

# Boreal Summer Intraseasonal Oscillation Impact on Western North Pacific Typhoons and Rainfall in Taiwan

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## ABSTRACT

This study discusses the boreal summer intraseasonal oscillation (BSISO) impact on the western North Pacific (WNP) typhoons and the summer rainfall in Taiwan. The real time BSISO1 and BSISO2 indices are created using the first two and the third and fourth principal components of the multivariate empirical orthogonal function analysis, based on outgoing long-wave radiation and zonal wind at 850 hPa from Lee et al. (2013). The results show that heavy rainfall in Taiwan and the associated WNP typhoon frequency patterns are closely related to the 10 - 30 days BSISO2 phases during the typhoon season (July - October). Taiwan has larger rainfall during BSISO2 phases 3, 4, and 5 when the major BSISO2 convection moves northwestward from the Philippine Sea to the Taiwan area. During phases 3 and 4 the anomalous low-level cyclonic flow and the increased typhoon frequency directly result in larger rainfall in Taiwan. Phase 5 exhibits enhanced low-level southwesterly flow which transports the moisture to Taiwan responsible for more summer rainfall on the island.

Key words: Boreal summer intraseasonal oscillation, Madden-Julian Oscillation, Typhoon, Taiwan

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## 1. INTRODUCTION

The Madden-Julian Oscillation (MJO; Madden and Julian 1971, 1972, 1994) is an eastward moving intraseasonal phenomenon that has broad impacts on weather and climate including precipitation, surface temperature, tropical cyclones, and monsoons (Jones et al. 2004; Zhang 2005; Donald et al. 2006). The typical MJO deep convection usually propagates eastward along the equator during the boreal winter. In contrast, the intraseasonal signal moves away from the equator in the Northern Hemisphere during the boreal summer and has northward/northwestward propagating variability with the intraseasonal time scale period to the Asian summer monsoon region (Yasunari 1979, 1980, 1981). This northward/northwestward propagating mode is usually named the intraseasonal oscillation (ISO) or, more specifically, boreal summer intraseasonal oscillation (BSISO) which has interactions with synoptic-scale disturbances (Murakami et al. 1986; Hsu and Li 2011; Hsu et al.

2011) and typhoon activities (Kim et al. 2008; Li and Zhou 2013; Chen and Chou 2014) over the western North Pacific (WNP). Therefore, the ISO has broad impacts on the Asian monsoon region and influences the local rainfall anomaly which could cause floods and droughts over South China and Taiwan (Yang and Li 2003; Hung and Hsu 2008; Mao et al. 2010; Hsu et al. 2015).

The interactions between the ISO, first transition of the Asian summer monsoon and the onset of Taiwan Meiyu in May and June were discussed in Hung and Hsu (2008). The MJO impact on Taiwan rainfall in the winter-half season was also investigated in Hung et al. (2014). In contrast, not many studies focused on the local ISO impact on the summer typhoon season in Taiwan. As shown in Fig. 1 (more detail about the data is described in the next section), Taiwan is located on the major typhoon tracks over the WNP. The main typhoon season in this area is July - October (JASO). In addition, typhoons contribute a large portion of the annual rainfall in Taiwan (Fig. 1b), causing floods that can frequently result in severe damage. On average, about 43.2%

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of the JASO rainfall in Taiwan is related to typhoons (Hung and Hsu 2010). Typhoons are considered the largest weather-related disaster in Taiwan (e.g., Wu and Kuo 1999).

Chen and Shih (2012) and Chen et al. (2013) studied the interaction between the ISO and some specific types of typhoon cases affecting Taiwan. There is still a gap in understanding the ISO influence on WNP typhoons and the summer rainfall in Taiwan. The MJO index derived by Wheeler and Hendon (2004) can represent the boreal winter eastward moving intraseasonal signal well, but cannot fully depict the northward/northwestward propagating intraseasonal mode during the boreal summer. This study therefore uses the BSISO index provided by Lee et al. (2013). The closely related BSISO, WNP typhoon activities, and the summer rainfall in Taiwan are discussed. The rest of this study is organized as follows. The data used in this work are provided in section 2. Comparisons of MJO/BSISO indices and Taiwan rainfall are discussed in section 3. The connection between the BSISO2 and the WNP typhoons is presented in section 4. The BSISO2 impacts on the summer rainfall in Taiwan are discussed in section 5. The BSISO, WNP typhoon activity, and heavy rainfall cases in Taiwan in JASO are presented in section 6. Conclusions are presented in section 7.

## 2. DATA

Several 1981 - 2010 global gridded variables including 850 hPa horizontal velocity and specific humidity in the WNP typhoon season (July - October) are obtained from the 40-year European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) and the ERA-Interim analysis (Uppala et al. 2005; Dee et al. 2011). The daily outgoing long-wave radiation (OLR) measurements (Liebmann and Smith 1996) since 1974 are also used. As already shown in Fig. 1, the historical typhoon tracks during 1981 - 2010 provided by the JTWC (Joint Typhoon Warning Center) are collected to calculate the typhoon frequency on the  $5^\circ \times 5^\circ$  grid box. In addition, the daily rainfall data from Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Climate Data Record (PERSIANN) were obtained from Tropical Rainfall Measuring Mission (TRMM) Multi-Satellite Precipitation Analysis (TMPA) product (Ashouri et al. 2015). It provides  $0.25^\circ$  grid data for the latitudes within  $60^\circ\text{S} - 60^\circ\text{N}$  from January 1983 to December 2012. Finally, in order to analyze the summer rainfall in Taiwan associated with the BSISO, the Taiwan Rainfall Index (hereafter TRI) since 1900, the

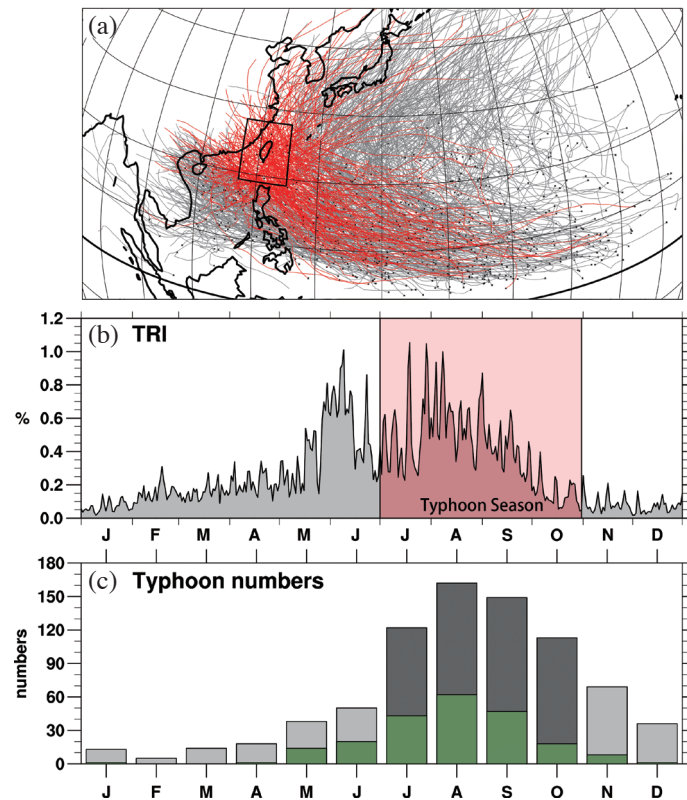


Fig. 1. (a) JTWC typhoon tracks over the WNP for 1981 - 2010. The gray lines represent the typhoon tracks and the red lines indicate the tracks for typhoons which move through the Taiwan area ( $19 - 28^\circ\text{N}$ ,  $117 - 125^\circ\text{E}$ , shown as the box). (b) The mean annual cycle of rainfall in Taiwan represented by the TRI for 1981 - 2010. The red shading shows the typhoon season (July - October) in Taiwan. (c) The monthly counts for the typhoon numbers over the WNP in 1981 - 2010. The green bars show the typhoon numbers in the Taiwan area, and the dark gray bars indicate the typhoon season of the WNP. (Color online only)

longest rainfall index in the Taiwan meteorological history, was obtained (Hung 2012). The TRI is based on the richest data from observational stations in Taiwan (1176 stations are used). The daily TRI are the mean for the rainfall averages of each station divided by its own annual sum climatology. Therefore, the daily TRI sum for any specific year is near 1 (i.e., 100%), and the TRI value in any time step means its proportion to the yearly climatology mean. Although the TRI can well represent the rainfall variations in Taiwan, the traditional rainfall observation data from the conventional weather stations operated by the Central Weather Bureau (CWB) in Taiwan are also used for comparison. Fifteen stations with elevation less than 100 m are selected. They are Tamsui (46690), Taipei (46692), Keelung (46694), Hualien (46699), Ilan (46708), Tainan (46741), Kaohsiung (46744), Chiayi (46748), Taichung (46749), Dawu (46754), Hsinchu (46757), Hengchun (46759), Chengkung (46761), Taitung (46766), and Wuqi (46777).

