Origins of Intraseasonal Precipitation Variability over North China in the Rainy Season

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ABSTRACT: We investigated the characteristics and mechanisms of subseasonal precipitation variability in North China during the rainy season (June–September). Two dominant intraseasonal modes with periods of 8–20 and 30–60 days were identified via spectral analysis. Together, they explain 62.8% of the total precipitation variability. Nearly all persistent heavy rainfall events in North China were observed concurrently with the enhanced positive phases of biweekly or/and 30–60-day precipitation modes. To elucidate the origins of these two intraseasonal precipitation variabilities, we performed moisture and vertical motion analyses. The moisture diagnosis results show that the anomalous lower-level southerly moisture from the tropical areas toward North China, are the key process causing abundant moisture for the anomalous precipitation occurrence. The local ascending motion anomalies associated with the occurrence of intraseasonal precipitation come mainly from the anomalous vorticity advection induced by the midlatitude wave train pattern propagating southeastward across the Eurasian continent, while the 30–60-day anomalies are determined by both upper-level perturbations along 40°N and northward-propagating intraseasonal convective activities from the tropics.

KEYWORDS: Asia; Precipitation; Moisture/moisture budget; Intraseasonal variability; Subseasonal variability

1. Introduction

North China, where Beijing and a number of major cities are located, is one of the most populous areas and main industrial bases in China. Influenced by the East Asian summer monsoon (Kripalani and Kulkarni 2001; Wu 2017), most precipitation in North China is concentrated in summer (Hao et al. 2015). Summer rainfall in North China is also modulated by midlatitude systems (Wang and He 2015; Yang et al. 2019). The complex interaction between tropical and midlatitude systems makes climate prediction for North China challenging.

Precipitation in North China shows significant interannual and interdecadal variability (Wu 2002). The interannual variation of North China precipitation before the late 1970s could be attributed to the amplitude change of the Indian summer monsoon (Kripalani and Kulkarni 2001; Zhang and Zhou 2012; Greatbatch et al. 2013). Through triggering the midlatitude circumpolar teleconnection pattern, a stronger (weaker) Indian summer monsoon often corresponds to an above-normal (below-normal) North China precipitation (Ding and Wang 2005). In addition, via the anomalous anticyclonic circulation over the northwestern Pacific forced by sea surface temperature (SST) anomalies, Pacific–Japan or East Asian–Pacific teleconnection may explain partially the North China precipitation variability on the interannual time scale, which is due to obvious dipole pattern of precipitation anomalies in South and North China (Yatagai and Yasunari 1994; Li et al. 2010; Huang et al. 2012; Stephan et al. 2018a). However, the connection between the Indian summer monsoon and North China precipitation became insignificant after the late 1970s. A distinct decrease in North China precipitation was observed during the past half century, which caused frequent droughts and exacerbated water shortage (Yu and Zhou 2007; Qian and Zhou 2014; Zhang et al. 2019). Pronounced interdecadal variability of North China precipitation was observed around 1980, which shifted from a wet to a dry condition (Jiang et al. 2017). As revealed by previous studies, the interdecadal change in North China precipitation is related to the weakened Indian summer monsoon due to tropical SST warming, but is also linked loosely to El Niño–Southern Oscillation (Chang et al. 2000; Wu and Wang 2002; Zhou et al. 2009; Lin et al. 2017). Other studies noted the modulation of the Pacific decadal oscillation (PDO) on the precipitation deficiency in North China (Li et al. 2010; Newman et al. 2016). Through inducing an anomalous cyclonic circulation over the northern North Pacific, the warm phase of the PDO causes unfavorable convective condition for the summer precipitation in North China (Yang et al. 2019).

Unlike the well-studied interannual and interdecadal variabilities, the origin and evolution of intraseasonal variability in North China precipitation are still unclear (Hao et al. 2015). Limited studies documented the dynamics of extratropical intraseasonal variability and its impact on local precipitation, compared to extensive studies on the tropical intraseasonal

