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RESEARCH ARTICLE

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Influence of boreal summer intraseasonal oscillation on rainfall extremes in the Philippines

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Abstract

This study investigates the impact of the northward/northwestward propagating 30–60-day mode of the boreal summer intraseasonal oscillation (BSISO) on the extreme rainfall events in the Philippines during the June–September (JJAS) season from 1979 to 2018. The Philippines domain is divided into the three latitudinal regions: Luzon region (13°–22°N), Visayas region (10°–13°N), and Mindanao region (5°–10°N) to account for the regional differences in the timing of extreme rainfall events. The probability density functions of JJAS rainfall are skewed towards higher values relative to the non-BSISO days in BSISO Phases 6–8, Phases 5–7, and Phases 4–6 over the Luzon, Visayas, and Mindanao regions, respectively, during which the probability of extreme rainfall events at the 95th percentile increases by as much as 80% in some stations in these regions. Further analyses of the large-scale circulation features show that the increase (decrease) in the probability of extreme rainfall events is associated with enhanced moisture convergence (divergence) induced by the cyclonic (anticyclonic) circulation anomalies of the BSISO and appearance of multiple tropical cyclones. About 36% of the total extreme rainfall events over the Luzon region are associated with TCs during Phases 7–8. On the other hand, TCs contribute by no more than 24% in all phases over the Visayas and Mindanao regions, indicating less TC influence in these regions. This study is the first attempt to clarify the impact of the BSISO on the extreme rainfall events in the Philippines.

KEYWORDS

BSISO, extreme rainfall, flood

1 | INTRODUCTION

Extreme rainfall events are one of the prominent natural hazards that can lead to catastrophic damages to agriculture, infrastructures, and loss of human lives. Poor urban planning and disaster mitigation measures exacerbate the impacts of these extreme rainfall events. As such, a better understanding of the physical processes inducing them is necessary to mitigate their impacts and to establish a better forecasting system.

In the subseasonal timescales, some studies have demonstrated the role of the boreal summer intraseasonal oscillation (BSISO) in modulating the rainfall variability including the rainfall extremes during the summer monsoon season over the Asian monsoon region (e.g., Kikuchi *et al*., 2012; Li *et al*., 2015; Hsu *et al*., 2016; Chen *et al*., 2017; Moon *et al*., 2018; Ren *et al*., 2018). Hsu *et al*. (2016) noted that the convective and circulation anomalies associated with the BSISO may induce changes in the local rainfall variation by altering the background conditions. Their study further demonstrated that the Yangtze River valley flooding event in 1998 coincided with the active phases (Phases 3 and 4) of the northward/northwestward propagating 30–60-day mode of the BSISO. Some studies such as those by Zhou and Chan (2005) and Annamalai and Slingo (2001) also demonstrated the impact of the BSISO on the onset of the summer monsoon over the South China Sea, and the active and break cycles of rainfall over the Indian subcontinent, respectively.

Unlike the Madden–Julian Oscillation (MJO; Madden and Julian, 1971), which propagates eastward along the equator in boreal winter, the BSISO shows a more complex nature and with a dominant northward/northwestward propagation over the Indian and western North Pacific monsoon regions (e.g., Kikuchi *et al*., 2012; Moon *et al*., 2018). Kikuchi *et al*. (2012) developed a bimodal index that captures the eastward propagation of MJO and northward/northwestward propagation of BSISO based on the extended empirical orthogonal function (EEOF) analysis of the bandpass filtered (25–90 days) outgoing longwave radiation (OLR). They noted that the predominant ISO mode at any particular time of the year can be determined from the proportions of OLR anomalies projected onto the MJO and BSISO modes. They found that the BSISO (MJO) is predominant during the June–October (December–April) season, while the rest of the months are transitional months between the two modes.

