Influence of boreal summer intraseasonal oscillation on rainfall extremes in southern China

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ABSTRACT: How boreal summer intraseasonal oscillation (BSISO) modulates the probability and spatial distributions of extreme rainfall occurrence over populous southern China was examined, using the newly proposed BSISO indices and two high-resolution rain-gauge-based rainfall datasets in China. The probability density function of May–August rainfall in southern China is skewed towards large values in phases 2–4 of the first component and in phases 5–7 of the second component of BSISO life cycle, during which the probability of extreme rainfall events at the 75th (90th) percentile increases by 30–50% (over 60%) relative to the non-BSISO period. The devastating floods with prolonged extreme rainfall in southern China over the three past decades occurred coincidently with these BSISO phases. The first component of BSISO, associated with 30–60-day eastward/northeastward-propagating ISO, is more favourable for the rainfall extreme over in-land China. In contrast, the second component of BSISO, related to the 10–30-day northwestward propagating ISO, tends to link with the rainfall extreme along the southeast coast of South China. Moisture budget indicates that the favourable environment for rainfall extreme is associated with southwesterly moisture convergence over southern China, while the moisture advection contributes insignificantly. This study suggests a potential for monitoring and probabilistic prediction of extreme rainfall events in southern China based on the real-time BSISO indices.

KEY WORDS Asian summer monsoon; extreme rainfall; flood; intraseasonal oscillation; southern China

Received 5 March 2015; Revised 24 May 2015; Accepted 26 May 2015

1. Introduction

Extreme rainfall events can lead to flood, landslide and mud flow with the potential to cause catastrophic losses of property, agriculture and human lives. In China, the 1998 Yangtze River flooding associated with heavy and prolonged rainfall events resulted in over 3000 death and $45 billion in economic loss (Huang et al., 1998). In June 2000, southern China experienced persistent heavy rainfall with losses exceeding $2 billion in Fujian Province (with its capital city at 26°N, 118°E) (Gao et al., 2013). Due to high vulnerability of populous regions to rainfall extremes, quantifying the distribution of extreme occurrence at the seasonal timescale and understanding the physical processes inducing prolonged heavy rainfall are crucial for establishing an extended-range (2–4 weeks) flood forecast system (Webster et al., 2010).

Previous flooding case studies found that the unusually persistent episodes of wet condition in southern China were related to convective phases of boreal summer intraseasonal oscillation (BSISO) (Yang and Li, 2003; Zhu et al., 2003; Mao and Wu, 2006; Gao et al., 2013; Liu et al., 2014; Li et al., 2015). The BSISO has been identified as the dominant source of short-term climate variability and extremes in Asia (e.g. Webster et al., 1998; Annamalai and Slingo, 2001; Lee et al., 2013; Moon et al., 2013). Compared to the equatorially-trapped eastward propagating Madden-Julian Oscillation (MJO; Madden and Julian, 1971), the BSISO is more complex in nature with prominent northward/northwestward propagations over the Indian monsoon region (e.g. Yasunari, 1980; Jiang et al., 2004; Annamalai and Sperber, 2005; Waliser, 2006) and with northward/northwestward propagations over the western North Pacific–East Asia region (e.g. Murakami, 1984; Hsu and Weng, 2001; Tsou et al., 2005; Yun et al., 2009; Chu et al., 2012). As the BSISO moves away from the equator into the Asian monsoon region, its convection and circulation anomalies may influence local rainfall variation by altering background conditions for weather systems (Hung and Hsu, 2008; Goswami, 2012; Li, 2014; Liu et al., 2014; Oh and Ha, 2015). The impacts of eastward-propagating MJO on rainfall variability in China and other regions have been noted (Jones et al., 2004; Donald et al., 2006; Zhang et al., 2009; Jia et al., 2011), while less attention was given to climatological relationship between BSISO and rainfall (especially in...
In this study, we examine the influences of lower- and higher-frequency BSISO modes on probability of extreme rainfall events in southern China during the summer monsoon season (May–August) based on newly proposed BSISO indices (Lee et al., 2013) and high-resolution gridded rainfall datasets. This work is a basic but crucial step towards forecasting the likelihood of persistent heavy rainfall in southern China at the extended range (Jones et al., 2004; Xavier et al., 2014).

