Long-term changes in wintertime persistent heavy rainfall over southern China contributed by the Madden–Julian Oscillation

LIU Yu and HSU Pang-Chi

Key Laboratory of Meteorological Disaster of Ministry of Education/Joint International Research Laboratory of Climate and Environment Change/Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science & Technology, Nanjing, China

ABSTRACT
During the boreal winter, abundant persistent heavy rainfall (PHR) amount and significant rainfall variability at subseasonal timescale are generally observed over the southern sector of East China, where the large-scale circulation and moisture transport are tightly connected with the equatorial Madden-Julian Oscillation (MJO). As the MJO convections occur over the equatorial Indian Ocean (MJO phases 1–4), the low-level moisture convergence is enhanced over southern China (SC, 108°–120°E, 21°–26°N) with the divergence to the north. Thus, a positive anomaly of PHR amount appears in SC but a negative anomaly of PHR amount is seen in the Yangtze River valley (YR, 113°–122°E, 28°–30°N). In contrast, the divergence (convergence) of moisture flux anomalies in the SC (YR) associated with the western equatorial Pacific MJO convections (phases 5–8) limits (benefits) the occurrence of PHR in the SC (YR). The wintertime PHR over southern China is found to undergo a long-term change over the past three decades (1979–2011) with a decreasing (an increasing) trend of PHR amount in the SC (YR). The change in PHR amount occurs consistently with the decadal change in MJO activity. In the earlier decade (1979–1994, E1), the active Indian Ocean (western Pacific) MJO events appeared more frequently while they became less frequent in the recent decade (1995–2011, E2). Accordingly, the Indian Ocean (western Pacific) MJO-related moisture convergence (divergence) anomalies in the SC tend to be weakened (enhanced), contributing to the decrease in PHR amount over the SC in the recent decade.

1. Introduction
Persistent heavy rainfall (PHR) with high intensity and long duration can easily cause flooding and landslides, and is one of the deadliest natural disasters. In China, a high frequency of PHR is observed during the summer monsoon season (April to September) over the southern sector of East China (Tang et al. 2006; Chen and Zhai 2013). Several works have focused on the key processes inducing PHR events over the Yangtze–Huai River basin, revealing that intraseasonal oscillation plays an important role (e.g., Mao and Wu 2006; Yang et al. 2010; Lu et al. 2014; Qi, Zhang, and Li 2016; Sun et al. 2016; Qi et al. 2019). Some researchers have examined the climatological features of summertime PHR, such as the frequency, duration and intensity (e.g., Tang et al. 2006; Chen and Zhai 2013) and their causes (e.g., Chen and Zhai 2013; Hong and Ren 2013; Li and Zhou 2015).

The variation and mechanisms of wintertime PHR in China have received less attention, probably because winter is not the major rainy season in the Asian monsoon region. However, wintertime PHR events accompanied by cold temperatures may result in deadly disasters and huge socioeconomic losses. For example, persistent freezing rain, ice, and snowfall in January 2008 affected large portions of southern and central China and caused around 129 deaths and extensive damage to transportation systems, with an estimated economic loss of at least...
151 billion Chinese Yuan (BBC news, http://news.bbc.co.uk/2/hi/asia-pacific/7231622.stm). Intraseasonal variability over the tropics, the subtropical wave guide, and blocking at high latitudes can all affect the occurrence and maintenance of winter PHR events (Hong and Li 2009; Ding and Li 2017).

Winter precipitation in the southern parts of East China shows significant variability at the subseasonal time scale (Jia et al. 2011; Yao, Lin, and Wu 2015), which is attributable to the activity of the Madden–Julian Oscillation (MJO; Madden and Julian 1971). The MJO is the dominant intraseasonal mode of the tropical atmosphere; it is vigorous and propagates eastwards along the equator during boreal winter (Madden and Julian 1994). During its journey, MJO-related convection in equatorial regions induces anomalous circulation as a Rossby wave response (Gill 1980). MJO-related moisture transport towards off-equatorial areas leads to the variation in the southeastern China rainfall at the intraseasonal time scale (Jia et al. 2011; Yao, Lin, and Wu 2015; Li et al. 2016). Previous works have addressed the MJO’s influences on rainfall in the cold season. How and to what extent the MJO exerts influences on wintertime PHR, however, need to be further elucidated. Whether or not the long-term variation in the MJO affects PHR, and the mechanisms responsible for decadal changes in wintertime PHR in the southern sectors of East China, are also discussed in this study. The results of this study may facilitate risk reduction and decision making at a longer lead time.