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oscillation. For the tropical monsoon precipitation, the effects of the boreal summer intraseasonal oscillation (BSISO) have been widely studied (Annamalai and Slingo 2001; Wang et al. 2006; Lau and Waliser 2012; Zhang 2013). The BSISO signals indeed provide the source of subseasonal predictability for summer monsoon rainfall (Fu et al. 2013; Li and Robertson 2015; Zhu et al. 2015). For example, using intraseasonal convection and circulation anomalies as the predictors in a statistical model, Hsu et al. (2015) showed that the forecast skill of low-frequency rainfall over South China reached 20–25 days. However, how and to what extent the BSISO exerts influences on North China precipitation have received little attention (Hao et al. 2020). In addition to the BSISO prevailing over the tropical monsoon regions, significant subseasonal signals were observed in midlatitude regions (Krishnamurti and Gadgil 1985). Unlike the baroclinic vertical structure of the tropical BSISO, the midlatitude intraseasonal mode exhibits a quasi-barotropic structure (Li and Wu 1990; Terao 1998; Wang et al. 2013; Nie et al. 2019). Ding and Wang (2007) found that the midlatitude Eurasian intraseasonal variability in the boreal summer may be initiated over the northeastern Atlantic and move southeastward along the waveguide of the westerly jet. These midlatitude intraseasonal perturbations can exert an influence on the biweekly rainfall variability over the Yangtze River basin when they arrive in East Asia (Yang et al. 2010). In the boreal winter, two Eurasian wave trains, which are also initiated over the northeastern Atlantic, largely affect the intraseasonal variability of the East Asian winter monsoon, with one propagating eastward along the polar front jet and the other propagating southeastward along the subtropical jet (Jiao et al. 2019). Stronger northerly wind and colder temperature anomalies occur over East Asia when the two wave trains work coherently. Yang and Li (2016) examined the propagation of winter intraseasonal temperature anomalies over midlatitude Eurasia. Cui et al. (2021) used these southeastward-propagating disturbances as the major predictability source for forecasting winter temperature over Southeast China in five operational models and obtained a useful forecast skill of 10–20 days.

This study aims to unravel the evolution features and mechanisms of intraseasonal variability in North China precipitation, and to identify the major sources of its subseasonal rainfall prediction. In section 2, we introduce the datasets and methods used. Basic statistical characteristics of intraseasonal precipitation variability in North China are given in section 3. Diagnostic results of moisture source and vertical motion anomalies conducive to the intraseasonal precipitation anomalies in North China are presented in section 4, followed by discussions on the origins of the intraseasonal variability in section 5. A summary and some further discussions are in section 6.

2. Data and methods

a. Data

We use the gridded daily precipitation dataset developed by the Asian Precipitation–Highly Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) project (Yatagai et al. 2012). This is the state-of-the-art observation-based precipitation dataset with a high resolution of 0.25°×0.25° in Asia. Its quality in China has been confirmed by several studies (e.g., Han and Zhou 2012; Hsu et al. 2016). A recent evaluation by Lai et al. (2020) indicated a high correlation between the APHRODITE data and China Meteorological Administration (CMA) gauge-observed precipitation data.

To investigate the structures and evolutions associated with anomalous precipitation, we use the following two reanalysis datasets: daily interpolated outgoing longwave radiation (OLR) from the National Oceanic and Atmospheric Administration (NOAA) with a resolution of 2.5°× 2.5° (Liebmann and Smith 1996), and daily three-dimensional variables from the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERAI) at 19 pressure levels from 1000 to 100 hPa (Dee et al. 2011). The ERAI variables used here are regridded to 1.5°× 1.5°, which includes horizontal wind (V), vertical velocity (ω), specific humidity (q), geopotential height (Z), and temperature (T). Since the precipitation from the APHRODITE is available until 2015, our study period covers 1979–2015.

In addition to the abovementioned datasets, we also use the regional heavy rainfall event data provided by the National Meteorological Information Center of the CMA to investigate the relationship between subseasonal precipitation and persistent heavy rainfall events in North China. The extreme rainfall events are calculated by using gauge-observed precipitation data. The threshold for extreme precipitation is set to 50 mm day⁻¹, which is widely used by operational meteorological services in China to identify rainfall event that is intense enough to greatly affect human activities and corporate productivities (Chen and Zhai 2013). Taking both persistence and accumulated amount of extreme precipitation into consideration, a persistent heavy rainfall event is defined as an event with daily precipitation amount exceeding 50 mm over more than 20 adjacent stations for at least three consecutive days (Niu et al. 2018). Note that there are a total of 290 stations in North China. We identified 30 extreme heavy rainfall events in North China during June–September of 1979–2015, with an average duration of 3.8 days.

