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Key Points:
• Sequential warm Meiyu fronts in middle to late June and cold fronts in early to middle July directly cause record-breaking Meiyu rainfall in 2020
• The NAO phase change leads to the alternation of the circulation regime of the East Asian summer monsoon from a warm- to cold-front period
• The prediction skill of the ECMWF S2S model on the 2020 Meiyu rainfall is higher in the warm front period but lower in the cold front period

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Abstract
In 2020, the Yangtze River (YR) suffered a long-lasting Meiyu season. The accumulated rainfall broke its record since 1961 and caused severe flooding and death in China. Our results show the sequential warm and cold Meiyu front regulated by the North Atlantic Oscillation (NAO) was responsible for this unexpected extreme Meiyu event. From 11 to 25 June with the positive NAO, the interaction between the South Asian High (SAH) and the western Pacific subtropical high maintained a warm front to strengthen the rainband north of the YR. Afterward, the coupling between SAH and midlatitude Mongolian Cyclone induced a cold front, which retreated the rainband to the south of YR from 30 June to 13 July with the negative NAO. Although the ECMWF S2S model successfully predicted the warm-front-related Meiyu rainfall, it failed to forecast the Meiyu rainfall in the cold-front period, suggesting a great challenge of S2S forecasting on Meiyu rainfall.

1. Introduction
Meiyu in China (also called Baiu in Japan and Changma in Korea) is the typical episode of the East Asian rainy season, generally starting in early June and ending in mid-July (Ding & Chan, 2005; Oh et al., 1997; Tanaka, 1992; Tao & Chen, 1987). However, the extremely enhanced Meiyu rainfall can induce severe flooding and cause great damage in East Asian countries. Therefore, the multiscale variability of Meiyu activity and its prediction has become one of the most important issues in these countries (Chen et al., 2017; Ding et al., 2020; Liu et al., 2020).

The Meiyu front is a quasi-stationary front representing the interaction between warm-wet air masses from the tropics and cold-dry air masses from middle-high latitudes. Its intensity and persistence directly determine the position and intensity of the Meiyu rainband (Ding, 1992, 2007; Ninomiya, 1984, 2000). In the lower troposphere, warm-and-wet air is transported by the low-level southwesterly wind west of the western Pacific subtropical high (WPSH) (Ha & Lee, 2007; Zhou & Yu, 2005), whereas cold-dry air embeds in the northerly wind west of the Mongolian Cyclone (MC, also termed cold vortex in Northeast China) (He et al., 2007). In the upper troposphere, the westerly jet and the South Asian High (SAH) upstream of the front could modulate either onset time or intensity of Meiyu rainfall (Li et al., 2019; Sampe & Xie, 2010). The year-to-year variation in Meiyu rainfall depends not only on the El Niño–Southern Oscillation (ENSO) and its resultant SST anomaly in the Indian Ocean (Kosaka et al., 2011; B. Wang et al., 2013) but also on the middle-high-latitude wave trains over the Eurasian continent (H. Hsu & Lin, 2007; Liu, Ke, & Ding, 2019; Z. Wang et al., 2018). On a subseasonal timescale, the intraseasonal oscillation (ISO) of the EASM is most crucial for Meiyu activity (Ding et al., 2020; Huang et al., 2019; Lau et al., 1988; Li et al., 2015; Song et al., 2016; B. Wang & Xu, 1997; C. Zhu et al., 2003). Moreover, the subseasonal variation of Meiyu rainfall is modulated by the Madden-Julian Oscillation (MJO) (X. Li et al., 2018) or the summer North Atlantic Oscillation (NAO) (Bollasina & Messeri, 2018).

In 2020, an extremely heavy Meiyu rainfall event occurred in the middle-lower reaches of the YR in China (Figure 1a). From 11 June to 15 July covering every Meiyu season in history, the accumulated precipitation around the YR in 2020 reached 167.2 mm and broke the record since 1961 (Figure 1b). Based on the meridional position of the anomalous rainband, this long-persisting Meiyu season was divided into two stages. One was from 12 to 25 June when the above-normal rainband located north of the YR. The other was from 30 June to 13 July when the rainfall was more abundant to the south of the YR. In late
July, the anomalous rainband attenuated greatly and settled to the north the YR, indicating the ending of the Meiyu season (Figure 1c).