2. Data and methods

To better capture the spatial distribution of PHR in China, we used high-resolution (0.25° × 0.25°) observation-based CN05.1 rainfall data produced by the National Climate Center of China (Wu and Gao 2013), instead of spatially unevenly distributed station data. The CN05.1 dataset was based on daily rainfall from over 2400 rain gauges in China. Previous works have documented that the amplitude and variation of CN05.1 rainfall are highly consistent with observations (Wu and Gao 2013) and other high-resolution precipitation datasets (Hsu, Lee, and Ha 2016). Since the strength and variability of wintertime rainfall are different from those in the summer monsoon season, which most studies of PHR have focused on (Tang et al. 2006; Chen and Zhai 2013; Hong and Ren 2013; Li and Zhou 2015), the definition of wintertime PHR is given in the next section along with the features of wintertime precipitation over the southern parts of East China.

The large-scale circulation and moisture fields were obtained from ERA-Interim (Dee et al. 2011). Daily-averaged zonal and meridional winds and specific humidity at 1.5° × 1.5° resolution were used. They included data at 19 pressure levels from 1000 to 100 hPa with an interval of 50 hPa. The common periods of these datasets are January 1979 to December 2012. Winter is defined as the period from December to February (DJF). As an example, the winter spanning from December 1979 to February 1980 would be referred to as the winter of 1979. Therefore, 33 winters (1979–2011) were analyzed in this study.

The phases of the MJO cycle were determined by the Real-time Multivariate MJO (RMM) indices proposed by Wheeler and Hendon (2004). The RMM indices were derived from the empirical orthogonal functions of 850- and 200-hPa zonal winds and OLR anomalies, which can be found on the website of the Australian Bureau of Meteorology (http://cawcr.gov.au/staff/mwheeler/map-room/RMM). Based on the MJO phase composites shown in Figure 8 of Wheeler and Hendon (2004), phase 1 represents the MJO initiation over the western Indian Ocean. The MJO strengthens and propagates eastwards over the central and eastern Indian Ocean in phases 2–4. The enhanced convective anomaly passes through the Maritime Continent and western Pacific warm pool in phases 5–7. As it moves further eastwards over the central Pacific in phase 8, the MJO-related convective activity weakens. Days with large RMM amplitude [((RMM1)2 + (RMM2)2)1/2 > 1] are defined as active MJO days.

3. Results

The climatology and variability of DJF rainfall over China derived from the CN05.1 dataset are shown in Figure 1(a,b). Similar to the summer monsoon rainfall, the winter-mean (DJF-mean) rainfall maximizes over the southern parts of East China (Figure 1(a)), while the amplitude of wintertime rainfall is about one-third of the summer rainfall in this region (Figure 1 of Hsu, Lee, and Ha 2016). The distribution of the standard deviation of DJF rainfall (Figure 1(b)) is similar to that of the mean state (Figure 1(a)), indicating that the wintertime rainfall has significant variability over the southern sector of East China (Jia et al. 2011). To identify the dominant signals of winter rainfall, the fast Fourier transform method is applied to the DJF rainfall time series over Southeast China (18°–35°N, 105°–122°E; box in Figure 1(b)) where large variability can be seen. Spectral analysis (Figure 1(c)) reveals significant peaks of variability at both synoptic (~8–10 days) and intraseasonal (~20 days and 30–60 days) scales. This suggests that synoptic and intraseasonal systems can modulate the occurrence of winter rainfall (Jia et al. 2011; Yao, Lin, and Wu 2015). The subseasonal (10–90 days) variability accounts for more than half of the total variability (Figure 1(b,d)).
Figure 1. (a) Mean and (b) standard deviation of DJF rainfall (units: mm d$^{-1}$) over China during 1979–2011. (c) Power spectra of DJF rainfall over southern parts of East China (18°–35°N, 105°–122°E; green box in (a) and (b)). The red line represents the red-noise spectrum. Units: mm$^2$ d$^{-2}$. (d) As in (b) but for the standard deviation of 10–90-day filtered rainfall. (e) Values of 90th percentile DJF rainfall (units: mm d$^{-1}$) during 1979–2011. (f) Total persistent rainfall amount in DJF in 1979–2011. Units: mm.
Since the mean and variability of rainfall in winter are vigorous in the southern parts of China, in the following we focus on the analysis of PHR variation and associated modulation of wintertime PHR by the MJO over this region.