Three ISO indices are acquired to catch the BSISO signal and compared in this study. The widely used ISO index is the daily real-time multivariate MJO (RMM) index from Wheeler and Hendon (2004). In their definition, the full MJO cycle is divided into 8 phases using a combined empirical orthogonal function (EOF) analysis of OLR and upper/lower level zonal wind. The first two principle components (PCs) from the EOF analysis are used to derive the RMM index (hereafter, the MJO index). Although this index can represent the boreal winter MJO well, the northward/northwestward propagating variability with the period of intraseasonal time scale during the boreal summer in the Asian summer monsoon region is not fully captured. Therefore, Lee et al. (2013) created two real-time indices: BSISO1 and BSISO2 based on a similar method, but focused on the 10°S - 40°N, 40 - 160°E area, for May - October in 1981 - 2010 to detect the BSISO variability. The BSISO1 and BSISO2 indices are defined by a combination of the first two PCs and the third and fourth PCs from the EOF analysis, respectively. A similar 8-phase life cycle is then defined for the BSISO1 and BSISO2. According to Lee et al. (2013), the BSISO1 has a canonical northward propagating feature with a period of about 30 - 60 days, while the BSISO2 has northward/northwestward propagating variability with a period of 10 - 30 days.

### 3. COMPARISONS OF MJO/BSISO INDICES WITH TAIWAN RAINFALL

In the present study, all three indices (MJO, BSISO1, and BSISO2) are used to verify the possible connection with the summer rainfall in Taiwan. The JASO Taiwan rainfall represented by the TRI for each MJO, BSISO1, and BSISO2 phase are shown in Figs. 2a, b, and c, respectively. The accumulated JASO values of TRI represent the annual total amount for each phase (unit: %) in the boreal summer. Therefore, the sum of TRI values for all 8 phases can be

considered as the mean annual proportion for the JASO season. As seen in Figs. 2a and b, the rainfall in Taiwan is not well correlated with the MJO and BSISO1 phases. For the MJO modes, large rainfall in Taiwan appears in phases 1 - 2 and 5 - 8. For the BSISO1 modes, large rainfall in Taiwan can be seen in phases 1, 2, 5, 7, and 8. No distinct peak phases are associated with the distribution of these modes. In contrast, the BSISO2 index exhibits large rainfall in phases 3 - 5 (shown in dark shading bars) and a clear rainfall maximum in phase 4 in Fig. 2c. Similar analysis for the typhoon frequency and the rainfall during typhoon-influenced days for each phase are shown in Figs. 2d - i, but this will be discussed in the next section.

In order to verify the accuracy of the Taiwan rainfall variation represented by the TRI data, the conventional weather station data from 15 CWB stations are averaged to compare with the results shown by the TRI in Figs. 3a and b. The typhoon-related rainfall in Taiwan represented by the TRI and CWB averaged rainfall is also shown in Figs. 3c and d, which will be discussed in the next section. The results from TRI and CWB rainfall are clearly similar. Therefore, the TRI data will be used in the following discussions in this paper.

According to Lee et al. (2013), the BSISO1 and BSISO2 represent the BSISO modes with periods of 30 - 60 and 10 - 30 days, respectively. For the rainfall variations of Taiwan and WNP area, the PERSIANN rainfall data and the band-pass filtered values are used to show the total variance, and the variances for the BSISO2 (10 - 30 days) and BSISO1 (30 - 60 days) modes in Fig. 4. The rainfall in Taiwan is associated with complex processes. Many factors, such as typhoons, terrain-effect, monsoon system, BSISO, and the multi-scale interaction, contribute to it. Although the BSISO1 (Fig. 4c) do not contribute large variations in the daily rainfall in these regions, its influence cannot be ignored. However, the results shown here indicate that the major variances in rainfall in the Taiwan area and the Pacific Ocean west of it (Fig. 4a) come from the BSISO2 mode (Fig. 4b). Therefore, the following discussion will focus on the BSISO2.

Because the TRI data is a rainfall index for the whole of Taiwan, the spatial rainfall pattern in Taiwan cannot be realized through the index. The horizontal pattern of the anomalous Taiwan rainfall (red/blue shading; mm day<sup>-1</sup>) for BSISO2 phases 1 - 8 in JASO is shown in Fig. 5. The data used in Fig. 5 is the same as the original records used to construct the TRI. The results in Fig. 5 confirm that large rainfall occurs in BSISO2 phases 3 - 5, especially the largest in phase 4. Therefore, the contribution from the BSISO2 will be discussed in the following sections.

### 4. BSISO2 AND THE WNP TYPHOONS

As defined in Hung and Hsu (2010) and Hung (2013), the area (19 - 28°N, 117 - 125°E) shown in Fig. 1a can be

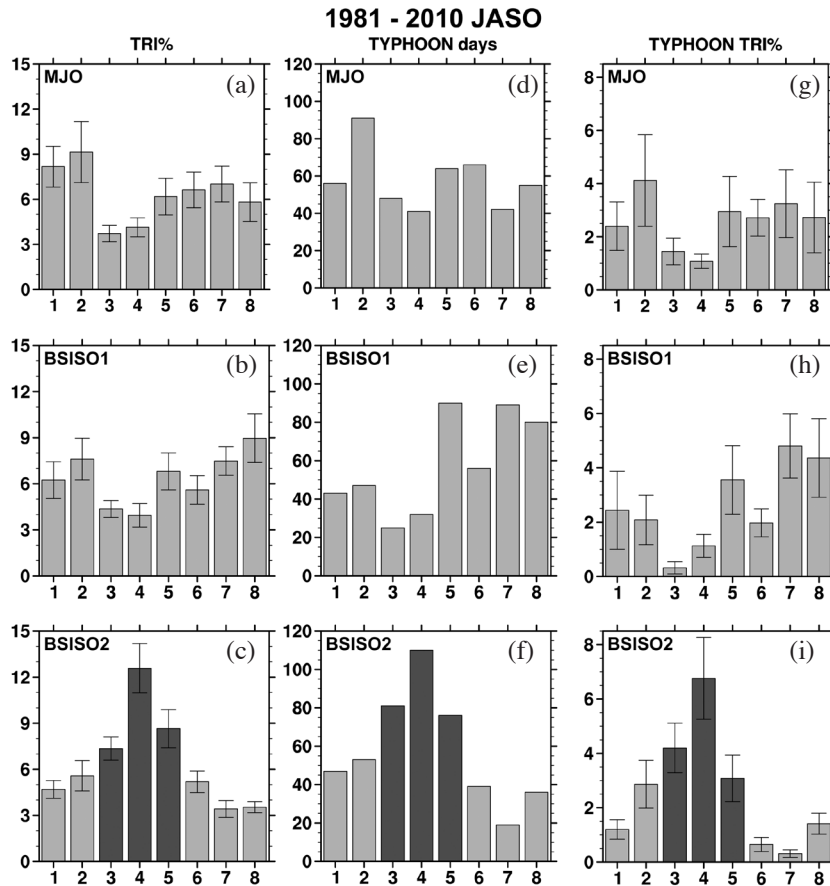


Fig. 2. The mean TRI values (unit: %) for (a) MJO, (b) BSISO1, and (c) BSISO2 phases 1 - 8 during JASO from 1981 to 2010. The dark gray bars indicate the phases 3, 4, and 5 for BSISO2 (details in the text). (d), (e), and (f) are similar to (a), (b), and (c), but for the numbers of days with typhoons in the Taiwan area. (g), (h), and (i) are similar to (a), (b), and (c), but for the TRI values during the typhoon days in Taiwan. In (a), (b), (c), (g), (h), and (i), the standard errors are plotted for references.