Historically, the other two intense Meiyu rainfall events around the YR took place in 1998 and 2016 following the super El Niño event, along with the significant MJO activity (Shao et al., 2018; Z. Zhu et al., 2003). However, neither a super El Niño event nor an active MJO occurred in this year. Thus, we are urgent to answer the following questions: (1) What caused this record-breaking Meiyu without either significant ENSO or active MJO? (2) Is the state-of-the-art subseasonal-to-seasonal (S2S) operational model able to predict Meiyu rainfall this year? To answer these questions, we used 2,479 in situ rainfall observations provided by the National Meteorological Information Center in China. We described the circulation and thermal fields in the troposphere using the JRA-55 reanalysis dataset developed by the JMA, with a horizontal resolution of 1.25 × 1.25° and 37 standard isobaric surfaces from 1,000 to 1 hPa (Harada et al., 2016; Kobayashi et al., 2015). The real-time S2S production released by ECMWF was applied to examine the prediction skill of Meiyu rainfall this year (please refer to the details in https://confluence.ecmwf.int/S2S/S2S/ECMWF+BModel+Description+CY45R1). The climatology was defined by the arithmetic mean of each variable from 1981–2010. The Meiyu front position was defined by the region where the meridional gradient of the 700-hPa equivalent temperature higher than 2.0 × 10⁻⁵ K m⁻¹ over East Asia (Fu & Qian, 2011). To reveal the subseasonal processes of Meiyu rainfall, we used a nonfiltered method to obtain the subseasonal anomaly (P.-C. Hsu et al., 2015).

### 2. Stepwise Swing of Meiyu Front and Circulation Regimes

The long-persisting Meiyu rainfall in 2020 features the stepwise swing of the Meiyu front and the circulation regimes on a subseasonal timescale. In the first period, the Meiyu front is enhanced near 35°N, where the rainfall increases considerably north of the YR (Figures 1c and 2a). In the lower troposphere, the WPSH evidently extends westward to South China and suppresses the local rainfall. The low-level southwesterly wind accelerates to bring more warm-and-wet air into the YR. In contrast, the anomalous northerly wind is relatively weak to the north of the front, indicating a warm front dominant in this period (Figure 2a). In the upper troposphere, a vast anomalous anticyclone is generated over East Asia, corresponding to the

![Figure 1](https://example.com/figure1.png)

### References

- Shao et al., 2018
- Z. Zhu et al., 2003
- Fu & Qian, 2011
- P.-C. Hsu et al., 2015
Therefore, the WPSH meets the SAH halfway to form a circulation pattern facilitating the above-normal Meiyu rainfall north of the YR (see section 3 for details).

In the second period, the intensified Meiyu front and rainband retreat to the south of the YR (Figure 1c). An anomalous cyclone with a vertically quasi-barotropic structure is maintained over Northeast Asia (NEA), suggesting an enhancement of the midlatitudinal MC (Figures 2b and 2d). The low-level northerly wind on its west strengthens remarkably to bring more cold-and-dry air into the YR (Figure 2b). Meanwhile, the anomalous WPSH is centered to the southeast of Japan, along with weak anomalies of low-level wind over South China. A cold front then determines the Meiyu rainband in this stage. In the upper troposphere, the more energetic MC with a cold air mass is gearing with the southward extension of the SAH main body (Figure 2d), which retreats the Meiyu rainband to the south of the YR. Thus, the above two subsections can be treated as the warm- and cold-front period, respectively. In late July, the Meiyu front becomes much weaker, corresponding to the attenuated anomalous rainband over East China.

3. Regulation by the Phase Transition of NAO

3.1. Linkage With NAO

The alternation of Meiyu warm and cold fronts follows the phase transition of the NAO. The NAO first shows a positive phase in mid-June, then enters an intense negative phase in late June and persists until late July (Figure 1d). In the warm-front period with a positive NAO, an anomalous upper-level ridge exists over Europe, whose wave energy emanates downstream along with the polar-front jet. It deepens the trough west of Lake Baikal and strengthens the NEA anticyclone in the upper troposphere (Figure 3a). The SAH thus extends eastwards north of the YR, presenting a negative anomaly of 200-hPa potential vorticity (PV) to the north of the anomalous Meiyu rainbow (Figure 4a). Though partly compensated by the negative PV advection due to anomalous PV and mean flow around YR, the positive PV advection, induced by the anomalous northerly wind on the east of the SAH, prevails to strengthen the ascent over the anomalous Meiyu