Considering that the amplitude of rainfall variation in winter is much smaller than that in summer, the fixed thresholds of extreme precipitation (50 and 25 mm d\(^{-1}\)) used in previous studies (Tang et al. 2006; Chen and Zhai 2013; Hong and Ren 2013; Li and Zhou 2015) for summer PHR are not suitable here. Instead, we used a percentile-based value to define the extremes (Hsu, Lee, and Ha 2016). PHR in this study is thus defined when rainfall above the 90th percentile persists for three or more days. The reference rainfall amount for each grid is determined by plotting the distribution of observed frequencies of all rainfall amount values during the winters of 1979–2011 and computing the top 10% of all occurrences. Figure 1(e) shows the distribution of the 90th percentile rainfall threshold in boreal winter, which indicates a 10% (90%) chance that the rainfall amount will fall above (below) this threshold for the given time period. Note that not only the southern China (SC: 21°–26°N, 108°–120°E) area but also the south of the Yangtze River valley (YR: 28°–30°N, 113°–122°E) show abundant PHR amounts (Figure 1(f)). Furthermore, it is important to note that all the results associated with the PHR pattern and its long-term change were highly consistent, regardless of whether the 90th or 95th percentile rainfall value was used as the extreme threshold; nor did the results change when fixed thresholds of 5 mm d\(^{-1}\) and 10 mm d\(^{-1}\) were applied to define the PHR.

The MJO’s influences on wintertime PHR are examined in Figure 2. Because the Indian Ocean MJO and western Pacific MJO generate distinct anomalous circulation patterns over East Asia (Gill 1980; Jia et al. 2011; Li et al. 2016), we first compared the changes in PHR amount in winter during phases 1–4 of the MJO (i.e., Indian Ocean MJO) and phases 5–8 (i.e., western Pacific MJO) relative to the climatological state. We found that the anomalies of wintertime PHR amount in SC (YR) tend to increase (decrease) when the MJO convection is over the Indian Ocean (Figure 2(a)). In contrast, the SC (YR) PHR amount shows negative (positive) anomalies when the MJO convection is located over the western equatorial Pacific (Figure 2(d)). The out-of-phase relationship in PHR amount anomalies between SC and YR during different MJO phases is shown more clearly in the area-averaged results (Figure 2(b,e)).

To understand the key processes contributing to the PHR, we examined the anomalies of low-level (1000–850-hPa integrated) moisture flux convergence during phases 1–4 (Figure 2(c)) and phases 5–8 (Figure 2(f)). The low-level convergent (divergent) anomaly of moisture flux appears consistently over the regions with increased (decreased) PHR in SC when the Indian Ocean (western Pacific) MJO is vigorous. The results indicate that the moisture convergent anomalies in the southern parts of East China associated with the equatorial MJO contribute positively to the occurrence of PHR and thus the PHR amount. The results of PHR modulation by the MJO generally agree with those observed in the summer monsoon season (Hong and Ren 2013; Li and Zhou 2015; Hsu, Lee, and Ha 2016). In both seasons, the major source of moisture for PHR occurrence over the southern sectors of East China is significantly controlled by MJO-induced circulation anomalies.