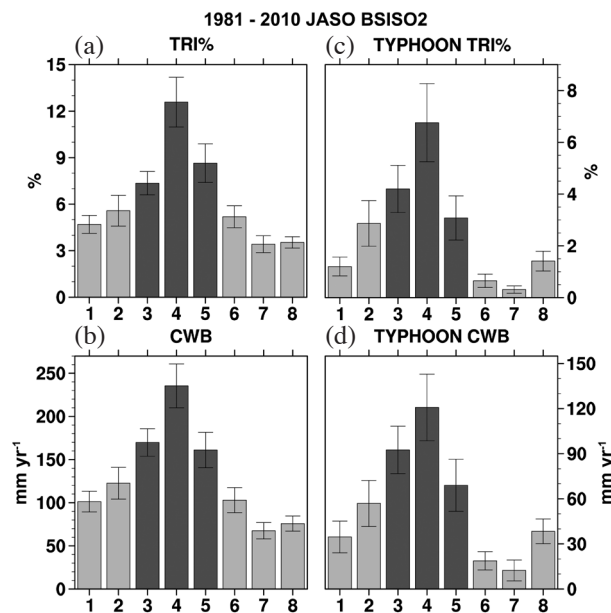


Fig. 3. The JASO (a) mean TRI values (unit: %) and (b) averaged CWB rainfall values (unit: mm) from 15 conventional weather stations in 1981 - 2010 for each BSISO2 phase. The standard errors are plotted for references. (c) and (d) are similar to (a) and (b), but for the values during typhoon days in Taiwan.

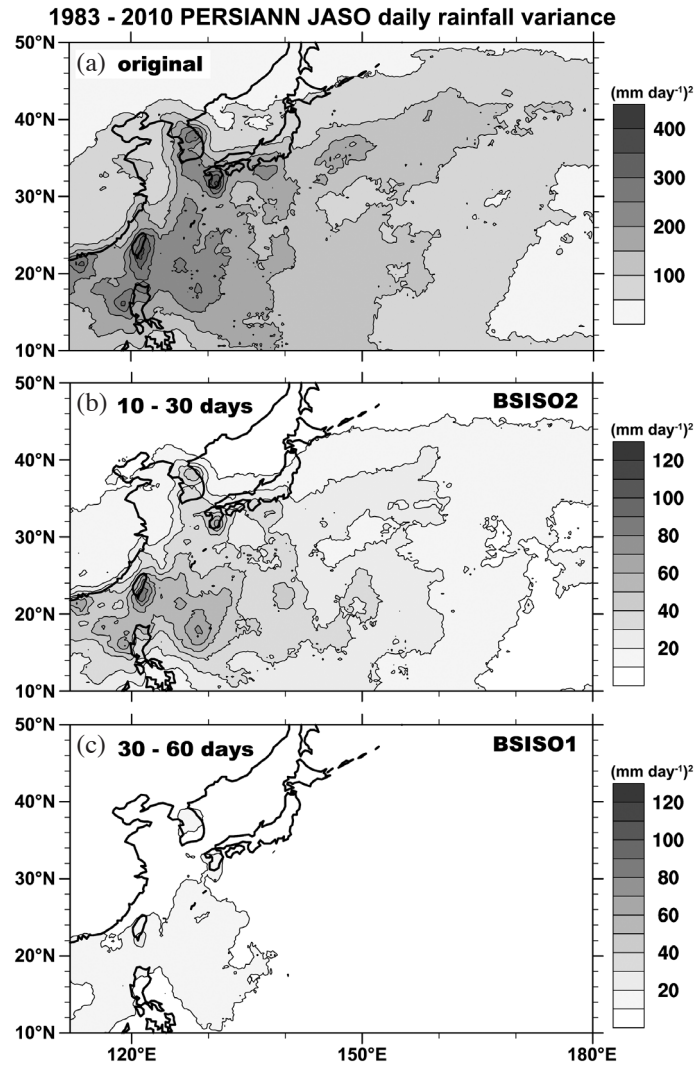


Fig. 4. The variances of the JASO daily rainfall from the PERSIANN data in 1983 - 2010 for (a) the original rainfall data, (b) the 30 - 60 days BSISO1 mode, and (c) the 10 - 30 days BSISO2 mode.

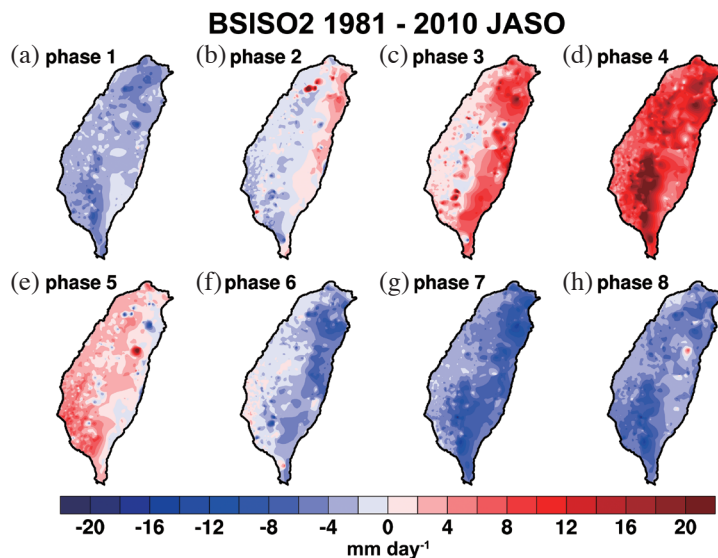


Fig. 5. The anomalous Taiwan rainfall (red/blue shading; mm day<sup>-1</sup>) for BSISO2 phases 1 - 8 [(a) to (h), respectively] in JASO. (Color online only)

used to count the number of typhoons affecting Taiwan. In Figs. 2d, e, and f, the numbers of total days with typhoons in the box are calculated for each phase of MJO, BSISO1, and BSISO2 indices in 1981 - 2010 JASO, respectively. As with the TRI result, the total typhoon-affected days in Taiwan are not correlated well with the MJO and BSISO1 phase indices (Figs. 2d and e). However, the BSISO2 index displays large peaks in phases 3 - 5 and the maximum occurs in phase 4 (Fig. 2f).

Because the typhoon rainfall contribution on the total JASO rainfall in Taiwan is about 43.2% on average (Hung and Hsu 2010), the connection between the ISO phases and the typhoon-related rainfall in Taiwan needs to be verified. The “typhoon-related rainfall” is defined as the rainfall value in Taiwan when a typhoon is located in the box centered on Taiwan, 19 - 28°N, 117 - 125°E, according to Hung and Hsu (2010). The typhoon-related rainfall in Taiwan repre-

sented by the TRI is calculated in Figs. 2g, h, and i for each phase of MJO, BSISO1, and BSISO2 indices, respectively. Only the BSISO2 index has a good connection with the typhoon-related rainfall in Taiwan. The peak phases 3 - 5 have the maximum value in phase 4, which is the same as the total rainfall and number of typhoon days counted in Taiwan. The rainfall in Taiwan is represented by the TRI here. The result is similar to the averaged values from the CWB station data (Fig. 3d). Therefore, based on the analysis in Fig. 2, the most important ISO mode affecting summer rainfall in Taiwan associated with typhoon activity is the BSISO2.