2. Data and methodology

To better capture spatial distribution of rainfall variability, we use daily high-resolution (0.25° × 0.25°) gridded rainfall instead of spatially uneven station data. Considering data uncertainty, two datasets were used.

Figure 1. (a) Mean and (b) standard deviation of May–August rainfall in China during 1981–2007 derived from the CN05.1 dataset. Units: mm day⁻¹. (c) Power spectra of May–August rainfall over southern China (18°–32.5°N, 105°–122°E, box in the upper panels). Dashed line represents the red-noise spectrum. The annual cycle is removed before the spectrum analysis. (d)–(f) Same as (a)–(c), except for the results derived from the APHRODITE-MA dataset.
One is the newly released CN05.1 dataset (Wu and Gao, 2013) from the National Climate Center in China. This dataset was derived from over 2400 daily station reports in China. Another is the state-of-the-art East Asia rainfall product from the Asian Precipitation-Highly Resolved Observational Data Integration towards Evaluation of the Water Resources (APHRODITE-MA), which was created primarily with the data obtained from a rain-gauge-observation network (Yatagai et al., 2012). The domain of the APHRODITE-MA product used in this study covers only China for comparison with the results of CN05.1. To analyse the linkage between BSISO and flooding events, the records of large and prolonged (>7 days) floods over southern China in 1982–2013 were collected from the Dartmouth Flood Observatory (Brakenridge, 2014). The European Centre for Medium-Range Weather Forecasts ERA-Interim (Dee et al., 2011) reanalysis at 1.5°×1.5° spatial resolution is used for calculating moisture budget. Daily-averaged zonal and meridional winds (u and v) and specific humidity (q) at 10 pressure levels (1000, 925, 850, 700, 600, 500, 400, 300, 200, and 100 hPa) are utilized.

The BSISO indices of Lee et al. (2013) were derived from the first four combined empirical orthogonal functions (EOFs) of outgoing longwave radiation (OLR) and 850-hPa zonal wind anomalies over the Asian summer monsoon region (10°S to 40°N, 40°–160°E). The first component of BSISO (BSISO1) defined by the first and second EOF modes explicitly represents the different phases of canonical northward/northeastward propagating feature with the period of about 30–60 days. The second component (BSISO2) defined by the third and fourth EOF modes captures the northward/northwestward propagating variability with the period of 10–30 days. Hopefully, the BSISO indices extracted without band-pass filtering may serve as effective indices for real-time prediction similar to the real-time multivariate MJO (RMM) index (Wheeler and Hendon, 2004). Lee et al. (2013) demonstrated that the two BSISO indices are capable of describing a large fraction of the total intraseasonal variability in Asia and better represents the northward propagation than the RMM index. The observed and forecasted daily BSISO indices are available online at http://www.apcc21.org/eng/service/bsiso/moni/japcc030602.jsp.

The common period for all the datasets (except for the Dartmouth flood records) mentioned above covers the period from 1981 to 2007. Thus, statistical analyses of BSISOs and rainfall extremes and moisture diagnosis are performed for the summer monsoon season (May to August) during 1981–2007 in this study.

3. Results

3.1. Summer rainfall variability in China

Climatology and variability of summer monsoon rainfall over China based on the CN05.1 and APHRODITE high-resolution rainfall datasets are compared in Figure 1. Overall, the features of rainfall distribution and variability in the two datasets are similar. However, the magnitude of summer rainfall variation in southern China in the CN05.1 (left panel) is slightly bigger than that in the APHRODITE (right panel). Summer-mean precipitation shows consistently a prominent southeast-northwest contrast in the two datasets (Zhang et al., 2009; Wu and Kao, 2013). Daily-averaged rainfall is greater than 4 mm day$^{-1}$ in southern China and about 1–3 mm day$^{-1}$ over most of northern and western China (Figure 1(a) and (d)). The standard deviations of summer monsoon rainfall in the two
Figure 3. Percentage changes (%) in probability of extreme events at 75th percentile for each of the eight phases of BSISO1 (upper two rows) and BSISO2 (bottom two rows) with respect to the non-BSISO state. The probability of 75th extreme occurrence in a given BSISO phase \((P)\) is calculated as the number of days when the rainfall exceeding 75th percentile divided by total number of days. Percentage change is computed as \([\frac{P_{\text{BSISO}} - P_{\text{non-BSISO}}}{P_{\text{non-BSISO}}} \times 100]\), where the \(P_{\text{non-BSISO}}\) represents the probability of 75th extreme occurrence in the non-BSISO period. Changes exceeding the 95% confidence level are dotted.

