear regression of precipitation on the respective principal component (PC) time series. EOF1 and EOF2 account for 31% and 13% of the total variance, respectively, and are well separated from each other and from other EOFs according to the criterion of North et al. (1982). EOF1 has a monopole spatial structure, and a positive (negative) phase of EOF1 corresponds to above (below) normal precipitation over southeastern China. The maximum center appears in the region south of the Yangtze River. EOF2 features a dipole pattern with opposite signs of variability over the Yangtze River basin and extreme South China (Fig. 1b). The corresponding patterns obtained by regression of gridded 850-hPa wind fields on the respective PC1 and PC2 time series are also illustrated in Fig. 1. A positive phase of PC1 is accompanied by anomalous westerlies over southeastern China, whereas a positive PC2 is associated with anomalous northeasterlies. The wintertime anomalous northerly wind is closely related to the cold surge, characterized by a progressive cold-air outburst from the Siberian high (SH), leading to a sharp temperature drop (Chang et al. 2006). It appears that EOF2 has a spatial phase shift to the southwest from EOF1, corresponding to a later phase of the expanding cold surge.

Power spectra of the principal components of the two leading EOFs (PC1 and PC2) are displayed in Fig. 2. PC1 and PC2 have a peak near 20 and 25 days, respectively, both statistically significant at the 99% confidence level. Both PC1 and PC2 also have large power spectrum values in the range of 10–30 days, indicating that EOF1 and EOF2 are related. Figure 3 shows their lag correlations. The correlation peaks when PC2 lags PC1 by one pentad (5 days). The small lag correlation between PC1 and PC2 suggests that they are largely independent. On the other hand, although the correlation of 0.27 is small, it noticeably exceeds the 0.05 statistical significance level according to a Student’s $t$ test. Therefore, PC1 and PC2 have a consistent but weak connection. Considering the spatial relationship of EOF1 and EOF2 in Fig. 1, the significant lagged correlation indicates that EOF1 and EOF2 represent a southward-propagating pattern of positive precipitation anomalies. The dependent (correlated) component of EOF1 and EOF2, on the other hand, suggests the possible existence of a common process.

The common process identified by EOF1 and EOF2 is the cold surge sequence, which in East Asia may last up to several weeks. Typically, a mild period (averaged in EOF1) ends with an initial cold front and rapid cooling, followed by successive reinforcing cold pulses (averaged...
together in EOF2) and a slow recovery to mild EOF1-like conditions. Because of pentad averaging (longer than the time scale of a single cold front) and differences between individual cold surge events, neither EOF is a “snapshot” of a single synoptic map. The limited correlation found above shows that most of a typical winter consists of more minor fluctuations.

4. Impact of the MJO

Where the precipitation anomaly time series at each of the 598 stations (pentad averaged and then filtered to remove long-term effects as described in section 2) is \( Z(t) \), we express \( Z(t) \) as a sum of MJO-related and MJO-independent [residual (RES)] components:

\[
Z(t) = Z_{MJO}(t) + Z_{RES}(t).
\] (1)

First, traditional multiple linear regression is used to compute the time series of the MJO-related component \( Z_{MJO}(t) \) at each station as a function of RMM1 and RMM2:

\[
Z_{MJO}(t) = a \times RMM1(t) + b \times RMM2(t),
\] (2)

with regression coefficients \( a \) and \( b \). Then, the non-MJO component \( Z_{RES}(t) \) is simply the “error,” or residual, of the regression process at pentad \( t \), as stated in (1).

Figure 4 shows the spatial field of the ratio of the MJO-related precipitation variance to the total subseasonal variance. The maximum influence of the MJO on wintertime precipitation variability in China is found over the southeast region, which accounts for up to 10% of the total subseasonal variance.

While WH04 show that the RMM indices do not properly represent northward-propagating MJO features. However, northward-propagating phenomena occur mostly outside China or outside the November–March study period, mostly over the western Pacific during the boreal summer and centered in the southern subtropical region of the Maritime Continent. The eastward-propagating MJO influence on winter precipitation in China is detected through anomalous local Hadley cell ascending or descending motion, which enhances or decreases precipitation. Therefore, the contribution of MJO to the boreal winter rainfall over China in Fig. 4 may not be noticeably underestimated.