The composited anomalous OLR and 850 hPa streamlines for each BSISO2 phase in 1981 - 2010 are shown in Fig. 6. As mentioned in Lee et al. (2013), the BSISO2 mode is a northward/northwestward propagating ISO with periods of 10 - 30 days. During phase 1, a major cyclonic anomaly

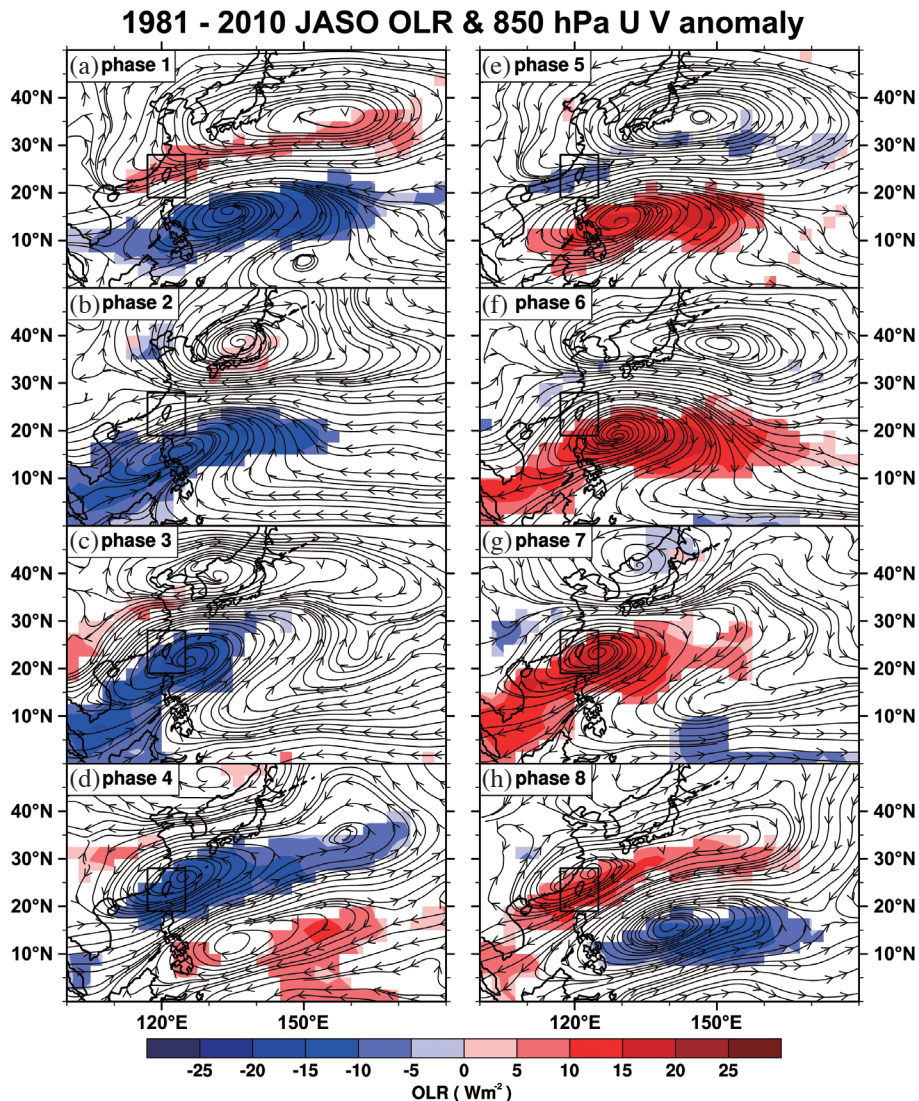


Fig. 6. The anomalous OLR (red/blue shading;  $W m^{-2}$ ) and 850-hPa streamline for BSISO2 phases 1 - 8 [(a) to (h), respectively] in JASO. The black box indicates the Taiwan area (19 - 28°N, 117 - 125°E). Only OLR anomalies exceed 95% confidence level are shown here. (Color online only)

located at the Philippine Sea gradually moves northwestward in phases 2, 3, and 4. During phases 3 and 4, the anomalous low-level cyclonic flow moves into the Taiwan area. In phase 5, this low-level cyclonic flow starts to dissipate while another center located to the east of Japan takes on the northeast-southwest tilting structure. The patterns of phases 5 - 8 are almost opposite to those of phases 1 - 4. An anticyclonic anomalous flow is developed over the Philippine Sea in phase 5 and gradually moves northwestward into the Taiwan area in phases 6 - 8. The cyclonic and anticyclonic flows accompanied with OLR anomalies indicate the active and inactive convection which refers to the rainfall pattern in the region as well.

In order to analyze the connection between the typhoon activity and the BSISO, the JASO historical typhoon tracks provided by the JTWC are collected to calculate the typhoon frequency on the  $5^{\circ} \times 5^{\circ}$  grid box for each BSISO2

phase in 1981 - 2010 (Fig. 7). The anomalous typhoon frequency patterns are similar to the OLR and 850 hPa flow shown in Fig. 6. This result implies that the typhoon activities over the WNP are related to the BSISO2 mode of ISO very much. During phases 8 and 1 - 2, more typhoon activities occur in the Philippine Sea. However, the positive typhoon frequency anomalies gradually move northwestward and the typhoon active region shifts into the Taiwan area during phases 3 - 5. These results show that the typhoon activity over the WNP is related to the BSISO2 mode and also linked with the local rainfall patterns in the Philippines, Taiwan, and Okinawa areas.

### 5. BSISO2 AND THE SUMMER RAINFALL IN TAIWAN

Through the 850 hPa flow composites, OLR and

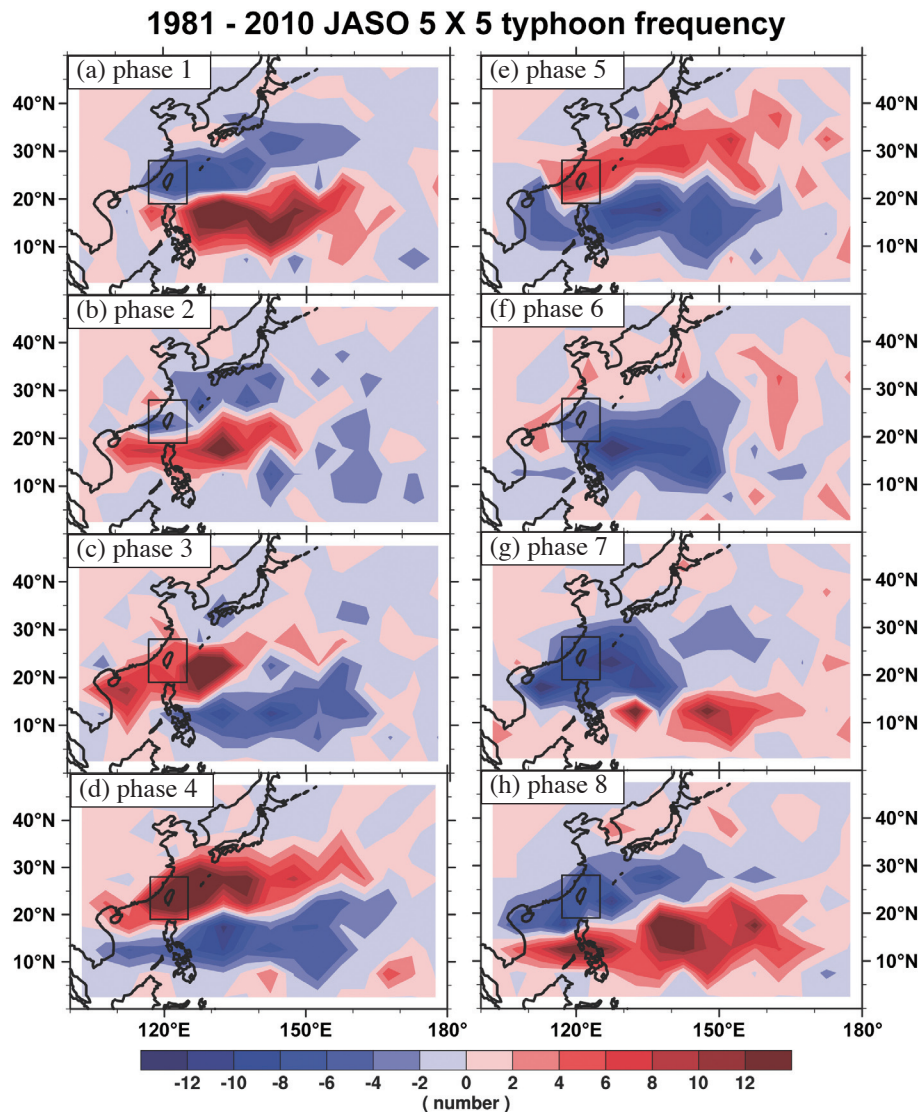


Fig. 7. Similar to Fig. 6, but for the  $5^{\circ} \times 5^{\circ}$  counts of the typhoon frequencies based on the JTWC data in 1981 - 2010. (Color online only)

typhoon frequency for each BSISO2 phase (Figs. 6 and 7), the connection between the local rainfall, typhoon activity, and the BSISO was suggested in the previous section. During phases 3 and 4 the anomalous low-level cyclonic flow and the increased typhoon frequency directly result in larger rainfall in Taiwan. However, during phase 5, although the positive typhoon frequency anomaly is still located in the Taiwan area, the major cyclonic flow has moved to the east of Japan. There must be some other mechanism that contributes the local rainfall in Taiwan as showed in Figs. 2c, f, and i.