The PHR amounts in YR and SC have experienced long-term changes over the past three decades (Figure 3). The YR PHR amount shows an increasing trend, which is statistically significant at the 90% confidence level (Figure 3(a)). In contrast, the SC PHR amount shows a decreasing trend during DJF in 1979–2011 (Figure 3(b)). The changes in SC PHR amount at the decadal time scale can also be seen from the differences in PHR amount between the earlier epoch (E1, 1979–1994) and the recent epoch (E2, 1995–2011). The SC PHR amount is reduced in the recent epoch; however, the YR PHR amount displays a larger amount during E1 than during E2 (Figure 4(a)). These decadal changes have no significant relationship with global sea surface temperature (SST) (not shown). Instead of SST anomalies, the atmospheric internal dynamics related to the MJO is found to play a role. The frequency of active MJO events in phases 1–4 (i.e., Indian Ocean MJO convection), which favors SC PHR, decreases during the recent epoch. In contrast, an increased frequency of the western Pacific MJO (phases 5–8) that contributes positively to YR PHR is observed during E2 (Figure 4(b)). The accumulation of less (more) frequent Indian Ocean (western Pacific) MJO convection generates less favorable (more conducive) moistening conditions for PHR in SC (YR) in the recent epoch. These findings suggest that the decadal variability of the MJO may be used as a potential predictor for the long-term (such as decadal time scale) prediction of PHR in the southern parts of East China.

4. Summary
This study examined the influences of the MJO and its long-term changes on PHR over the southern parts of East China in boreal winter, which causes freezing ice/snow disasters but has received relatively less attention in the literature. PHR, with a large rainfall amount...
Figure 2. (a) Anomalies of DJF PHR amount (units: mm 90 d$^{-1}$) during phases 1–4 of MJO relative to the climatological state. Stippling indicates the change in PHR amount is statistically significant at the 0.1 level. (b) Area-averaged wintertime (DJF) PHR amount anomalies (units: mm 90 d$^{-1}$) during MJO phases 1–4 over SC (red bar; 21°–26°N, 108°–120°E) and YR (blue bar; 28°–30°N, 113°–122°E). (c) As in (a) but for the 1000–850-hPa integrated moisture flux in each winter (contours; units: 10$^{-8}$ kg cm$^{-2}$ s$^{-1}$). Shading marks the areas with changes significant at the 0.1 level. (d–f) As in (a–c) but composites of MJO phases 5–8.
exceeding the 90th percentile threshold for more than three days (Hsu, Lee, and Ha 2016), occurs frequently over SC and YR. However, the PHR amounts over the two regions show opposite features in terms of their modulation by the MJO’s phase evolution. During phases 1–4, as the MJO convection is active over the equatorial Indian Ocean, anomalous low-level moisture convergence prevails over the SC and favors abundant (decreased) PHR amounts in SC (YR). In contrast, the MJO convection induces moisture divergent anomalies in SC but anomalous moisture convergence in YR during phases 5–8 of the MJO. The PHR amount decreases in SC but increases in YR.

The long-term variation of MJO activity shows its impact on the decadal changes in wintertime PHR over the southern sectors of East China. The PHR amounts show a decreasing trend over SC but an increasing trend over YR during the past three decades (1979–2011). These PHR changes in SC and YR are closely linked to the decadal variation of the MJO. Compared to the earlier epoch (1979–1994), the Indian Ocean (western Pacific) MJO convection along with anomalous moisture convergence (divergence) in SC occur less (more) frequently in the recent epoch of 1995–2011. This condition leads to reduced SC PHR amounts in the recent epoch. Meanwhile, the YR PHR amount increases because of the positive contribution of enhanced low-level moisture convergence induced by the active MJOs over the western Pacific during the winter seasons of 1995–2011. The relationship between PHR and the MJO at the decadal time scale still exists when extending the rainfall data (1979–2017, based on CPC daily precipitation (Xie et al. 2007)), albeit the trends in PHR over the two areas are less significant.