The study domain of North China is defined as (35°–43°N, 110°–120°E), which contains several provincial capitals across several provinces, municipalities, and autonomous regions (Fig. 1a). Limited by water vapor transport, summer precipitation in North China is much less than that in South and Northeast China. According to the time series of climatological daily precipitation shown in Fig. 1b, the rainy season in North China is from June to September. Thus, we focus on the precipitation variability during June–September. The area-averaged daily precipitation in the rainy season of North China is about 2–3 mm day⁻¹ (Fig. 1a).

b. Methods

1) MOISTURE FLUX CONVERGENCE DIAGNOSIS

Horizontal moisture flux convergence (MFC), which is part of the moisture budget equation (Yanai et al. 1973), is a useful
derived parameter that can be used in analyzing model outputs and observations to understand convective initiation (Banacos and Schultz 2005). Thus, we study the evolution characteristics of moisture associated with intraseasonal activities by using horizontal MFC (simply referred to as MFC). MFC at a constant pressure surface can be separated into two terms:

\[-\nabla \cdot (qV) = -\nabla \cdot q \nabla - q \nabla \cdot V.\]  

(1)

The first term on the right-hand side of Eq. (1) represents horizontal advection of moisture, and the second term is horizontal moisture convergence.

To extract signals at different time scales, we apply the Lanczos filter using 201 weights (Duchon 1979). Each variable can be separated into three components: low-frequency background state, and intraseasonal and high-frequency components. Note that the periods of these components vary for different inground state, and intraseasonal and high-frequency components. can be separated into three components: low-frequency back-

2) OMEGA EQUATION APPROXIMATION

To identify the key processes that contributed to the vertical motion associated with enhanced precipitation, we adopt the quasigeostrophic omega equation (Nie and Fan 2019). According to Holton (2004), the quasigeostrophic omega equation can be written as follows:

\[\left(\nabla^2 + \frac{f^2}{\sigma} \frac{\partial^2}{\partial P^2}\right) \omega = \frac{f}{\sigma} \frac{\partial [V \cdot \nabla (\xi + f)]}{\partial P} + \frac{R}{Pc_p} \nabla^2 (V \cdot \nabla T) - \frac{R}{Pc_p} \nabla \cdot \frac{dQ}{dt},\]  

(3)

where \(\omega\) is the vertical motion in the pressure coordinate, \(f\) is the Coriolis parameter, \(\sigma\) is the static stability parameter, \(P\) is pressure, \(V\) is the geostrophic wind vector, \(\xi\) is the relative vorticity calculated by using \(V\), \(T\) is temperature, \(Q\) is diabatic heating, and \(R\) and \(c_p\) are the gas constant and specific heat, respectively. As the residual of the thermodynamic equation (Yanai et al. 1973), \(Q\) is computed as follows:

\[Q = c_p \frac{\partial T}{\partial t} - c_p (\omega \sigma - V \cdot \nabla T),\]  

(4)

where \(\sigma = RT/(c_p P) - \partial T/\partial P\) is the static stability. \(Q\) represents the total diabatic heating, which includes radiative heating, latent heat release, and surface turbulent heat fluxes.

Since the left-hand side of Eq. (3) is proportional to vertical motion, that is, \([\nabla^2 + (f^2/\sigma)(\partial^2/\partial P^2)]\omega \propto -\omega\), \(\omega\) is proportional to

\[\omega = f \frac{\partial [V \cdot \nabla (\xi + f)]}{\partial P} + \frac{R}{P} \nabla^2 (V \cdot \nabla T) + \frac{R}{Pc_p} \nabla \cdot \frac{dQ}{dt}.\]  

(5)

As with the omega equation approximation [Eq. (5)], the vertical motion can be explained by three physical processes:
differential vorticity advection (first term), the Laplace of thermal advection (second term), and diabatic heating (last term).

3. Characteristics of intraseasonal precipitation in North China

To identify the dominant modes of subseasonal precipitation variability in North China, we use the Fourier transform method with a tapered scale of 0.1 on the precipitation time series during each boreal summer (June–September) of 1979–2015 (37 years). The averaged spectrum for the 37 years is taken to represent the climatological spectral analysis result (black curve in Fig. 2a). Since the annual cycle and long-term variation are not the subjects of this study, the signals with a period longer than 90 days were removed before spectral analysis. To verify the statistical significance of the spectral power, we add the power spectrum of mean Markov red noise (red curve in Fig. 2a), which is calculated using the autocorrelation at lag –1 day, and its 90% confidence level (dashed blue curve in Fig. 2a). Two pronounced intraseasonal modes are identified, with spectral peaks at 8–20 and 30–60 days. Note that there are three individual spectral peaks (13.5, 10.2, and 8.2 days) within the band of 8–20 days. We looked into each of their related convective and circulation fields, and found that these three peaks exhibit similar large-scale structures and evolutions. Thus, we integrated them into one biweekly mode. As expected, signals at the synoptic time scale are also significant, with spectral peaks of 3.5, 4, and 6 days. As documented in Hao et al. (2015), light rainfall events in North China occur frequently (about every 3.5 days) during the boreal summer.