To examine associations between the above precipitation EOF modes and the tropical convection of the MJO, simultaneous regressions of the MJO-related OLR with respect to PC1 and PC2 are shown in Fig. 5. In Fig. 5a, enhanced convection over the equatorial Indian Ocean and reduced convection in the equatorial western Pacific is observed. Such a tropical west–east dipole convection anomaly distribution corresponds well to MJO phase 3 defined by WH04. This phase has a relatively high frequency of occurrence; about 15% of the MJO days are in phase 3. In Fig. 5b, the negative OLR anomaly moves eastward to the Maritime Continent, which is similar to MJO phase 5. The above results suggest that MJO phases 3 and 5 tend to be related to an enhanced precipitation anomaly in South China (EOF1) and a dipole-like precipitation anomaly (EOF2), respectively.

To see the evolution of the MJO-related convection and upper-level convergence field associated with the leading mode of subseasonal precipitation variability in China, the lagged regression maps of the MJO-related OLR and 200-hPa velocity potential with respect to PC1 are displayed at lags from \(-2\) to \(+2\) in Fig. 6. A lag of \(-n\) indicates that the OLR anomaly leads PC1 by \(n\) pentads.
Negative OLR anomalies (above normal convection) are found in tropical Africa and the western Indian Ocean, accompanied by positive OLR anomalies (below normal convection) near the Maritime Continent two pentads before the enhanced precipitation in South China (lag 52). The tropical convection anomalies move eastward from lag 52 to 0. When above-normal precipitation occurs in South China, the enhanced tropical convection reaches the eastern Indian Ocean and the reduced convection moves to the western Pacific, a pattern similar to phase 3 of the MJO. The tropical MJO-related convection keeps propagating eastward. Convection is enhanced over the Maritime Continent at lag 51 (Fig. 6d), and the tropical convection anomaly looks similar to MJO phase 5 by lag 52 (Fig. 6e). The tropical upper-divergence anomalies of the 200-hPa velocity potential correspond well to the convection anomalies of the MJO in Fig. 6. Jeong et al. (2008) and He et al. (2011) found significant increases of precipitation in eastern China, Japan, and Korea Peninsula when the MJO is in phases 2 and 3. He et al. (2011) suggest that the precipitation anomaly in the East Asian region is associated with the MJO tropical convection through an equatorial Rossby wave response and local Hadley circulation anomalies. Results in Fig. 6 are generally consistent with findings in these studies. When the MJO propagates eastward, the related precipitation anomaly over the Yangtze River basin (the area shaded in gray, which represents positive precipitation anomaly statistically significant at the 5% level) propagates southward from lag 52 to lag 52. While the aforementioned studies have provided significant insight into the impacts of the MJO on East Asian climate, our results indicate that a significant part of the subseasonal precipitation variability in China is independent of the MJO.

5. The non-MJO-related variability

An EOF analysis is performed on the MJO-independent component of the pentad precipitation anomaly in China for the 33 extended winters. The leading two EOFs (not shown) look very similar to those anomalous easterlies over the tropics. An anticyclone forms to the north of the tropical easterlies, and southwesterlies are found over East Asia. When the negative OLR anomaly moves eastward to the Maritime Continent, anomalous northerlies occur over the east coast of China. The northerly wind leads to reduced precipitation in the Yangtze River basin and increased precipitation in South China, resulting in a precipitation anomaly similar to EOF2 in Fig. 1b. Jeong et al. (2008) report a significant increase of precipitation in eastern China, Japan, and Korea Peninsula when the MJO is in phases 2 and 3. He et al. (2011) suggest that the precipitation anomaly in the East Asian region is associated with the MJO tropical convection through an equatorial Rossby wave response and local Hadley circulation anomalies. Results in Fig. 6 are generally consistent with findings in these studies. When the MJO propagates eastward, the related precipitation anomaly over the Yangtze River basin (the area shaded in gray, which represents positive precipitation anomaly statistically significant at the 5% level) propagates southward from lag 52 to lag 52. While the aforementioned studies have provided significant insight into the impacts of the MJO on East Asian climate, our results indicate that a significant part of the subseasonal precipitation variability in China is independent of the MJO.
obtained using the total subseasonal anomaly (Fig. 1), which is not surprising as the MJO influence on the subseasonal precipitation variability in China is limited (Fig. 4). Therefore, processes other than the MJO likely determine the two leading modes of subseasonal precipitation variability in China. We next identify the precursors and predictability sources from both the tropical and middle-to-high latitude regions associated with the two leading modes of subseasonal precipitation variability in China during winter using lead–lag regression analysis.