Figure 2. Subseasonal anomalies of atmospheric circulation (vectors, m s$^{-1}$) and rainfall (shading, mm day$^{-1}$) over East Asia in the two Meiyu periods in 2020. (a, c) Warm-front period. (b, d) Cold-front period. Left column: circulation at 850 hPa (wind speeds higher than 1.0 m s$^{-1}$ are plotted). Right column: circulation at 200 hPa (wind speeds higher than 4.0 m s$^{-1}$ are plotted). Purple curves in the left and right columns indicate the 152- and 1,276-gpm contours of the 850- and 200-hPa geopotential heights, respectively. Dashed and solid lines represent the climatological and 2020 cases, respectively.
rainband (Figures 4b and 4c). The outflow then sinks over South China, where the low-level WPSH is prominently enhanced and extending westward, providing more moisture to the north of the YR. A baroclinic structure of circulation thus establishes over East China, which presents the stronger low-level warm front and upper-level anticyclone north of the YR (Figure 3c). A closed meridional circulation finally maintains over East China to persist the anomalous Meiyu rainfall in the positive NAO phase.

When the NAO enters its negative phase in the cold-front period, Europe is beneath a striking deeper trough in the upper troposphere. It acts as a wave source to enhance the upper-level ridge over Northwest Asia and the cyclone over NEA with a deep barotropic structure via a wave train between 40°N and 60°N (Figure 3b). The NEA cyclone (i.e., stronger MC), characterized by a remarkable positive PV anomaly at 200 hPa, brings more positive PV southward not only by the anomalous northerly wind but also via the mean flow transport on the PV anomaly (Figures 4a–4c). As a result, the high PV intrudes to the south of the YR to develop the ascending over the anomalous Meiyu rainband (Figures 4b and 4c). The descending develops beneath the NEA cyclone, then diverges southward near the surface and merges into the ascending south of the YR in early to middle July (Figure 3d).

In the two periods, the daily NAO index is significantly positively correlated with both the anomalous geopotential height over Europe (black line in Figure 1d) and NEA (pink line in Figure 1d), showing temporal correlation coefficients (TCCs) of +0.56 and +0.48, respectively. Both exceed the 95% confidence level in a two-tailed Student’s t test. However, the significant correlation between the NAO and NEA cyclone index would vanish if we exclude the Europe ridge in a partial correlation analysis. A lagged correlation analysis suggests that the 3-day-lagged (7-day-lagged) anomalous geopotential height over Europe (NEA) is most relevant to the NAO index, consistent with the timescale of the subseasonal downstream response over East Asia to the NAO (Bollasina & Messori, 2018). The circulation over Europe then bridges the NAO and the East Asian climate as reported by Liu, Zhu, et al. (2019).

We further diagnoses each component of the anomalous meridional advection to show how the anomalies of the upper-level circulation modulate the Meiyu front property and rainband position in 2020. In the warm-front period, the stronger WPSH extends westward under the influences of the eastward extension of the SAH and the positive PV advection in the upper troposphere. As a result of the warm-wet advection
due to the stronger southwesterly wind over South China, the lower-tropospheric air becomes warmer and wetter to support the warm front (Figures 4e and 4h). In contrast, the meridional advection anomaly due to the anomalous thermal and moisture fields is minimal near the anomalous Meiyu front (Figures 4f and 4i). In this way, the anomalous WPSH modulated by the SAH anomaly determines the warm front and strengthens Meiyu rainfall north of the YR in middle to late June.

In the cold-front period, the positive PV advection induced by the more energetic MC becomes remarkable. In the lower troposphere, the air becomes colder and drier along with the YR because of the meridional cold and dry advection produced by the anomalous northerly wind (Figures 4e and 4h). The southward intrusion of the colder and drier air mass further increases the warm and wet advection over the anomalous Meiyu rainband by enlarging the anomaly of meridional temperature and moisture gradient, respectively (Figures 4f and 4i). Therefore, the cold front with above-normal Meiyu rainfall persists south of the YR in early to middle July. In late July, the anomalies of the PV, air temperature, and specific humidity, as well as their advection become much weaker around the YR, as the ending of the Meiyu season in 2020.