To estimate the fraction of precipitation variability explained by the biweekly and 30–60-day components, we compute the ratios of the standard deviations of the 8–20- and
30–60-day-filtered precipitation with respect to the standard deviation of daily precipitation during the boreal summer, respectively (Figs. 2b and 2c). The ratio of the biweekly mode is larger than that of the 30–60-day mode because of the larger amplitude of the biweekly variability (Fig. 4). Over North China, the biweekly and 30–60-day components account for 42.8% and 20.0% of the total precipitation variability, respectively. Therefore, these two components together can explain more than half of the summer precipitation variability in North China.

The importance of the tropical BSISO lies in its tight connection with persistent heavy rainfall over South China (Hsu et al. 2016; Chen and Zhai 2017). Here, we also find that the occurrences of persistent heavy rainfall events in North China are concurrent with biweekly and 30–60-day modes. Figure 3 shows the time series of North China domain-averaged precipitation associated with each heavy precipitation event (bar) and of biweekly (blue) and 30–60-day (red) variations. The average amplitude of these extreme rainfall events is 8.4 mm day$^{-1}$ when the area-averaged precipitation over the entire North China is calculated, which is about 4 times of summer-mean precipitation in North China (Fig. 1a). The biweekly mode has a larger amplitude than the 30–60-day mode and seems to play a more important role in the occurrence of extreme heavy rainfall events. Among 30 persistent heavy rainfall events, 25 (18) events were observed concurrently with the enhanced biweekly (30–60-day) precipitation variability with the amplitude greater than one standard deviation. There were 14 events occurred in the peak phases of both enhanced modes. These events tended to induce
either larger amount of precipitation (e.g., events 3, 6, and 7) or persistent downpours (e.g., events 9, 13, 21, and 22). That implies the occurrence of enhanced biweekly and 30–60-day modes may increase the extremity of heavy rainfall events. It is also noted that nearly all persistent heavy rainfall events (29/30) were linked to the modulation of either the enhanced biweekly or 30–60-day variability in North China. Thus, understanding how the intraseasonal modes modulate local precipitation and trigger persistent heavy rainfall events is crucial for improving weather disaster prediction.

4. Mechanisms responsible for intraseasonal precipitation variation in North China

To elucidate the mechanisms responsible for the biweekly and 30–60-day precipitation variation, we perform composite analyses for anomalous environmental conditions associated with the strong biweekly and 30–60-day precipitation cases (with amplitude exceeding 1.5 standard deviation) during June–September. To isolate the effects of individual modes, we select only the events during which one mode is of large amplitude (>1.5 standard deviation) but the other mode is weak (<1.0 standard deviation) for composite. Using this rule, we find 74 (29) strong biweekly (30–60-day) precipitation events during the summers of 1979–2015. Events (12) with large amplitude of both biweekly and 30–60-day variability are excluded. Figure 4 shows the temporal evolutions of biweekly and 30–60-day precipitation anomalies in North China, composited relative to the day with maximum value (lag 0 day). For the biweekly mode (Fig. 4a), the precipitation anomaly grows from the lowest value of the dry phase (lag −5 days) to its positive peak (lag 0 day). The positive precipitation anomaly lasts for six days (lag −3 to +3 days) and then decreases to a negative anomaly after lag +3 days. The lower-frequency (30–60-day) variability varies slowly, with a positive tendency (growing phase) of precipitation from lag −19 to −1 day (Fig. 4b). The positive precipitation anomalies last for 20 days from lag −10 to +10 days.