datasets are also similar, revealing greater amplitudes over southeastern China than northwestern China (Figure 1(b) and (e)). This indicates that summer monsoon rainfall variability is comparatively vigorous over southern China. To identify dominant periodicity, the fast Fourier transform (FFT) is applied to the rainfall time series averaged over southern China (18°–32.5°N, 105°–122°E). The spectral analysis shows that the monsoon rainfall has significant peaks at intraseasonal (10–60 days) and synoptic (<10 days) scales (Figure 1(c) and (f)). The two peaks are significantly larger than the red-noise spectral level, suggesting that the major rainfall events in southern China during the boreal summer are closely associated with not only the synoptic-scale disturbances but also the BSISO activity at the 10–60 day time scale (Mao et al., 2010; Yang et al., 2010; Hsu et al., 2015). Although the two datasets show highly consistent results, to reduce the uncertainty arising from these datasets, only the results based on a simple average of the CN05.1 and APHRODITE with equal weight are shown in the following analyses.

3.2. Modulations of BSISO on rainfall extremes

To elucidate the influences of BSISO on rainfall in southern China, the changes in probability density functions (PDFs) of rainfall amount during different BSISO1 and BSISO2 phases with respect to the non-BSISO period...
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Percentage changes of 90th ENS rain probability in BSISO1 phases

Figure 4. Same as Figure 3 but for the percentage changes (%) in probability of extreme events at 90th percentile.

Percentage changes of 90th ENS rain probability in BSISO2 phases

To define the occurrence of rainfall extremes, a percentile-based threshold is adopted since it describes rare events in the tails of the statistical distributions (Zhang et al., 2011). Increasing the percentile threshold can identify dramatic extremes, but lead to smaller samples to obtain robust results. Here we use two thresholds to define the extreme events for testing the robustness of results, similar to the approach in Xavier et al. (2014). An extreme event is defined by daily rainfall amount in a given grid greater than its 75th (90th) percentile of all rain days in 1981–2007 summer monsoon seasons, referred to as 75th (90th) extremes.

Figure 3 illustrates regional changes in the frequency of extreme occurrence. During phases 2–4 of the BSISO1, the probability of 75th extremes grows mostly over the Yangtze River Valley (top row). There is about 30–50% increase in probability of extreme occurrences during

when the normalized BSISO amplitude is smaller than 1) are examined (Figure 2). PDFs are presented as box plots with values for the 5th (lower bound), 25th (lower quartile), median, 75th (upper quartile) and 95th (upper bound) percentiles. The BSISO1, the canonical northward propagating component mainly with the 30–60 day periodicity, is first investigated. It is found that during phases 2–4 of the BSISO1 the median and 75th percentile of rainfall skew towards high values (i.e. wet conditions) compared to the non-BSISO state. Figure 9 of Lee et al. (2013) showed that phases 3–4 are favourable for convective activity with strong southwesterly wind anomalies over southern China. Conversely, median, 75th and 95th percentiles of rainfall all decrease (i.e. dry conditions) during phases 6 and 7 of the BSISO1 (Figure 2(a)). Similar relationships between PDF shifts and BSISO1 life cycles are also identified based on CN05.1 and APHRODITE rainfall (not shown).
phases 2–4 of the BSISO1 compared to the non-BSISO period. During phases 6–7, on the contrary, the frequency of extreme occurrence decreases by about 20–40% over southern China (second row in Figure 3). There is a much bigger change in the probability of 90th extremes. As shown in Figure 4, the probability of 90th extremes increases (reduces) by over 60% (45%) in the Yangtze River (southeastern China) during phases 2–4 (phases 6–7) of the BSISO1. The results based on the ensemble rainfall here are highly consistent with those derived from individual datasets (not shown), suggesting that the modulation of the BSISO1 (30–60 day mode) on the rainfall extremes in southern China is robust.