a. Tropical convection

In the tropical region, although the MJO is the dominant mode of subseasonal variability, there is still a significant part of variability that is independent of the MJO. To examine how the precipitation variability in China is associated with MJO-independent tropical convection, simultaneous regressions of the residual OLR anomaly with respect to PC1 and PC2 are presented in Fig. 7. In Fig. 7a, a remarkable north–south dipole structure of OLR anomalies is observed along 120°E, with suppressed convection in the tropical South China Sea and the Maritime Continent when the precipitation is enhanced in South China. The positive anomaly center of OLR in the tropics moves southeastward to the tropical western Pacific in Fig. 7b. The regression of the residual part of OLR with PC2 shows a clear dipole structure over eastern China with strong negative OLR anomalies in South China (with a minimum of about $-8 \text{ W m}^{-2}$) and positive anomalies in the Yangtze River basin (maximum of about $4 \text{ W m}^{-2}$). Such anomalous OLR moves southward, causing the precipitation anomaly dipole of EOF2 (Fig. 1b).

The negative OLR anomaly in South China shown in Fig. 7b is absent in the regression of the MJO-related OLR, and the positive OLR anomaly in the Yangtze River basin is much weaker (maximum of about $1 \text{ W m}^{-2}$) (Fig. 5b), implying that the enhanced precipitation of EOF2 in South China is not related to the MJO. Instead, it is likely that the positive precipitation anomaly moves southeastward from EOF1 to EOF2 through a process independent of the MJO, which, as discussed later, is likely to be the East Asian winter monsoon cold surge. The southeastward propagation of the precipitation variability from EOF1 to EOF2 (Fig. 1) coincides with the movement of tropical suppressed convection (Fig. 7). Cold surges are driven by waves on the polar jet and occur much more frequently than the 30–50-day MJO cycle. In Fig. 7a, when PC1 is positive, southeastern China is in the warm sector ahead of the cold surge, and enhanced convection there is associated with compensating subsidence and suppressed convection in the South China Sea. In Figs. 1b and 7b, when PC2 is positive, the cold surge associated with anomalous northeasterlies crosses southern China, enhanced convection moves to the southeast, and the tropical suppressed convection moves east to the western Pacific. The minor contribution of MJO to China winter precipitation variability suggests that when a cold surge development occurs around MJO phase 3, MJO and the cold surge can interact as a coupled phenomenon.

As EOF2 has a peak correlation to EOF1 with a lag of one pentad, Fig. 8 shows lead–lag regressions of the residual part of the OLR anomaly with respect to PC1 of the total precipitation anomaly EOF1 in Fig. 1a. Lagged regression patterns in Fig. 8 show the evolution of tropical convection related to the monopole structure of the precipitation anomaly. At lag = $-2$ pentads, there exists a positive OLR anomaly in the Maritime Continent ($100°-140°E$) as well as a negative OLR anomaly (enhanced convection) centered near $60°E$. At lags = $-1$ and 0, as the positive OLR anomaly expands and moves slightly southeastward, the negative OLR anomaly moves southeastward and intensifies, so at lag = 0, a dipole OLR anomaly pattern (Fig. 8c).
indicates increased precipitation over South China (see EOF1 in Fig. 1a) and relative dryness throughout the Yangtze River basin. At lag = 1, the dipole OLR anomaly pattern moves eastward with the positive anomaly expanding southward to the Philippine Sea. Large negative OLR anomalies centered over South China and the East China Sea are found in both Figs. 7b and 8c, indicating a possible shift of subseasonal precipitation variability from EOF1 to EOF2.

Non-MJO-related OLR patterns in Fig. 8 resemble the eastward-intensified MJO mode identified by Hirata et al. (2013), as their MJO mode includes spectral power from 20 to 90 days, whereas the MJO defined by WH04 focuses on periods from 30 to 80 days. Around 40%–60% of the intraseasonal variance in tropical convection over the eastern Indian Ocean and the western Pacific fits the traditional MJO definition, as measured by the simultaneous amplitude of the PCs associated with the first two EOFs of one or more atmospheric variables (WH04). Therefore, the first two EOFs in WH04 are not enough to represent all MJO variability, and as noted by Liu (2014), the residuals in Fig. 8 include important components of the eastward-intensified MJO mode identified by Hirata et al. (2013).