The meridional-vertical profiles of dynamic and thermodynamic conditions over North China (along 35°–43°N) associated with the occurrence of enhanced biweekly and 30–60-day precipitation events (at lag 0 day) are displayed in Fig. 5. Geopotential height anomalies of the two modes both show a westward-tilted structure with height (Figs. 5a and 5d). Thus, for the fixed location over North China (areas between the two green lines), low pressure anomalies in the lower troposphere are coupled with mid- to high-level high pressure anomalies. Although the two modes exhibit similar structures, they have different amplitudes. Consistent with the amplitude of precipitation anomalies (Fig. 4), the biweekly perturbations are of greater intensity than the 30–60-day perturbations (Fig. 5). The low pressure anomalies induce moisture convergence and upward motion (Figs. 5b,c and 5e,f) for enhanced precipitation over North China, as will be shown in the next section. Positive moisture anomalies maximize in the lower troposphere (1000–700 hPa; Figs. 5b and 5e), while ascending motion anomalies appear in the middle troposphere (600–300 hPa; Figs. 5c and 5f). The thermodynamic (moisture) and dynamic (upward motion) conditions associated with the biweekly and 30–60-day variability provide favorable environments for triggering rainfall events. In the following, we diagnose which physical processes are the key
FIG. 5. Meridional–vertical profiles of 8–20-day-filtered (a) geopotential height (m), (b) specific humidity (g kg$^{-1}$), and (c) omega ($10^{-2}$ Pa s$^{-1}$) averaged along 35–43°N at lag 0 day. (d)–(f) As in (a)–(c), but for the 30–60-day-filtered fields. Green lines delineate the study domain of North China.
contributors to the increased moisture and ascending motion perturbations.

**a. Moisture flux convergence diagnosis**

Figures 6 and 7 show the lead-lag composites of vertically (1000–700 hPa) integrated MFC relative to the occurrence of enhanced biweekly and 30-60-day precipitation events (lag 0 day), respectively. For the biweekly mode, anomalous MFC leads 1 day before the anomalous precipitation (Fig. 6a), triggering and supporting the enhanced precipitation. We further separate MFC into horizontal moisture advection and convergence term \[-(q \cdot \nabla q)\] and horizontal moisture convergence \[-(q \cdot \nabla q)\]. Notably, \(-(q \cdot \nabla q)\) plays a major role in causing the MFC anomalies, while \(-(q \cdot \nabla q)\) is of smaller amplitude. However, moisture advection shows a positive contribution throughout the preconditioning period (lag −5 to −1 days), and moisture convergence only displays a positive effect after the appearance of positive precipitation anomaly (lag −3 to +3 days). Thus, during the developing phase of the biweekly precipitation (lag −5 to −1 days), the positive value of MFC is largely contributed by \(-(q \cdot \nabla q)\), while \(-(q \cdot \nabla q)\) experiences a phase transition and shows a net negative effect (Fig. 6b). Based on Eq. (2), we further separate \(- (q \cdot \nabla q)\) into nine terms. As shown in Fig. 6c, the sum of the nine terms on the right-hand side of Eq. (2) (the second bar from the left) is almost identical to the left-hand side of Eq. (2) (the leftmost bar). This suggests the scale-decomposed diagnoses are reliable. The moisture advection anomaly is mainly induced by the advection of background moisture by the biweekly flow (i.e., \(- (q \cdot \nabla q)\): Term 2 in Fig. 6c), as it exhibits the largest amplitude and varies simultaneously with the total moisture advection anomaly (figure not shown).

Similar to the biweekly mode, the 30-60-day \(- (q \cdot \nabla q)\) [MFC and \(- (q \cdot \nabla q)\)] is nearly in quadrature (phase) with precipitation anomalies (Fig. 7a). However, for the source of the 30-60-day MFC anomaly before the occurrence of maximum precipitation (lag −19 to −1 days), both moisture advection and convergence processes contribute positively (Fig. 7b). Based on further decompositions of \(- (q \cdot \nabla q)\) and \(- (q \cdot \nabla q)\), these two processes both come mainly from the interaction between background moisture field and 30-60-day wind anomalies (i.e., \(- (q \cdot \nabla q)\) and \(- (q \cdot \nabla q)\): Terms 2 in Figs. 7c and 7d). The relatively small terms \(- (q \cdot \nabla q)\),
$V \cdot \nabla q^*$, $-(q \cdot \nabla V)^*$, $-(q' \cdot \nabla V)$, and $-(q' \cdot \nabla V')$; Terms 3, 6, 7, and 8 in Figs. 7c and 7d] are related to synoptic eddy interacting with low-frequency background and intraseasonal fields. They were found to play a positive role in modulating the intraseasonal diabatic heating and surface latent heat flux, highlighting the upscale feedback of synoptic eddies to the intraseasonal variability (Hsu and Li 2011; Gao et al. 2019). However, these effects are weak here, suggesting that the synoptic-scale activity and related nonlinear interaction processes have limited influences on the 30–60-day moisture advection and convergence associated with the North China rainfall variability. As indicated by the first two bars in Figs. 7c,d, the decompositions of the 30–60-day $-(V \cdot \nabla q)^*$ and $-(q \cdot \nabla V)$ are also nearly closed.