3.2. Forecast Skill of the ECMWF S2S Model

The real-time prediction skill of the ECMWF S2S model on Meiyu rainfall is distinct between the warm- and cold-front periods in 2020. The prediction skill was assessed by the metrics of the widely used anomaly correlation coefficient (ACC) and root-mean-square error (RMSE), which was calculated between the observed and predicted accumulated precipitation anomalies over YR with varied lead times. In the warm-front

Figure 4. Left column: 105–125°E averaged latitude-temporal cross section of the subseasonal anomalies of (a) the 200-hPa PV (shading, PVU) and horizontal winds (vectors, m s⁻¹), (b, c) the meridional PV advection (shading, PVU day⁻¹) due to anomalous meridional flow \((-\nu'^{\partial PV/\partial y})\) and PV \((-\nu^{{\partial PV^'}/\partial y})\), respectively. Middle column: similar to the left column, but the shading and vectors in (d) are for the 700-hPa subseasonal anomalies of air temperature (K) and winds (m s⁻¹). And the shading in (e) and (f) denote the meridional temperature advection (K day⁻¹) induced by anomalous meridional flow \((-\nu'^{\partial T/\partial y})\) and temperature \((-\nu^{{\partial T^'}/\partial y})\), respectively. Right column: similar to the left column, but the shading and vectors in (g) are for the 850-hPa subseasonal anomalies of specific humidity (g kg⁻¹) and winds (m s⁻¹), and the shading in (h) and (i) denote the meridional moisture advection (g kg⁻¹ day⁻¹) induced by anomalous meridional flow \((-\nu'^{\partial q/\partial y})\) and specific humidity \((-\nu^{{\partial q^'}/\partial y})\), respectively. Variables with bars and superscripts indicate the climate-mean value and subseasonal anomaly, respectively. Purple contours and dots indicate the position of the Meiyu front and large rainfall anomaly higher than 4.0 mm day⁻¹, respectively.
period, the ECMWF S2S model can capture the features of the Meiyu rainband even 30 days in advance (Figures 5a and 5b). As the decreasing of the lead time, the median ACC increases from 0.1 to above 0.4, while the ensemble spread range gradually narrows, along with a stable range of RMSE between 6.0 and 8.0 mm day$^{-1}$. However, the prediction skill is much lower in the cold-front stage (Figures 5a and 5b). The median ACC is negative when the lead time is longer than 7 days, in which the RMSE is greater than 10.0 mm day$^{-1}$. The lower ACC and higher RMSE remain in the prediction even when a lead time is less than 1 week. In addition, the ACC and RMSE are consistently poor in each individual members of the ensemble.

In the warm-front period, the prediction skill of SAH and WPSH is high, in contrast to the large bias between predicted and observed middle-high-latitude MC and wave train in the cold-front period (figure not shown). For the ECMWF S2S model, the prediction skill on the Meiyu rainband is high when the tropical circulation and warm-wet air mass is dominant, but the skill decreases dramatically when the midlatitude circulation and cold-dry air mass becomes critical.

4. Summary and Discussion

A record-breaking Meiyu rainfall event took place in 2020, causing severe flooding and a number of deaths in China and Japan. Here, we identified the warm- and cold-front stages of this Meiyu season and ascribed the alternation of the circulation regime to the phase transition of the NAO. In middle to late June, the positive NAO induces the eastward extension of SAH and the westward extension of WPSH, leading to the stronger southerly wind over South China. The warm front thus becomes enhanced and results in the anomalous Meiyu rainband north of the YR. Afterward, the NAO enters its intense negative phase in early July. A wave train along the polar-front jet emerges to strengthen the midlatitude MC, which not only enhances the ascending near the YR by dynamical procedure but maintains a stronger cold front along with the YR by anomalous meridional temperature and moisture advection. Finally, the Meiyu rainband retreats south of the YR in early to middle July. The ECMWF S2S model shows a higher prediction skill for warm front-related rainfall, but it fails to predict cold front-caused rainfall during the Meiyu season in 2020. Thus, a great challenge still exists in the S2S dynamical prediction of Meiyu rainfall, especially when the middle-high-latitude impact is crucial. The predictability of the extratropical circulation is much lower than either the MJO or the BSISO in the S2S forecast (Hung et al., 2013). It also limits the seasonal rainfall predictability of the EASM (Kosaka et al., 2012).