The findings of this study indicate that wintertime PHR in the southern parts of East China possesses multi-scale features associated with equatorial MJO activity and its decadal variation. It has been found previously that MJO signals provide a source of subseasonal predictability of PHR in Southeast China (Hsu et al. 2015), although the subseasonal prediction of extreme weather events is still a challenging issue for operational centers (Vitart and Robertson 2018). The results of this study further suggest that the MJO is important not only for subseasonal prediction but also may serve as a predictor for the decadal

![Figure 3. Time series of DJF PHR amount anomalies (10³ mm 90 d⁻¹) during 1979–2011 over (a) YR (28°–30°N, 113°–122°E) and (b) SC (21°–26°N, 108°–120°E). The dashed line represents the linear trend in PHR amount, with the trend slope (10³ mm 90 d⁻¹) shown in the upper-right corner. The asterisk indicates that the trend slope is statistically significant at the 0.1 level based on the Mann–Kendall test.](image-url)

![Figure 4. (a) Area-averaged accumulated wintertime (DJF) PHR amount anomalies (units: 10³ mm) during E1 (1979–1994, red bars) and E2 (1995–2011, blue bars) relative to the climatology. (b) As in (a) but for the numbers of active MJO days with RMM amplitude greater than 1 for phases 1–4 (two left bars) and phases 5–8 (two right bars).](image-url)
prediction of wintertime PHR. Understanding in detail the mechanisms responsible for the decadal changes in the MJO and related PHR anomalies is an ongoing avenue of research for our group.

Acknowledgments

The authors would like to thank the anonymous reviewers for their help in improving the manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Key R&D Program of China [grant number 2018YFC1505804].

References

Chen, Y., and P. M. Zhai. 2013. “Persistent Extreme Precipitation Events in China during 1951–2010.” Climate Research 57 (2): 143–155. doi:10.3354/cr01171.

Dee, D. P., S. M. Uppala, A. J. Simmons, P. Berrisford, P. Poli, S. Kobayashi, U. Andrae, et al. 2011. “The ERA-Interim Reanalysis: Configuration and Performance of the Data Assimilation System.” Quarterly Journal of the Royal Meteorological Society 137 (656): 553–597. doi:10.1002/qj.828.

Ding, F., and C. Li. 2017. “Subtropical Westerly Jet Waveguide and Winter Persistent Heavy Rainfall in South China.” Journal of Geophysical Research: Atmospheres 122 (14): 7385–7400. doi:10.1002/2017JD026530.

Gill, A. E. 1980. “Some Simple Solutions for Heat-induced Tropical Circulation.” Quarterly Journal of the Royal Meteorological Society 106 (449): 447–462. doi:10.1002/qj.49710644905.

Hong, -C.-C., and T. Li. 2009. “The Extreme Cold Anomaly over Southeast Asia in February 2008: Roles of ISO and ENSO.” Journal of Climate 22 (13): 3786–3801. doi:10.1175/2009JCLI2864.1.

Hong, W., and X. Ren. 2013. “Persistent Heavy Rainfall over South China during May–August: Subseasonal Anomalies of Circulation and Sea Surface Temperature.” Acta Meteorologica Sinica 27 (6): 769–787. doi:10.13351/st13351-013-0607-8.

Hsu, P.-C., J.-Y. Lee, and K.-J. Ha. 2016. “Influence of Boreal Summer Intraseasonal Oscillation on Rainfall Extremes in Southern China.” International Journal of Climatology 36 (3): 1403–1412. doi:10.1002/joc.4433.

Hsu, P.-C., T. Li, L. You, J. Gao, and H.-L. Ren. 2015. “A Spatial-temporal Projection Model for 10–30 Day Rainfall Forecast in South China.” Climate Dynamics 44 (5–6): 1227–1244. doi:10.1007/s00382-014-2215-4.

Jia, X., L. Chen, F. Ren, and C. Li. 2011. “Impacts of the MJO on Winter Rainfall and Circulation in China.” Advances in Atmospheric Sciences 28 (3): 521–533. doi:10.1007/s00376-010-9118-z.

Li, R. C. Y., and W. Zhou. 2015. “Multiscale Control of Summertime Persistent Heavy Precipitation Events over South China in Association with Synoptic, Intraseasonal, and Low-frequency Background.” Climate Dynamics 45 (3–4): 1043–1057. doi:10.1007/s00382-014-2347-6.

Li, W., P.-C. Hsu, J. He, Z. Zhu, and W. Zhang. 2016. “Extended-range Forecast of Spring Rainfall in Southern China Based on the Madden–Julian Oscillation.” Meteorology and Atmospheric Physics 128 (3): 331–345. doi:10.1007/s00703-015-0418-9.