To understand how the biweekly and 30–60-day circulation anomalies work on the background moisture field, resulting in the increased MFC for precipitation, we illustrate the distributions of background moisture (shading) and wind perturbations (vectors) associated with both subseasonal modes (Fig. 8). It is obvious that the low-frequency background moisture fields for both modes are abundant in the tropics,
especially over the Asian summer monsoon regions. The bi-weekly southerly anomaly, observed between the anomalous cyclone over Mongolia and the anticyclonic anomaly over the Korea Peninsula, transports moisture from South China and the western Pacific toward North China (Fig. 8a).

For the 30–60-day mode (Fig. 8b), anomalous southerly wind also prevails over East China and brings moisture to North China. Meanwhile, the southerly anomalies tend to be weakened in North China, causing moisture convergence there.

b. Vertical motion diagnosis

Here, we diagnose the processes associated with the dynamic condition (ascending motion anomaly) that is also conducive to the occurrence of enhanced precipitation. Based on the omega equation approximation [Eq. (5)], we first compare the contributions from different physical processes to the vertical motion associated with the biweekly mode at 400 hPa (Fig. 9a), where the upward motion is the strongest (Fig. 5c).

The evolutions of vertical differential of vorticity advection (term $v_1$) and diabatic heating processes (term $v_3$) vary consistent with the anomalous precipitation, while the thermal heating-related process (term $v_2$) leads 90°–180° ahead of the convection (figure not shown). Thus, the background westerly jet that maximizes along 35°–45°N during the boreal summer strongly advects the anomalous vorticity into the regions above North China, causing ascending motion anomaly. Even with a relatively small effect, the Laplace of thermal advection also favors upward motion anomaly (term $v_2$ in Fig. 9b), and the results of its decomposition suggest that the warm advection of background temperature by anomalous southerly perturbations is the dominant process (figure not shown). The diabatic heating process is the secondary contributor to the upward motion anomaly due to the intense latent heating release accompanied by the convection (term $v_3$ in Fig. 9b).

Similar to the diagnostic results of the biweekly vertical motion anomaly, all the vorticity advection, thermal advection and diabatic heating processes contribute to the upward vertical motion associated with the occurrence of the 30–60-day precipitation (Figs. 10a,b). Among the three processes, vertical differential of vorticity advection anomaly is the most important (term $v_1$ in Fig. 10b), in which the anomalous vorticity advected by background thermal wind (term 2 in Fig. 10c) plays a major role.

5. Linkage with the intraseasonal wave patterns

Although the intraseasonal wind and vorticity perturbations are identified to be the key factors inducing the moisture accumulation and upward motion anomalies when they
interact with the background moisture and circulation fields, the origins of these anomalous flows are still unclear. Are they linked to tropical BSISO activity or/and mid- to high-latitude subseasonal wave train? To address this, we illustrate the composites of geopotential height, OLR and circulation anomalies associated with the biweekly and 30-60-day modes, respectively (Figs. 11 and 12). For the biweekly mode, well-organized upper-level wave train structures are observed over the Eurasian continent, propagating southeastward from the northeastern Atlantic into the Northwestern Pacific (Figs. 11a–e). At lag 0 day when the precipitation anomaly reaches its maximum over North China, significant upper-level high pressure anomaly appears above North China (Fig. 11e), which is consistent with Fig. 5a. The anomalous OLR and low-level wind fields also display northwest–southeast-tiled wave train patterns propagating from the Eurasian continent to the northwest Pacific. The negative OLR perturbation arrives in North China at lag 0 day (Fig. 11j), suggesting the help of deep convection on precipitation occurrence. The southerly anomaly that transporting moisture toward North China is clearly shown along with the dipole structure of cyclonic anomaly over Mongolia and anticyclonic anomaly over East China–Japan (Figs. 11i,j). Based on the evolution of the biweekly mode, we conclude that the anomalous flow conditions (lower-level southerly and low pressure anomaly coupled with upper-level high pressure anomaly) associated with the biweekly precipitation are tightly connected with the southeastward-propagating midlatitude wave train perturbations.