One provoking question is why such a record-breaking event occurred in a weak ENSO environment compared with 1998 and 2016. This is probably attributed to global warming, which could increase the heavy rainfall near the YR in the Meiyu season (Zhu et al., 2012). In late July, the anomalous rainband moves to north of the YR. As the seasonal weakening of the basic westerly flow, the downstream effect of the NAO...
become weak. But the WPSH extends westward remarkably, which may be induced by the warmer SST in the Indo-Pacific warm pool (Annamalai et al., 2005) or the enhanced atmospheric heat source over eastern Tibetan Plateau in deep summer (Hu & Duan, 2015). Further investigation is necessary for a comprehensive understanding of this record-breaking Meiyu flood over East Asia on multiple timescales.

**Conflict of Interest**

The authors declare that they have no conflicts of interest.

**Data Availability Statement**

The in situ rainfall records were downloaded from http://data.cma.cn/en/?r=indexwebsite. The JRA-55 reanalysis data set was obtained from the National Center for Atmospheric Research, Computational and Information Systems Laboratory (https://doi.org/10.5065/D6HH6H41). The NAO index was provided by NOAA/CPC from the website (https://www.cpc.ncep.noaa.gov/products/predict/CWlink/pna/nao.shtml). The ECMWF S2S production was downloaded from http://s2s.cma.cn/indexwebsite.

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**References**

Annamalai, H., Liu, P., & Xie, S.-P. (2005). Southwest Indian Ocean SST variability: Its local effect and remote influence on Asian monsoons. *Journal of Climate*, 18(20), 4150–4167. https://doi.org/10.1175/JCLI3533.1

Bollasina, M. A., & Messori, G. (2018). On the link between the subseasonal evolution of the North Atlantic Oscillation and East Asian climate. *Climate Dynamics*, 51, 3537–3557. https://doi.org/10.1007/s00382-018-4095-5

Chen, G., Sha, W., Iwasaki, T., & Wen, Z. (2017). Diurnal cycle of a heavy rainfall corridor over East Asia. *Monthly Weather Review*, 145, 3365–3389. https://doi.org/10.1175/MWR-D-16-0423.1

Ding, Y. (1992). Summer monsoon rainfalls in China. *Journal of the Meteorological Society of Japan. Ser. II*, 70(1B), 373–396. https://doi.org/10.2151/jmsj1965.70.1B_373

Ding, Y. (2007). The variability of the Asian summer monsoon. *Journal of the Meteorological Society of Japan Series II*, 85B, 21–54. https://doi.org/10.2151/jmsj1965.85B.21

Ding, Y., & Chan, J. C. L. (2005). The East Asian summer monsoon: An overview. *Meteorology and Atmospheric Physics*, 91(1), 117–142. https://doi.org/10.1007/s00703-005-0125-z

Ding, Y., Liang, P., Yi, Y., & Zhang, Y. (2020). Multiscale variability of Meiyu and its prediction: A new review. *Journal of Geophysical Research: Atmospheres*, 125, e2019JD031496. https://doi.org/10.1029/2019JD031496

Fu, J.-L., & Qian, X.-H. (2011). The structure of a typical Mei-Yu front identified by the equivalent temperature. *Atmospheric and Oceanic Science Letters*, 4(2), 109–113. https://doi.org/10.1080/16742834.2011.11446913

Ha, E.-I., & Lee, S.-S. (2007). On the interannual variability of the Bonin high associated with the East Asian summer monsoon rain. *Climate Dynamics*, 28(1), 67–83. https://doi.org/10.1007/s00382-006-0169-x

Harada, Y., Kamahori, H., Kobayashi, C., Endo, H., Kobayashi, S., Ota, Y., & et al. (2016). The JRA-55 reanalysis: Representation of atmospheric circulation and climate variability. *Journal of the Meteorological Society of Japan Series II*, 94, 269–302. https://doi.org/10.2151/jmsj.2016.015