According to several previous studies regarding the MJO and the monsoon, the moisture supply can be a very important mechanism that results in increasing local rainfall (Jia et al. 2011; Hung et al. 2014). Therefore, the low-level 850 hPa moisture convergence/divergence is calculated using the velocities multiplying the specific humidity ( $uqi$  and  $vqj$ ; where  $q$  is the specific humidity), and the composites are made based on each phase of BSISO2 to verify the moisture supply associated with the BSISO (Fig. 8). The 850-hPa

moisture transport represented by the vectors is very similar to the low-level anomalous flow as seen in Fig. 6. The moisture divergence shown in the red/blue shading (red = divergence; blue = convergence) also indicates the northward propagation. In addition to the direct effect of the cyclonic flow located in the Taiwan area, the enhanced low-level southwesterly flow transporting moisture to Taiwan is responsible for greater rainfall in Taiwan during phase 5 as seen in Fig. 2c. The stronger southwesterly flow, as observed in Fig. 6e, along with the moisture convergence (Fig. 8e) is the main reason for greater rainfall in Taiwan during phase 5. In contrast, during phases 6 and 7, the southwesterly flow and the moisture convergence area move northward and less rainfall is observed in Taiwan.

Although the moisture convergence can be seen in northern China in phases 6 and 7, the major cyclonic circulation has already moved to the oceanic area east of Japan (Fig. 6f). There is no increased typhoon activity to exhibit positive typhoon frequency anomalies in northern China or

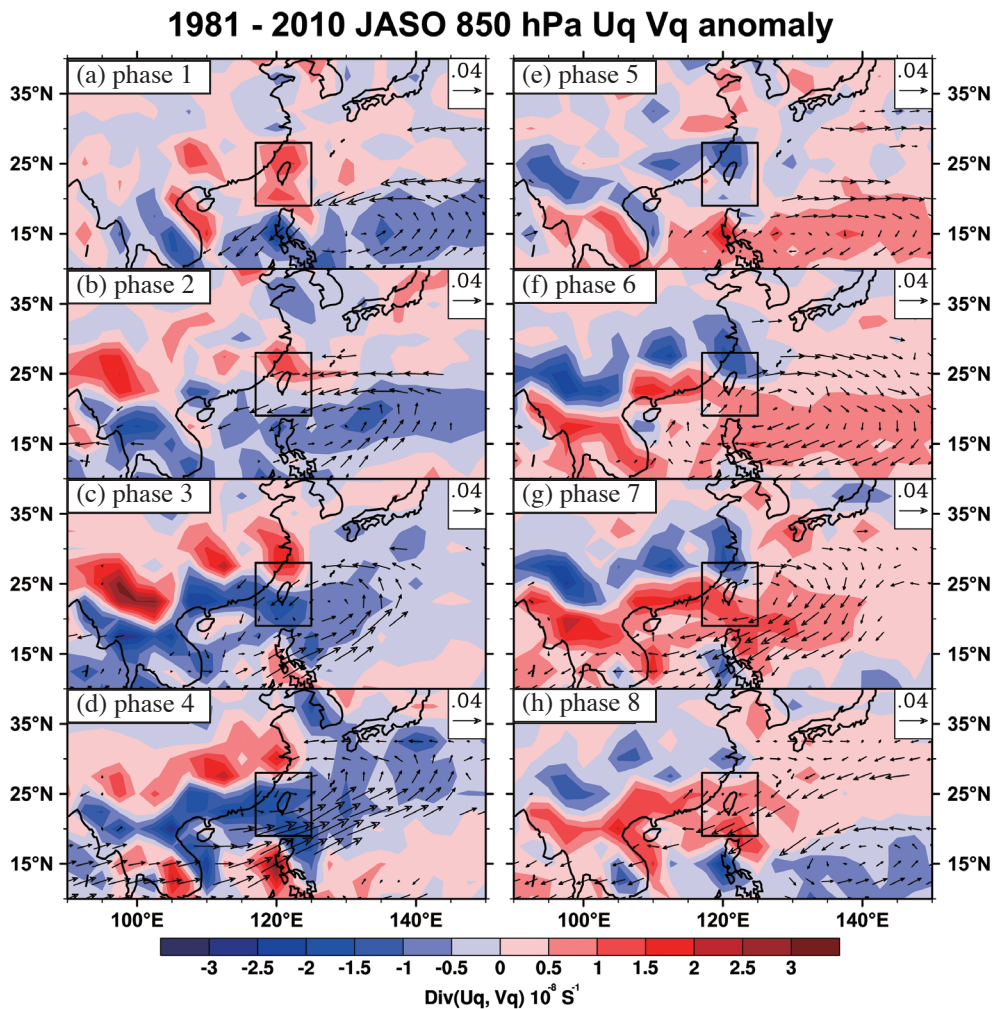


Fig. 8. Similar to Fig. 6, but for the 850 hPa moisture transport shown by the vectors  $uqi$  and  $vqj$  ( $q$  is the specific humidity) and the moisture divergence shown in the red/blue shading (red = divergence; blue = convergence), respectively (unit:  $10^8 \text{ s}^{-1}$ ). Only the magnitudes of the vectors  $uqi$  and  $vqj$  anomalies exceed 95% confidence level are shown here. (Color online only)



the oceanic area east of Japan in phases 6 and 7. Therefore, no increased deep convection represented by OLR is observed in these two areas. There is no increased rainfall in Taiwan, either.

## 6. HEAVY RAINFALL CASES IN TAIWAN ASSOCIATED WITH BSISO AND WNP TYPHOONS

In order to verify the connection among the heavy Taiwan rainfall, the BSISO and WNP typhoons, a detailed analysis is provided in the following. According to Lee et al. (2013), the BSISO can be considered as two modes, the BSISO1 (with the periods of 30 - 60 days) and the BSISO2 (with the periods of 10 - 30 days). The real-time indices are used here to apply this study to practical operations. The day-to-day BSISO1 and BSISO2 phase numbers in 1981 - 2010 are plotted in Figs. 9a and b, respectively. The rainfall condition in Taiwan represented by the filtered TRI values ( $> 10$  day) are greater than or equal to one standard deviation (in dark gray) and less than or equal to minus one stan-

dard deviation (in light gray), as shown in Fig. 10a. The typhoon days in Taiwan are shown in Fig. 10b.

With the above information, the total days for the heavy rainfall ( $\geq$  one standard deviation) and typhoons in Taiwan separated by the BSISO1 and BSISO2 phases can be seen in Figs. 11a and b, respectively. The results show that, for the BSISO1, the heavy rainfall days occur mostly in phases 1, 2, 7, and 8. Using a similar calculation for the typhoon days in Taiwan (same definition as in Fig. 2), the peak phases are in 5, 7, and 8. Apparently, the BSISO1 is not suitable for use for explaining the heavy rainfall cases in Taiwan associated with the influence of WNP typhoons. In contrast, the BSISO2 clearly shows that the heavy rainfall days and the typhoon days in Taiwan occur mainly in phases 3, 4, and 5 with the peak in phase 4. To catch the signals of BSISO to apply on the forecast of heavy rainfall cases in Taiwan associated with typhoons, the BSISO2 is better than the BSISO1.