The origins of local anomalies associated with the 30-60-day precipitation seem to be more complex than those of the biweekly mode. Although the upper-level 30-60-day wave train perturbations appear over the Eurasian continent, their structure is less organized (Figs. 12a–e). The high pressure anomaly above North China at lag 0 day seems to propagate westward from the western North Pacific. Besides the midlatitude systems, significant convective signals also appear over the Asian summer monsoon regions (Figs. 12f–j). These tropical intraseasonal signals propagate gradually northward from the equatorial oceans to ~30°N, similar to the idealized evolution of the BSISO during its phases 1 to 4 (Lee et al. 2013, in their Fig. 9). At lag −20 to −15 days, significant convective signals appear over the equatorial Indian Ocean and suppressed...
signals are observed over the Bay of Bengal, South China Sea, and western equatorial Pacific (Figs. 12f,g). Then, the convective signals gradually move northward, with large variability over the Arabian Sea, Bay of Bengal and South China Sea at lag 0 day (Figs. 12h–j). Meanwhile, suppressed signals appear over Northeast Asia, resulting in a northwestward extension of the western North Pacific subtropical high which is centered over the central subtropical Pacific (figure not shown). The associated lower-level southerly wind anomaly is then enhanced, and transports moisture into North China during lag −5 to 0 days (Figs. 12i–j). The results in Fig. 12 imply that the anomalous 30–60-day perturbations triggering precipitation over North China come from both midlatitude and tropical intraseasonal systems.

6. Summary and discussion

Two significant intraseasonal signals exist in the summer precipitation of North China, with spectral peaks at 8–20 and 30–60 days, respectively. These two components can explain 62.8% of the daily precipitation variability. Through modulating background conditions, the intraseasonal perturbations affect the occurrence of persistent extreme events. Nearly all persistent heavy rainfall events are concurrent with the enhanced biweekly or/and 30–60-day precipitation variability, suggesting the importance of subseasonal variation in causing weather disasters (Hsu et al. 2016; Chen and Zhai 2017; Hao et al. 2020). Although the intraseasonal signals of precipitation in North China are documented in previous studies (Hao et al. 2015, 2020), their origins and mechanisms need to be elucidated.

In this study, we carried out a series of composite analysis and diagnosis to understand the physical processes causing the biweekly and 30–60-day precipitation variations. For both intraseasonal components, abundant moisture and ascending motion perturbations are essential for the occurrence of enhanced precipitation anomalies (Hao et al. 2015, 2020). Through the diagnosis of low-level vertically integrated MFC, we revealed that the transport of background moisture by the biweekly and 30–60-day southerly anomalies is the dominant process for local moisture accumulation in North China. The results of omega diagnosis show that the dominant process inducing the ascending motion anomaly is related to the advections of upper-level biweekly and 30–60-day vorticity perturbations by the background westerly jet as the positive (negative) upper-level vorticity perturbation lags behind (leads ahead of) the convection perturbation over North China. Therefore, negative vertical gradient of anomalous vorticity advection causes the upward motion over North China, supporting the intraseasonal precipitation events. Warm advection of summer mean temperature by anomalous wind and intense latent heating release accompanied by the convection also contribute to ascending motion anomaly, but serve as secondary effects.
Considering that the amplitude and distribution of low-frequency background flow and moisture fields are relatively stable, the anomalous intraseasonal lower-level southerly in East China and upper-level anticyclonic ahead of precipitation are the key factors modulating the local precipitation anomalies over North China. Tracking and recognizing the sources of these intraseasonal circulation anomalies may help improve subseasonal predictability for North China precipitation. As summarized in Fig. 13, the biweekly mode (Fig. 13a) is tightly linked to the southeastward-propagating wave train across the Eurasian continent at the upper troposphere (200-hPa ellipses), coupled with the low-level circulation anomalies (850-hPa ellipses) that influence not only the precipitation over North China shown here but also the precipitation anomalies in other regions where the wave train passes through, such as Northwest China and East Asia (Ding and Wang 2007; Yang et al. 2010). Different from the biweekly anomalies prevailing over Eurasia, the anomalous 30–60-day fields (Fig. 13b) are driven by the compound effect of upper-level perturbations along 40°N (200-hPa ellipses) and other factors.
ellipses) and tropical BSISO over the Indian Ocean and Northwest Pacific (850-hPa pink circle). The circulation anomalies associated with the northward-propagating BSISO play a key role in moisture transport by inducing the westward extension of the western North Pacific subtropical high and the southerly anomaly (Mao and Wu 2006; Yang et al. 2010). Accompanied by the westward movement of upper-level anticyclonic anomaly from the North Pacific toward North China,