In addition to the BSISO1 modulation, the 10–30 day BSISO signal (of BSISO2), which is more active during the pre-monsoon and monsoon onset periods, also affects significantly the PDFs of rainfall in southern China (Figure 2(b)). During phases 5–7 of the BSISO2, the PDFs are skewed positively with larger values for all 5th, 25th, median, 75th and 95th rainfall percentiles compared to non-BSISO and other phases. The regional increases in 75th (90th) extremes have a northwestward progression from southeastern coast towards the Yangtze River during phases 4–7 [the third and fourth rows in Figure 3 (Figure 4)], reflecting the characteristics of 10–30 day northwestward propagating BSISO mode with a southwest-to-northeast tilt (Yang et al., 2010; Lee et al., 2013). Opposite features are seen during phases 8, 1 and 2 for reductions of 75th (90th) extremes. Compared to the BSISO1, both extremely wet and dry events occur more often along the southeast coast in association with the BSISO2.

We further assess the BSISO relationship with historical floods recorded in the recent decades. As introduced
in the first section, 1998 Yangtze River flood (2000 Fujian flood) was the most devastating flooding events occurred in the Yangtze River Valley (southeastern China) over the past half-century. Their occurrences corresponding to BSISO1 and BSISO2 phases, respectively, in Figure 5 confirm the statistic results in Figures 2–4. According to Figures 3 and 4, the wet events in the Yangtze River Valley are favoured during phases 2–4 of BSISO1. Coincidently, the catastrophic flooding in the middle and lower reaches of the Yangtze River appeared in phases 3 and 4 of BSISO1 life cycle in 1998 (Figure 5(a)). The flood occurred in southeastern China with maximum rainfall during 15–19 June 2000 was associated with phases 6–7 of the BSISO2 (Figure 5(b)), consistent with the results shown in Figures 2–4. Due to the longer periodicity of the BSISO1 than that of the BSISO2, the 1998 wet event in the Yangtze River Valley lasted longer than that in 2000 Fujian. Along with the two flooding cases, the climatological (1982–2013) relationship between BSISO life cycle and occurrence of observed floods is given in
Figure 6. It shows that majority of the prolonged flood events (90%) over southern China occurred in phases 2–5 of the BSISO1; only ~10% of flooding cases appeared during phases 6, 7, 8, and 1 of BSISO1 (Figure 6(a)). The modulation of BSISO2 on the occurrence of floods is also robustly identified. Around 70% of large flood events in history occur in phases 4–7 of the BSISO2 life cycle with a peak in phase 6 (Figure 6(b)).

3.3. Moisture diagnosis for occurrences of rainfall extremes

To understand the moisture processes resulting in the extreme occurrences (O’Gorman and Schneider, 2009), column-integrated moisture convergence ($-q \nabla \cdot V$) and advection ($-V \cdot \nabla q$) during the BSISO phases with high probability of rainfall extremes are examined. It is found that moisture convergence plays a key role in providing a favourable environment for the occurrence of extreme events during phases 2–4 of the BSISO1 (Figure 7(a)–(c)). During these phases, the cyclonic anomalies move northeastward from the equator towards the South China Sea. Meanwhile, the anticyclonic anomaly over the western Pacific also propagates northeastward and intensifies (Figure 7(a)–(c)). The southeasterly anomaly between the cyclonic and anticyclonic circulation induces moisture transport from the Philippine Sea and South
China Sea into southern China, providing favourable conditions for enhanced rainfall over southern China. In contrast, the moisture advection contributes marginally and negatively to rain extremes over southern China and the Yangtze River Valley (Figure 7(d)–(f)).

The 10–30-day BSISO variability (BSISO2) also exerts significant influence on monsoon rainfall in southern China via modulating the atmospheric moisture convergence instead of moisture advection (Figure 8). The moisture convergence over southern China during phases 5–7 of the BSISO2 life cycle is induced by southwesterly-northeasterly convergence associated with the anticyclonic anomaly over the Philippine Sea and the cyclonic anomaly near Japan. As the anomalous anticyclone moves northwestward from the Philippine Sea towards the east of Taiwan, a northwestward progression of moisture convergence (Figure 8(a)–(c)) and regions with increased extreme rainfall events appear accordingly (Figures 3 and 4). Due to the differences in spatial structure and the associated moisture processes between the two BSISO components, the BSISO1 is more favourable for the rainfall extreme over in-land southern China, while the BSISO2 tends to link with the rainfall extreme along the southeast coast of South China.