To clearly see the impact of BSISO2 mode on the heavy rainfall in Taiwan and the typhoon activity in the vicinity of Taiwan, the day-to-day phase condition for the heavy rainfall

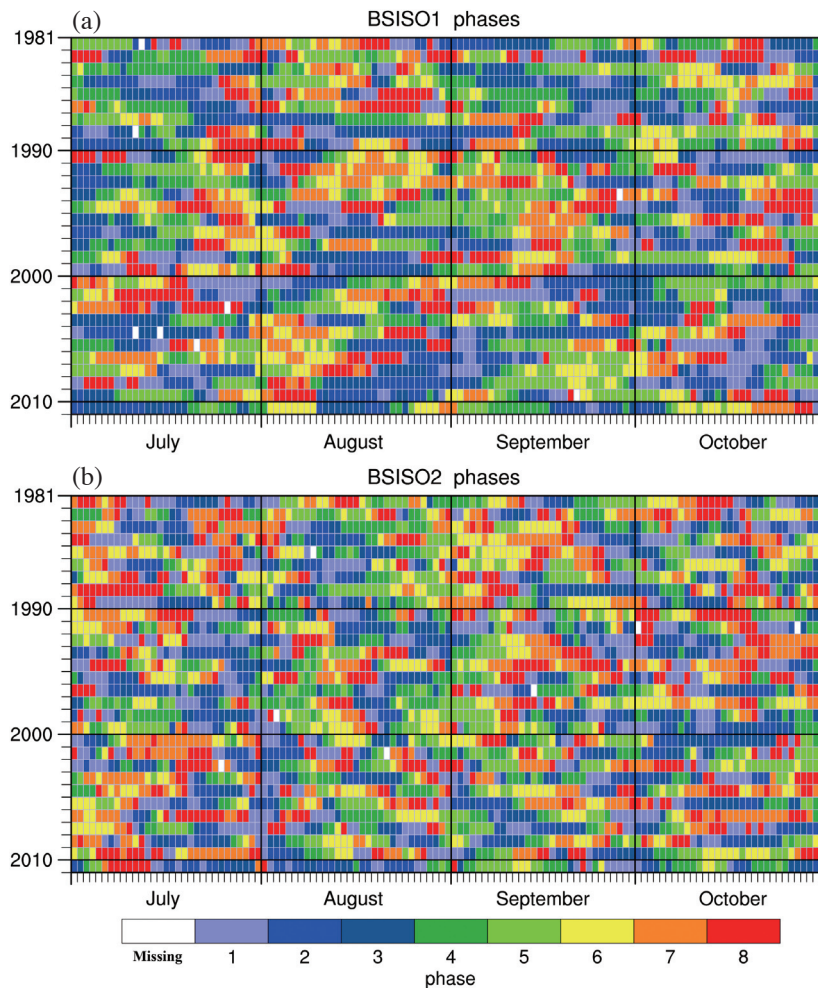


Fig. 9. The JASO day-to-day phase numbers in 1981 - 2010 for (a) BSISO1 and (b) BSISO2. (Color online only)

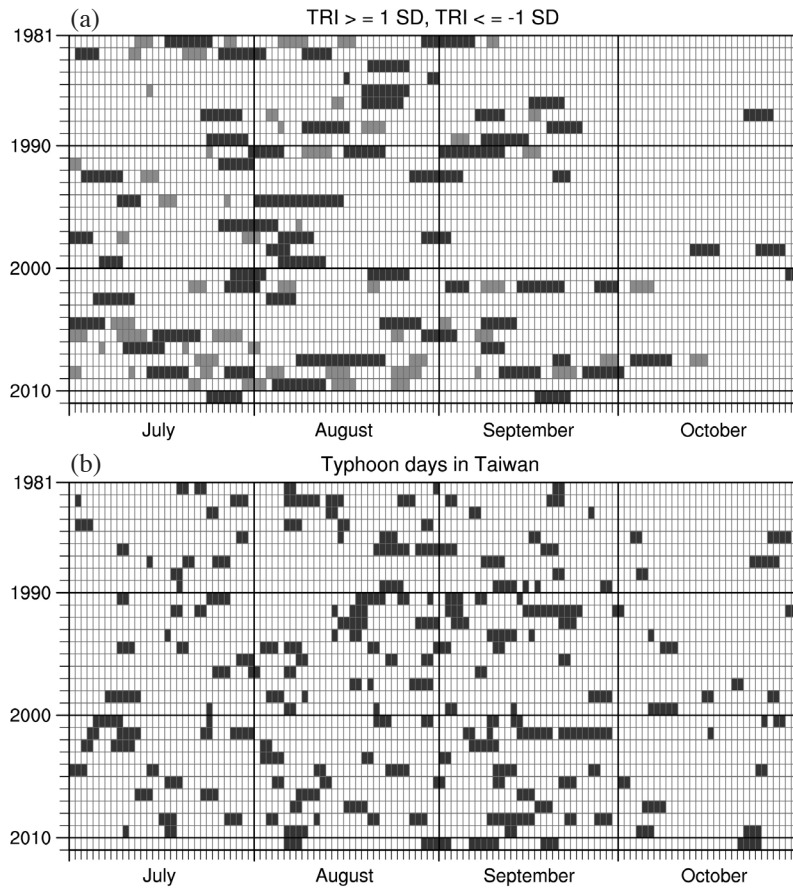


Fig. 10. (a) The JASO day-to-day Taiwan rainfall conditions represented by the filtered TRI data (> 10 days). The dark (light) gray indicate days with TRI value  $\geq$  ( $\leq$ ) one standard deviation. (b) The days defined as “typhoon days” in Taiwan during JASO in 1981 - 2010.

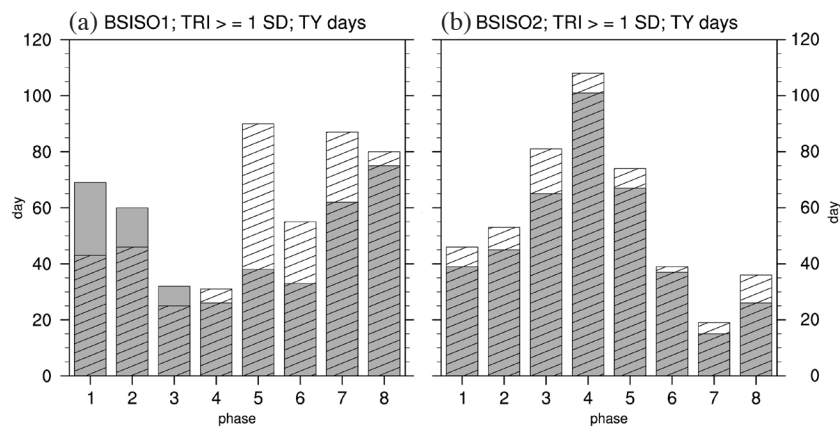


Fig. 11. (a) The total counts for the days with filtered (> 10 days) TRI values  $\geq$  one standard deviation in 1981 - 2010 (in gray bars) and the typhoon days in Taiwan (in slash bars) for each BSISO1 phase. (b) is similar to (a) but for BSISO2.

days and typhoon days in Taiwan in 1981 - 2010 are shown in Figs. 12a and b, respectively. The days with phases 3, 4, and 5 of the BSISO2 are filled in red. Otherwise, the color is in blue. As the same results shown in Fig. 2, most heavy rainfall cases and typhoon days in Taiwan are in red (the phases 3, 4, and 5). These three phases in the total eight BSISO2 phases occupy 59 and 58% of the total heavy rainfall and typhoon day cases, respectively. This result shows that, for the area as Taiwan with many typhoons over the WNP in the boreal summer, the BSISO2 mode is a very good indicator in real-time operations to watch for predicting possible heavy rainfall events associated with typhoons.

## 7. CONCLUSION

Previous studies have indicated that the ISO or the MJO have significant impacts on the Asian-Australian monsoon weather and climate (e.g., Wheeler et al. 2009; Goswami 2012; Hsu 2012). During the boreal summer, the northward/northwestward propagating signals are important features of the ISO. This study discussed the BSISO impact on the WNP typhoons and the summer rainfall in Taiwan. The real time BSISO2 index created by the third and fourth princi-

pal components of the multivariate EOF analysis based on OLR and zonal wind at 850 hPa from Lee et al. (2013) was used. The results indicated that the active/inactive periods and the associated horizontal patterns of the WNP typhoon frequency are closely related to the BSISO2 phases during the typhoon season (July - October). The conceptual model is provided in Fig. 13.