**FIG. 12.** As in Fig. 11, but for the evolutions of 30–60-day-filtered convection and circulations at lags −20, −15, −10, −5, and 0 days associated with enhanced 30–60-day precipitation events. The green plus sign in (a)–(e) indicates the center of 200-hPa high pressure anomalies. The green plus sign and magenta minus sign in (f)–(j) indicate the centers of suppressed and active convective anomalies, respectively.
the 30–60-day convective perturbations are established, which supports enhanced precipitation in North China.

Due to the modification by different large-scale intraseasonal processes, the dominant periodicity in different regions of East China is different (Mao et al. 2010; Yang et al. 2010; Hao et al. 2015; Li et al. 2015; Stephan et al. 2018b). As the tropical BSISO signals propagate northward from the equator toward the Asian summer monsoon regions, they greatly modulate the monsoon rainfall, intraseasonal variability, and local weather events in South China (Zhang et al. 2009; Chen et al. 2016). We then analyzed the wave train structures and evolutions associated with the biweekly mode during June–July and August–September, respectively. The overall structures of the wave train pattern and the anomalous circulations modulating the North China precipitation are similar during early and late summers, despite a larger wave train amplitude in late summer (figure not shown).

Unlike the well-organized biweekly wave train pattern, the pattern of the 30–60-day wave train is unclear (Figs. 12a–e). This may be partly due to the composite method adopted in this study, which may have mixed wave trains with different paths. We looked into the wave train pattern for each of the enhanced 30–60-day precipitation events (totally 29 cases), and found a diversity of wave train patterns. The enhanced and well-organized wave train patterns are only found in the cases (9/29) with a strong positive pressure anomaly at 200 hPa over North China. Weaker and less-organized wave trains appeared in the other cases (20/29). Neither of these wave train patterns reveal the two paths that were identified during the boreal winter (Jiao et al. 2019). The seasonality of intraseasonal wave trains may be influenced by the seasonal migration and intensity change of the westerly jet stream (Kuang and Zhang 2005).

Through triggering the circumglobal teleconnection pattern, previous studies showed that the Indian summer monsoon largely affects the North China rainfall on the interannual time scale (Wu 2002; Ding and Wang 2005). We also checked the potential relationship between the intraseasonal wave train and the convective signal over the Indian summer monsoon regions by calculating the correlation coefficients between intraseasonal geopotential height and OLR fields as in Ding and Wang (2005), but found the 30–60-day wave trains seem to be uncorrelated with tropical heating (figure not shown). By assuming the biweekly and 30–60-day modes are independent from each other, we investigate the individual mechanism of

![Diagram](image_url)
each intraseasonal mode in this study. However, they may interact with each other at specific timing. Our further analysis revealed that the 30–60-day geopotential height show out-of-phase (in-phase) condition at lag \(-16\) (+3) days with the biweekly geopotential height at lag 0 day. How and to what extent the nonlinear interaction between the two modes at the midlatitude affects local precipitation need further investigation.

Subseasonal-to-seasonal prediction remains a challenge (Vitart et al. 2017). All the large-scale anomalies and key processes responsible for the intraseasonal precipitation over North China identified here (Fig. 13) can help select useful predictors for forecasting summer precipitation in North China. Thus, constructing a statistical prediction model based on the findings in the current study is our ongoing work. Besides, how well the dynamic models predict the precipitation over North China and what the key processes contributing to precipitation are worthy of further study, both will help improve the subseasonal prediction skill of precipitation over North China.

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Data availability statement. APHRODITE precipitation data can be obtained from the website at http://aphrodite.st.hiroasaki-u.ac.jp/. ERA-Interim data can be downloaded from the site at https://apps.ecmwf.int/datasets. NOAA OLR data can be obtained from the site at https://psl.noaa.gov/psd/data/gridded/data.interp_OLR.html.

REFERENCES