Lu, R., H. Dong, Q. Su, and H. Ding. 2014. “The 30–60-day Intraseasonal Oscillations over the Subtropical Western North Pacific during the Summer of 1998.” Advances in Atmospheric Sciences 31 (1): 1–7. doi:10.1007/s00376-013-3019-x.

Madden, R. A., and P. R. Julian. 1971. “Detection of a 40–50 Day Oscillation in the Zonal Wind in the Tropical Pacific.” Journal of the Atmospheric Sciences 28 (5): 702–708. doi:10.1175/1520-0469(1971)028<0702:DO5O>2.0.CO;2.

Madden, R. A., and P. R. Julian. 1994. “Observations of the 40–50-day Tropical oscillation-A Review.” Monthly Weather Review 122 (5): 814–837. doi:10.1175/1520-0493(1994)122<0814:OTODAT>2.0.CO;2.

Mao, J., and G. Wu. 2006. “Intraseasonal Variations of the Yangtze Rainfall and Its Related Atmospheric Circulation Features during the 1991 Summer.” Climate Dynamics 27 (7–8): 815–830. doi:10.1007/s00382-006-0164-2.

Qi, Y., T. Li., R. Zhang, and Y. Chen. 2019. “Interannual Relationship between Intensity of Rainfall Intraseasonal Oscillation and Summer-mean Rainfall over Yangtze River Basin in Eastern China.” Climate Dynamics. Advance online publication. doi:10.1007/s00382-019-04680-w.

Qi, Y., R. Zhang, and T. Li. 2016. “Structure and Evolution Characteristics of Atmospheric Intraseasonal Oscillation and Its Impact on the Summer Rainfall over the Yangtze River Basin in 1998.” Chinese Journal of Atmospheric Sciences (in Chinese) 40 (3): 451–462. doi:10.3878/jissn.1006-9895.1507.15107.

Sun, X., G. Jiang, X. Ren, and X.-Q. Yang. 2016. “Role of Intraseasonal Oscillation in the Persistent Extreme Precipitation over the Yangtze River Basin during June 1998.” Journal of Geophysical Research: Atmospheres 121 (18): 10453–10469. doi:10.1002/2016JD025077.

Tang, Y. B., J. J. Gan, L. Zhao, and K. Gao. 2006. “On the Climatology of Persistent Heavy Rainfall Events in China.” Advances in Atmospheric Sciences 23 (5): 678–692. doi:10.1007/s00376-006-0678-x.

Vitart, F., and A. W. Robertson. 2018. “The Sub-Seasonal to Seasonal Prediction Project (S2S) and the Prediction of Extreme Events.” NPJ Climate and Atmospheric Science 1 (1): 3. doi:10.1038/s41612-018-0013-0.

Wheeler, M. C., and H. H. Hendon. 2004. “An All-season Real-time Multivariate MJO Index: Development of an Index for Monitoring and Prediction.” Monthly Weather Review 132 (8): 1917–1932. doi:10.1175/1520-0493%282004%29132<1917%3AAAMMI>2.0.CO%3B2.

Wu, J., and X. J. Gao. 2013. “A Gridded Daily Observation Dataset over China Region and Comparison with the Other Datasets.” Chinese Journal of Geophysics (in Chinese) 56 (4): 1102–1111. doi:10.6038/cjg20130406.

Xie, P., A. Yataegai, M. Chen, T. Hayasaka, Y. Fukushima, C. Liu, and S. Yang. 2007. “A Gauge-based Analysis of Daily
Precipitation over East Asia.” *Journal of Hydrometeorology* 8 (3): 607–626. doi:10.1175/JHMS83.1.

Yang, J., B. Wang, B. Wang, and Q. Bao. 2010. “Biweekly and 21–30-day Variations of the Subtropical Summer Monsoon Rainfall over the Lower Reach of the Yangtze River Basin.”

Journal of Climate 23 (5): 1146–1159. doi:10.1175/2009JCLI3005.1.

Yao, Y., H. Lin, and Q. Wu. 2015. “Subseasonal Variability of Precipitation in China during Boreal Winter.” *Journal of Climate* 28 (16): 6548–6559. doi:10.1175/JCLI-D-15-0033.1.