Based on the 1981 - 2010 data in the typhoon season, Taiwan has larger rainfall in BSISO2 phases 3, 4, and 5 when the major BSISO2 convection moves northwestward from the Philippine Sea into the Taiwan area. During phases 3 and 4, the anomalous low-level cyclonic flow and the increased typhoon frequency directly result in larger rainfall in Taiwan. For phase 5 the enhanced low-level southwest-erly flow that transports moisture into Taiwan is responsible for greater summer rainfall in Taiwan. Based on several independent observational datasets, the connection between local rainfall in Taiwan, WNP typhoon activities, and the BSISO2 is suggested. Real-time BSISO data and a forecast service were recently provided by the APEC Climate Center (APCC) (Kim 2015). The BSISO indices are predictable from 7-day to over 20-day forecast lead time. The better predictability of BSISO2 from APCC and the results in this

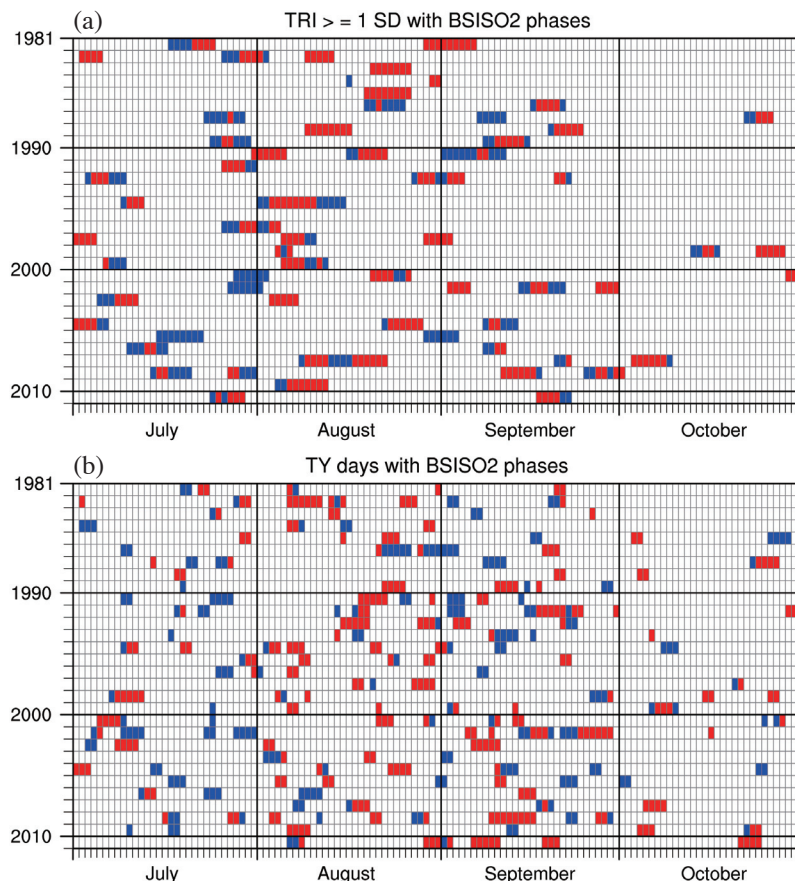


Fig. 12. Similar to Fig. 10, but the color in red indicates that the phases of BSISO2 are 3, 4, and 5. Otherwise, the color is in blue. (Color online only)

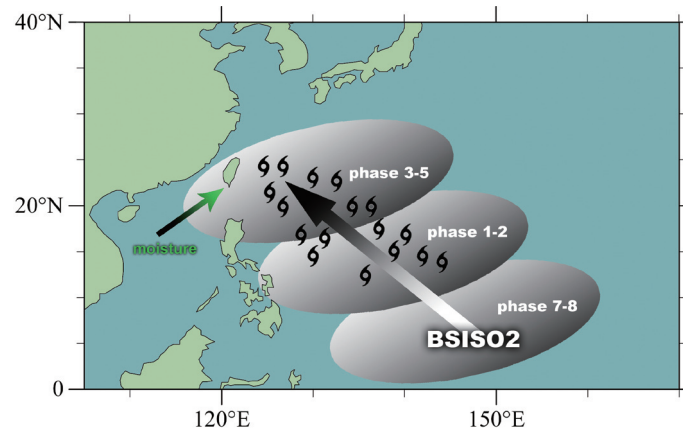


Fig. 13. The conceptual model for explaining the BSISO2 mechanism impacts on JASO rainfalls in Taiwan and the WNP typhoons. The gray shaded circles represent the major BSISO2 convection with the phases indicated. The big arrow and the small green arrow refer to the movement direction of the BSISO2 mode and moisture supply, respectively. In addition, the small typhoon symbols indicate the major typhoons occurring in the area. (Color online only)

work are informative for weather forecasters in Taiwan and the Philippines to project possible active/inactive typhoon periods and the associated rainfall conditions during the summer season. With this knowledge, the mechanism can be also used for intraseasonal weather prediction as a conceptual model.

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## REFERENCES

- Ashouri, H., K. L. Hsu, S. Sorooshian, D. K. Braithwaite, K. R. Knapp, L. D. Cecil, B. R. Nelson, and O. P. Prat, 2015: PERSIANN-CDR: Daily precipitation climate data record from multisatellite observations for hydrological and climate studies. *Bull. Amer. Meteorol. Soc.*, **96**, 69-83, doi: 10.1175/BAMS-D-13-00068.1. [[Link](#)]
- Chen, G. and C. Chou, 2014: Joint Contribution of multiple equatorial waves to tropical cyclogenesis over the western North Pacific. *Mon. Weather Rev.*, **142**, 79-93, doi: 10.1175/MWR-D-13-00207.1. [[Link](#)]
- Chen, J. M. and C. F. Shih, 2012: Association between northward-moving tropical cyclones and southwesterly flows modulated by intraseasonal oscillation. *J. Climate*, **25**, 5072-5087, doi: 10.1175/JCLI-D-11-00264.1. [[Link](#)]
- Chen, J. M., P. H. Tan, and C. F. Shih, 2013: Heavy rainfall induced by tropical cyclones across northern Taiwan and associated intraseasonal oscillation modulation. *J. Climate*, **26**, 7992-8007, doi: 10.1175/JCLI-D-12-00692.1. [[Link](#)]
- Dee, D. P., S. M. Uppala, A. J. Simmons, P. Berrisford, P. Poli, S. Kobayashi, U. Andrae, M. A. Balmaseda, G. Balsamo, P. Bauer, P. Bechtold, A. C. M. Beljaars, L. van de Berg, J. Bidlot, N. Bormann, C. Delsol, R. Dragani, M. Fuentes, A. J. Geer, L. Haimberger, S. B. Healy, H. Hersbach, E. V. Hólm, L. Isaksen, P. Kållberg, M. Köhler, M. Matricardi, A. P. McNally, B. M. Monge-Sanz, J. J. Morcrette, B. K. Park, C. Peubey, P. de Rosnay, C. Tavolato, J. N. Thépaut, and F. Vitart, 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Q. J. R. Meteorol. Soc.*, **137**, 553-597, doi: 10.1002/qj.828. [[Link](#)]
- Donald, A., H. Meinke, B. Power, A. de H. N. Maia, M. C. Wheeler, N. White, R. C. Stone, and J. Ribbe, 2006: Near-global impact of the Madden-Julian Oscillation on rainfall. *Geophys. Res. Lett.*, **33**, L09704, doi: 10.1029/2005GL025155. [[Link](#)]
- Goswami, B. N., 2012: South Asian monsoon. In: Lau, W. K. M. and D. E. Waliser (Eds.), *Intraseasonal Variability in the Atmosphere-Ocean Climate System*, Springer Berlin Heidelberg, 19-61, doi: 10.1007/3-540-27250-X\_2. [[Link](#)]
- Hsu, H. H., 2012: East Asian Monsoon. In: Lau, W. K. M. and D. E. Waliser (Eds.), *Intraseasonal Variability in the Atmosphere-Ocean Climate System*, Springer Berlin Heidelberg, 63-94, doi: 10.1007/3-540-27250-X\_3. [[Link](#)]
- Hsu, P. C. and T. Li, 2011: Interactions between boreal summer Intraseasonal oscillations and synoptic-scale disturbances over the western North Pacific. Part II: Apparent heat and moisture sources and eddy momentum transport. *J. Climate*, **24**, 942-961, doi: 10.1175/2010JCLI3834.1. [[Link](#)]
- Hsu, P. C., T. Li, and C. H. Tsou, 2011: Interactions between