To further investigate impacts of the Maritime Continent convection on precipitation, Fig. 9 shows the variability of the local Hadley circulation (the residual of the meridional and vertical velocity, in a cross section averaged between 110°E and 120°E), using a lead–lag regression against PC1. Figure 9 demonstrates that a positive PC1, which corresponds to reduced convection in the Maritime Continent, is preceded by a weakened local Hadley cell at lag = −2. The upward motion appears between 20° and 30°N one pentad later and expands northward at lag = 0, which is consistent with eastward movement of reduced convection in the Maritime Continent, is preceded by a weakened local Hadley cell at lag = −2. The upward motion appears between 20° and 30°N one pentad later and expands northward at lag = 0, which is consistent with eastward movement of reduced convection in the Maritime Continent and enhanced convection toward 120°E between 20° and 40°N. Meanwhile, low-level southerly wind anomalies occur from 10° to 25°N, corresponding to the monopole precipitation anomaly in EOF1. At lag = 1, tropospheric descending motion occurs between 30° and 40°N, causing northerly wind to the south of 35°N in the lower troposphere, which is associated with the dipole structure of EOF2.

b. Cold surges

The EOF2 dipole mode of subseasonal precipitation in Fig. 1b is strongly related to the East Asian winter monsoon cold surge (Chen et al. 2000). Figure 10 shows the lagged regression of the residual part of the 2-m SAT anomaly against PC1, with the possible influence of the MJO removed. At lag = −3 (not shown), there is a negative SAT anomaly in Siberia, indicating that there exists cooling over northern Asia three pentads before a

FIG. 6. Lagged regressions of anomalies of OLR (shaded; W m⁻²) and 200-hPa velocity potential (contours; 10⁸ m² s⁻¹; negative contours dashed) onto PC1, related to the possible influence of winter MJO, for lags from −2 to 2 pentads. With negative lags, OLR leads PC1. The magnitude of the plotted anomalies corresponds to one standard deviation of PC1, and in both shaded and contoured areas the regression is statistically significant at the 5% level according to a Student’s t test.
positive PC1. This is a very significant precursor for the leading mode of the subseasonal variability of winter precipitation. One pentad later (Fig. 10a), the negative SAT anomaly develops, and a northeast–southwest tilted band of cold SAT can be found, with its center over northern Asia. At lag $= -1$ (Fig. 10b), the negative SAT anomaly intensifies and continues extending southeastward, indicating the invasion of cold air into the western part of China. At lag $= 0$ (Fig. 10c), the center of the cold SAT is located in mainland China, and its front reaches the east coast of China. When the SAT leads PC1 by one pentad (Fig. 10d), the negative SAT anomaly covers the east coast of China, while the positive anomaly almost disappears. This sequence, even with pentadal averaging, is reminiscent of a wintertime cold surge in East Asia (Lau et al. 1983). The above results demonstrate that the wintertime East Asian cold surge is a contributing factor for the leading mode of the subseasonal variability of winter precipitation in China.

A cold surge is generated by a southward flow from the Siberian high. Figure 11 shows the lagged regression of the residual part of SLP against PC1, with the possible influence of the MJO removed. A significant positive SLP anomaly appears in northwest Europe two pentads before a positive PC1 (Fig. 11a), which extends to north Siberia one pentad later (Fig. 11b) and intensifies and moves southeastward at lag $= 0$ (Fig. 11c), causing anomalous southwesterlies over southeastern China shown in Fig. 1a. The positive SLP anomaly penetrates beyond the eastern part of China at lag $= 1$ pentad (Fig. 11d) and causes anomalous northeasterlies over southeastern China shown in Fig. 1b, indicative of an outbreak of cold air in Fig. 10d. The wind change from southwesterlies to northeasterlies due to a cold surge from lag $= 0$ to 1, together with the shifting OLR pattern from Fig. 8c to Fig. 8d, supports the significant correlation when PC2 lags PC1 by one pentad in Fig. 3.