4. Conclusion

Different from the previous flooding case studies, this study quantitatively examined the statistic relationship of two BSISO modes with the probability and spatial distributions of monsoon rainfall extremes in southern China and the moisture processes related to these modes. The BSISO indices proposed recently by Lee et al. (2013) were employed to describe the life cycles of 30–60 day and 10–30 day modes, and two high-resolution (0.25° × 0.25°) rain-gauge-based rainfall datasets (CN05.1 and APHRODITE) were used to show the robustness of extreme rainfall features.

The spectral analysis of summer monsoon rainfall during 1981–2007 show pronounced subseasonal variability with a period of 10–60 days. Both the BSISO1 (30–60 day) and BSISO2 (10–30 day) modes influence significantly the occurrence of extreme rainfall events, in agreement with the case studies that identified the active role of BSISOs in floods of the Yangtze River Valley and southern China (Yang and Li, 2003; Mao and Wu, 2006; Li et al., 2015). During phases 2–4 of the BSISO1 and phases 5–7 of the BSISO2, when the anomalous southwesterly moisture convergence is observed over southern China, the probability of extreme rainfall events at the 75th (90th) percentile increases by 30–50% (over 60%) relative to the non-BSISO period. The historical prolonged (>7 days) floods occurred coincidently with these BSISO phases when the probability of rainfall extremes increase. Statically, about 90% (70%) of flood events in southern China occur in phases 2–5 (4–7) of the BSISO1 (BSISO2) life cycle. On the contrary, decreased frequency of rainfall extremes and floods appears during phases 6–7 (8, 1–2) of the BSISO1 (BSISO2).

Preferred locations of wet extreme occurrence modulated by the two BSISO modes are slightly different. Pronounced increases in extreme events appear in the Yangtze River Valley in phases 2–4 of the BSISO1, while the positive anomalies of rainfall extremes display a northwestward progression from the southeastern coast towards the Yangtze River during phases 5–7 of BSISO2 life cycle. The column-integrated moisture budget suggests that enhanced moisture convergence, rather than moisture advection process, plays a key role in the occurrence of rainfall extremes.

The statistical relationship between BSISO life cycle and probabilistic changes in rainfall extremes has the potential for monitoring and probabilistically forecasting extreme rainfall events in southern China using the real-time BSISO indices. Although the current study focuses on the rainfall extremes over southern China, the findings could apply to the wide Asian monsoon regions where the BSISO is vigorous during summer season. Recently, real-time forecast of the BSISO indices at the APEC Climate Center (APCC, http://www.apcc21.org/eng/service/bsiso) indicated that several operational coupled models show useful skills (correlation coefficient greater 0.5) for the indices beyond 20 days. Further demonstration of this skill is our ongoing research.

The current study focused on the modulation of BSISOs on extreme rainfall events over the whole Asian summer monsoon season (May to August). The East Asian monsoon rainbelt undergoes a significant northward migration during the summer monsoon season (e.g. Wang and Lin, 2002). Recent studies also found that the BSISO-related signals reveal different features in early and late summer seasons when the background circulation varies (Yang et al., 2014). Whether or not the two BSISO modes exert different influences on rainfall extremes over southern China during different monsoon stages is worth further examination. This is also part of our future research.

Acknowledgements

We thank the anonymous reviewers for their constructive comments. This work is supported by the China National 973 Project (2015CB453200), the Natural Science Foundation of Jiangsu Province, China (BK20140046), the Specially-Appointed Professor by universities in Jiangsu Province, and the Jiangsu Shuang-Chuang Team Award. Lee and Ha were supported by the GRL grant of the National Research Foundation (NRF) funded by the Korean Government (NRF-2011-0021927). This is the ESMC contribution number 053.

References


Brakenridge GR. 2014. Global Active Archive of Large Flood Events. Dartmouth Flood Observatory, University of Colorado.