He, J., Wu, Z., Jiang, Z., Miao, C., & Han, G. (2007). “Climate effect” of the northeastern cold vortex and its influences on Meiyu. *Chinese Science Bulletin*, 52(5), 671–679. https://doi.org/10.1007/s11434-007-0053-x

Hsu, H.-H., & Lin, S.-M. (2007). Asymmetry of the tripole rainfall pattern during the east Asian summer. *Journal of Climate*, 20(7), 4443–4458. https://doi.org/10.1175/JCLI4246.1

Hsu, P.-C., Li, T., You, L., Gao, J., & Ren, H.-L. (2015). A spatial–temporal model for 10–30 day rainfall forecast in South China. *Climate Dynamics*, 44, 1227–1244. https://doi.org/10.1007/s00382-014-2215-4

Hu, J., & Duan, A. (2015). Relative contributions of the Tibetan Plateau thermal forcing and the Indian Ocean Sea surface temperature basin mode to the interannual variability of the East Asian summer monsoon. *Climate Dynamics*, 45, 2697–2711. https://doi.org/10.1007/s00382-015-2503-7

Huang, W.-R., Liu, F.-Y., Chen, J.-H., & Deng, L. (2019). Impact of boreal summer intra-seasonal oscillations on the heavy rainfall events in Taiwan during the 2017 Meiyu season. *Atmosphere*, 10, 205. https://doi.org/10.3390/atmos10040205

Hunag, M.-L., Lin, J.-L., Wang, W., Kim, D., Shinoda, T., & Weaver, S. J. (2013). MJO and convectively coupled equatorial waves simulated by CMIP5 climate models. *Journal of Climate*, 26, 6185–6214. https://doi.org/10.1175/JCLI-D-12-0541.1

Kobayashi, S., Ota, Y., Harada, Y., & Al, E. (2015). The JRA-55 reanalysis: General specifications and basic characteristics. *Journal of the Meteorological Society of Japan*, 93, 5–48. https://doi.org/10.2151/jmsj.2015-001

Kosaka, Y., Chowdary, J. S., Xie, S.-P., Min, Y.-M., & Lee, J.-Y. (2012). Limitations of seasonal predictability for summer climate over East Asia and the northwestern Pacific. *Journal of Climate*, 25(21), 7574–7589. https://doi.org/10.1175/JCLI-D-12-00099.1

Kosaka, Y., Xie, S.-P., & Nakamura, H. (2011). Dynamics of interannual variability in summer precipitation over East Asia*. *Journal of Climate*, 24(20), 5435–5453. https://doi.org/10.1175/2011JCLI4099.1

Lau, K. M., Yang, G. J., & Shen, S. H. (1988). Seasonal and intraseasonal climatology of monsoon moisture rainfall over East Asia. *Monthly Weather Review*, 116(1), 18–37. https://doi.org/10.1175/1520-0493(1988)116<0018:SAICO>2.0.CO;2

Li, H., He, S., Fan, K., & Wang, H. (2019). Relationship between the onset date of the Meiyu and the South Asian anticyclones in April and the related mechanisms. *Climate Dynamics*, 52, 209–226. https://doi.org/10.1007/s00382-018-4131-5

Li, J., Mao, J., & Wu, G. (2015). A case study of the impact of boreal summer intraseasonal oscillations on Yangtze rainfall. *Climate Dynamics*, 44, 2683–2702. https://doi.org/10.1007/s00382-014-2425-9

Li, X., Gollan, G., Greatbatch, R. J., & Lu, R. (2018). Intraseasonal variation of the East Asian summer monsoon associated with the Madden–Julian Oscillation. *Atmospheric Science Letters*, 19, e794. https://doi.org/10.1002/asl.794
Liu, B., Zhu, C., Su, J., Ma, S., & Xu, K. (2019). Record-breaking northward shift of the Western North Pacific subtropical high in July 2018. Journal of the Meteorological Society of Japan, 97, 913–925. https://doi.org/10.2151/jmsj.2019-047

Liu, Q., Zeng, W., Chen, G., & Guan, P. (2020). Corridors of Mei-Yu-season rainfall over eastern China. Journal of Climate, 33, 2603–2626. https://doi.org/10.1175/jcli-d-19-0649.1