The cold surge is displayed well not only in SLP but also in $Z_{500}$ (Fig. 12). A significant wave train originating from the North Atlantic is observed at lag $= -2$ (Fig. 12a), with a trough in the North Atlantic, a ridge in northwestern Europe, and a trough in northwestern Asia. The trough in northwestern Asia is enhanced at lag $= -1$ (Fig. 12b) and moves southeastward, indicating the dispersion of the wave train from the North Atlantic at lag $= -2$. Accompanying the expansion and southeastward extension of the trough to the east coast of China, the westerlies weaken in the extratropical region, which is favorable for a southward outbreak of cold air. Meanwhile, the positive anomaly over the middle-to-high latitudes in Siberia and the negative anomaly in East Asia suggest the development of a Ural Mountains blocking high and a trough in central Asia (these are the centers of anomalies reaching their largest scale in Fig. 12c), which favors the invasion of cold air from high latitudes into mainland China from the west and north. At lag $= 0$, a large negative anomaly is present in mainland China, corresponding to a cold surge outbreak. The association of cold surges over East Asia with a large-scale wave train across the Eurasian continent was observed in previous studies (e.g., Takaya and Nakamura 2005; Jeong et al. 2006). Park et al. (2014) found that a wave train starts about 12 days before the cold surge when a negative upper-tropospheric height anomaly develops in the North Atlantic. They also suggested that the height anomaly could possibly originate from the lower stratosphere over the North Atlantic. However, further studies are needed to fully understand the mechanism of the wave train.

Interactions between the cold surge and tropical convection activity have been discussed in previous studies (Jeong et al. 2005; Wang et al. 2012). Our results also indicate that the convection over the Maritime Continent and the cold surge from the extratropics are partially phase locked. The depressed convection over the Maritime Continent develops and expands (Figs. 8a–c) as the Siberian high strengthens and a cold surge moves through China (Figs. 11a–c and 12a–c). The
Maritime Continent convection is weakest when the Siberian high is strongest (Figs. 8c and 12c).

6. Summary

In this study, two dominant patterns of the sub-seasonal variability of wintertime precipitation in China from 1979 to 2012 are identified, and their signal sources
from both the tropics and extratropics are analyzed. The positive phase of EOF1 is characterized by a monopole (enhanced precipitation) in South China, and EOF2 has a meridional dipole structure with precipitation anomalies of opposite signs (dry over the Yangtze River basin and moist in coastal South China). The maximum lagged correlation is found (about 0.27) when PC2 lags PC1 by one pentad. While these two modes are mostly independent and an EOF may mix characteristics of multiple phenomena, the logical southeastward propagation of the wet anomaly from PC1 to PC2 suggests that these modes mostly reflect precipitation patterns at different stages in the propagation of an East Asian cold surge.

In the tropics, MJO phases 3 and 5 are found to be associated with EOF1 and EOF2, respectively. Such impacts of the MJO on these two EOF modes are consistent with previous reports but are limited since the MJO explains about 10% of the total variance in South China. Further analysis suggests that tropical Maritime Continent convection independent of MJO likely plays a more important role in these two EOF precipitation modes. Reduced convection (a warm OLR anomaly)
over the tropical Maritime Continent exists two pentads before the positive phase of the EOF1 mode and gradually retreats southeastward one pentad after the positive phase of EOF1, and the final OLR anomaly pattern is consistent with the dipole precipitation anomaly in South China. The out-of-phase relationship between precipitation in South China and in the tropical Maritime Continent region is likely connected by a local Hadley cell vertical circulation.

Finally, precipitation patterns associated with cold surges of the Siberian high strongly resemble the EOF1 mode positive precipitation anomaly as the cold surge develops, followed in a few days by a shift to the EOF2 precipitation dipole (moist over southern coastal China and dry inland as the cold surge crosses southern China). The amplitude of the Siberian high largely determines the intensity of the cold surge. A significant enhancement of the positive anomaly of SLP over central Siberia is found two pentads before the positive phase of EOF1. The outbreak of the cold surge along the east coast of southern China is related to the southeastward movement of the Siberia high, leading to a southeastward movement of the reduced tropical Maritime Continent convection and enhanced northeasterlies in southern China.

Our results indicate that the leading modes of subseasonal variability of the winter precipitation in China have statistically significant precursors about two pentads in advance. These preceding signal sources from the tropical MJO and tropical Maritime Continent convection and the Siberia high in the extratropics provide valuable information on the predictability of the subseasonal variability of wintertime precipitation in China.

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