- boreal summer Intraseasonal oscillations and synoptic-scale disturbances over the western North Pacific. Part I: Energetics diagnosis. *J. Climate*, **24**, 927-941, doi: 10.1175/2010JCLI3833.1. [[Link](#)]
- 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 Dyn.*, **44**, 1227-1244, doi: 10.1007/s00382-014-2215-4. [[Link](#)]
- Hung, C. W., 2012: The construction of TCCIP Taiwan Rainfall Index (TRI) and its applications. *J. Geogr. Sci.*, **67**, 73-96, doi: 10.6161/jgs.2012.67.04. (in Chinese) [[Link](#)]
- Hung, C. W., 2013: A 300-year typhoon record in Taiwan and the relationship with solar activity. *Terr. Atmos. Ocean. Sci.*, **24**, 737-743, doi: 10.3319/TAO.2013.02.18.01(A). [[Link](#)]
- Hung, C. W. and H. H. Hsu, 2008: The first transition of the Asian summer monsoon, intraseasonal oscillation, and Taiwan mei-yu. *J. Climate*, **21**, 1552-1568, doi: 10.1175/2007JCLI1457.1. [[Link](#)]
- Hung, C. W. and H. H. Hsu, 2010: Contribution of typhoons to the rainfall in Taiwan. 14th International Conference on Geography in Taiwan, NTNU, Taipei, Taiwan.
- Hung, C. W., H. J. Lin, and H. H. Hsu, 2014: Madden-Julian oscillation and the winter rainfall in Taiwan. *J. Climate*, **27**, 4521-4530, doi: 10.1175/JCLI-D-13-00435.1. [[Link](#)]
- Jia, X., L. Chen, F. Ren, and C. Li, 2011: Impacts of the MJO on winter rainfall and circulation in China. *Adv. Atmos. Sci.*, **28**, 521-533, doi: 10.1007/s00376-010-9118-z. [[Link](#)]
- Jones, C., D. E. Waliser, K. M. Lau, and W. Stern, 2004: Global occurrences of extreme precipitation and the Madden-Julian oscillation: Observations and predictability. *J. Climate*, **17**, 4575-4589, doi: 10.1175/3238.1. [[Link](#)]
- Kim, H. S., 2015: Improvement of the real-time forecast system on the BSISO(I): Verification for the BSISO forecast. Research Report 2015-06, APEC Climate Center, Busan, Republic of Korea, 114 pp.
- Kim, J. H., C. H. Ho, H. S. Kim, C. H. Sui, and S. K. Park, 2008: Systematic variation of summertime tropical cyclone activity in the western North Pacific in relation to the Madden-Julian oscillation. *J. Climate*, **21**, 1171-1191, doi: 10.1175/2007JCLI1493.1. [[Link](#)]
- Lee, J. Y., B. Wang, M. C. Wheeler, X. Fu, D. E. Waliser, and I. S. Kang, 2013: Real-time multivariate indices for the boreal summer intraseasonal oscillation over the Asian summer monsoon region. *Climate Dyn.*, **40**, 493-509, doi: 10.1007/s00382-012-1544-4. [[Link](#)]
- Li, R. C. Y. and W. Zhou, 2013: Modulation of western North Pacific tropical cyclone activity by the ISO. Part I: Genesis and intensity. *J. Climate*, **26**, 2904-2918, doi: 10.1175/JCLI-D-12-00210.1. [[Link](#)]
- Liebmann, B. and C. A. Smith, 1996: Description of a complete (interpolated) outgoing longwave radiation dataset. *Bull. Amer. Meteorol. Soc.*, **77**, 1275-1277.
- Madden, R. A. and P. R. Julian, 1971: Detection of a 40-50 day oscillation in the zonal wind in the tropical Pacific. *J. Atmos. Sci.*, **28**, 702-708, doi: 10.1175/1520-0469(1971)028<0702:DOADOI>2.0.CO;2. [[Link](#)]
- Madden, R. A. and P. R. Julian, 1972: Description of global-scale circulation cells in the tropics with a 40-50 day period. *J. Atmos. Sci.*, **29**, 1109-1123, doi: 10.1175/1520-0469(1972)029<1109:DOGSCC>2.0.CO;2. [[Link](#)]
- Madden, R. A. and P. R. Julian, 1994: Observations of the 40-50-day tropical oscillation—A review. *Mon. Weather Rev.*, **122**, 814-837, doi: 10.1175/1520-0493(1994)122<0814:OOTDIO>2.0.CO;2. [[Link](#)]
- Mao, J., Z. Sun, and G. Wu, 2010: 20-50-day oscillation of summer Yangtze rainfall in response to intraseasonal variations in the subtropical high over the western North Pacific and South China Sea. *Climate Dyn.*, **34**, 747-761, doi: 10.1007/s00382-009-0628-2. [[Link](#)]
- Murakami, T., L. X. Chen, and A. Xie, 1986: Relationship among seasonal cycles, low-frequency oscillations, and transient disturbances as revealed from outgoing longwave radiation data. *Mon. Weather Rev.*, **114**, 1456-1465, doi: 10.1175/1520-0493(1986)114<1456:RASCLF>2.0.CO;2. [[Link](#)]
- Uppala, S. M., P. W. Kållberg, A. J. Simmons, U. Andrae, V. D. C. Bechtold, M. Fiorino, J. K. Gibson, J. Haseler, A. Hernandez, G. A. Kelly, X. Li, K. Onogi, S. Saarinen, N. Sokka, R. P. Allan, E. Andersson, K. Arpe, M. A. Balmaseda, A. C. M. Beljaars, L. van de Berg, J. Bidlot, N. Bormann, S. Caires, F. Chevallier, A. Dethof, M. Dragosavac, M. Fisher, M. Fuentes, S. Hagemann, E. Hólm, B. J. Hoskins, L. Isaksen, P. A. E. M. Janssen, R. Jenne, A. P. McNally, J. F. Mahfouf, J. J. Morcrette, N. A. Rayner, R. W. Saunders, P. Simon, A. Sterl, K. E. Trenberth, A. Untch, D. Vasiljevic, P. Viterbo, and J. Woollen, 2005: The ERA-40 re-analysis. *Q. J. R. Meteorol. Soc.*, **131**, 2961-3012, doi: 10.1256/qj.04.176. [[Link](#)]
- Wheeler, M. C. and H. H. Hendon, 2004: An all-season Real-time Multivariate MJO index: Development of an index for monitoring and prediction. *Mon. Weather Rev.*, **132**, 1917-1932, doi: 10.1175/1520-0493(2004)132<1917:AARMMI>2.0.CO;2. [[Link](#)]
- Wheeler, M. C., H. H. Hendon, S. Cleland, H. Meinke, and A. Donald, 2009: Impacts of the Madden-Julian oscillation on Australian rainfall and circulation. *J. Climate*, **22**, 1482-1498, doi: 10.1175/2008JCLI2595.1. [[Link](#)]
- Wu, C. C. and Y. H. Kuo, 1999: Typhoons Affecting Taiwan: Current Understanding and Future Challenges. *Bull. Amer. Meteorol. Soc.*, **80**, 67-80, doi: 10.1175/1520-0477(1999)080<0067:TATCUA>2.0.CO;2. [[Link](#)]
- Yang, H. and C. Li, 2003: The relation between atmospheric

- intraseasonal oscillation and summer severe flood and drought in the Changjiang-Huaihe River Basin. *Adv. Atmos. Sci.*, **20**, 540-553, doi: 10.1007/BF02915497. [[Link](#)]
- Yasunari, T., 1979: Cloudiness fluctuations associated with the northern hemisphere summer monsoon. *J. Meteorol. Soc. Jpn.*, **57**, 227-242.
- Yasunari, T., 1980: A quasi-stationary appearance of 30 to 40 day period in the cloudiness fluctuations during the summer monsoon over India. *J. Meteorol. Soc. Jpn.*, **58**, 225-229.
- Yasunari, T., 1981: Structure of an Indian summer monsoon system with around 40-day period. *J. Meteorol. Soc. Jpn.*, **59**, 336-354.
- Zhang, C., 2005: Madden-Julian Oscillation. *Rev. Geophys.*, **43**, RG2003, doi: 10.1029/2004RG000158. [[Link](#)]