Liu, Y., Ke, Z., & Ding, Y. (2019). Predictability of East Asian summer monsoon in seasonal climate forecast models. International Journal of Climatology, 39, 5688–5701. https://doi.org/10.1002/joc.6180

Ninomiya, K. (1984). Characteristics of Baiu Front as a predominant subtropical front in the summer northern hemisphere. Journal of the Meteorological Society of Japan, 62(6), 880–894. https://doi.org/10.2151/jmsj1965.62.6_880

Ninomiya, K. (2000). Large- and meso-alpha-scale characteristics of Meiyu/Baiu front associated with intense rains in 1–10 July 1991. Journal of the Meteorological Society of Japan, 78(2), 141–157. https://doi.org/10.2151/jmsj1965.78.2_141

Oh, J.-H., Kwon, W.-T., & Ryoo, S.-B. (1997). Review of the research on changma and future observational study (kormex). Advances in Atmospheric Sciences, 14(2), 207–222. https://doi.org/10.1007/s00376-997-0020-2

Sampe, T., & Xie, S. P. (2010). Large-scale dynamics of the Meiyu-Baiu Rainband: Environmental forcing by the westerly jet. Journal of Climate, 23(1), 113–134. https://doi.org/10.1175/2009JCLI3128.1

Shao, X., Li, S., Liu, N., & Song, J. (2018). The Madden–Julian oscillation during the 2016 summer and its possible impact on rainfall in China. International Journal of Climatology, 38, 2575–2589. https://doi.org/10.1002/joc.5440

Song, Z., Zhu, C., Su, J., & Liu, B. (2016). Coupling modes of climatological intraseasonal oscillation in the East Asian summer monsoon. Journal of Climate, 29, 6363–6382. https://doi.org/10.1175/JCLI-D-15-0794.1

Takaya, K., & Nakamura, H. (2001). A formulation of a phase-independent wave-activity flux for stationary and migratory quasigeostrophic eddies on a zonally varying basic flow. Journal of the Atmospheric Sciences, 58(6), 608–627. https://doi.org/10.1175/1520-0469(2001)058<0608:AFOAPI>2.0.CO;2

Tanaka, M. (1992). Intraseasonal oscillation and the onset and retreat dates of the summer monsoon over east, Southeast Asia and the Western Pacific region using GMS high cloud amount data. Journal of the Meteorological Society of Japan Series II, 70(1B), 613–629. https://doi.org/10.2151/jmsj1965.70.1B_613

Tao, S., & Chen, L. (1987). A review of recent research of the east Asian summer monsoon in China. In C.-P. Chang & T. N. Krishnamurti (Eds.), Monsoon Meteorology (pp. 60–92). New York: Oxford Univ. Press.

Wang, B., Xiang, B., & Lee, J.-Y. (2013). Subtropical high predictability establishes a promising way for monsoon and tropical storm predictions. Proceedings of the National Academy of Sciences of the United States of America, 110, 2718–2722. https://doi.org/10.1073/pnas.1214626110

Wang, B., & Xu, X. (1997). Northern hemisphere summer monsoon singularities and climatological intraseasonal oscillation. Journal of Climate, 10(5), 1071–1085. https://doi.org/10.1175/1520-0442(1997)010<1071:NHSMSS>2.0.CO;2

Wang, Z., Yang, S., Lau, N.-C., & Duan, A. (2018). Teleconnection between summer NAO and East China rainfall variations: A bridge effect of the Tibetan Plateau. Journal of Climate, 31, 6433–6444. https://doi.org/10.1175/JCLI-D-17-0413.1

Zhao, T.-J., & Yu, R.-C. (2005). Atmospheric water vapor transport associated with typical anomalous summer rainfall patterns in China. Journal of Geophysical Research, 110, D08104. https://doi.org/10.1029/2004JD005413

Zhu, C., Nakazawa, T., Li, J., & Chen, L. (2003). The 30–60 day intraseasonal oscillation over the western North Pacific Ocean and its impacts on summer flooding in China during 1998. Geophysical Research Letters, 30(18), 1952. https://doi.org/10.1029/2003GL017817

Zhu, C., Wang, B., Qian, W., & Zhang, B. (2012). Recent weakening of northern East Asian summer monsoon: A possible response to global warming. Geophysical Research Letters, 39, L09701. https://doi.org/10.1029/2012GL051155