Only few studies have examined the impact of the BSISO on the rainfall of the Philippines. Olaguera *et al*. (2021) examined the impact of the BSISO on the monsoon break following the southwest monsoon onset over Luzon Island. They found that about 59% of the total monsoon break cases in Luzon from 1979 to 2018 occurred concurrently with the suppressed phases (Phases 1–4) of the BSISO. It is suggested that the suppression of convective activities during the suppressed phases of the BSISO around Luzon Island favours the southwestward expansion of the western North Pacific subtropical high (WNPSH) leading to the monsoon break. Natoli and Maloney (2019) and Riley-Dellaripa *et al*. (2020) examined the impact of the BSISO on the diurnal cycle of rainfall in the Philippines. In particular, Riley-Dellaripa *et al*. (2020) examined the impact of topography on the July–August 2016 diurnal cycle of rainfall over Luzon Island during the active and suppressed phases of the BSISO through numerical simulations. They found that the peak of the mean diurnal cycle of rainfall over Luzon Island is delayed by 1.5 hr and has a 9% larger amplitude during the active phase of the BSISO relative to its suppressed phase in their true topography experiment. Bagtasa (2020) recently examined the impact of the eastward propagating MJO on the southwest monsoon rainfall of the Philippines. He found that tropical cyclone (TC) activity is enhanced over the western North Pacific when the MJO traverses the equatorial region in Phases 5–7. This enhanced TC activity induces strong southwesterly flow, moisture transport, and anomalous rainfall to the western region of the Philippines.

While the aforementioned studies examined the impact of BSISO and eastward propagating MJO on the monsoon break, diurnal cycle, and southwest monsoon rainfall in the Philippines, there remains a research gap on the relationship between the northward/northwestward propagating BSISO and extreme rainfall events in the country. As will be shown later, we found that the BSISO can also modulate the occurrence of large-scale heavy rainfall events and dry weather conditions in the country. The impact of subseasonal variabilities on extreme rainfall events have also been documented in previous studies (e.g., Yumul Jr *et al*., 2010; Pullen *et al*., 2015). The majority of the flooding events during boreal summer in the Philippines are due to TCs (e.g., Cruz and Narisma, 2016) or its interaction with the prevailing monsoon southwesterly flow (e.g., Cayanan *et al*., 2011). Other factors are related to prolonged monsoon rains (e.g., Yumul Jr *et al*., 2011). How the BSISO contributes to the occurrence of extreme rainfall/flooding events during boreal summer will be examined in this study. It is believed that the results of this study may help improve the extreme rainfall forecasting system of the country. The rest of the paper is organized as follows. Section 2 describes the different data sets and methodologies used in this study. The impact of the BSISO on the extreme rainfall in the Philippines is presented in section 3. Summary and discussions are provided in section 4.

2 | DATA AND METHODOLOGY

2.1 | Data

In this study, we used the following data sets:

1. Daily rainfall data from 42 synoptic stations (Figure 1) across the country from 1979 to 2018 and provided by

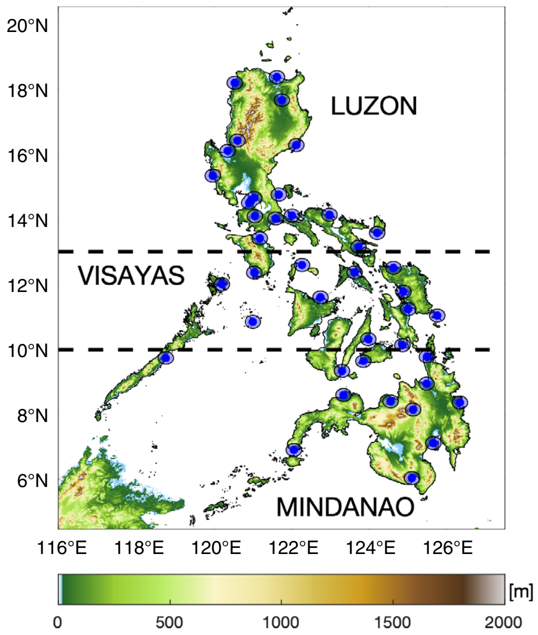

FIGURE 1 The location of the 42 PAGASA stations used in this study (blue dots with black circles) and the topography (m) of the Philippines. The horizontal dashed lines divide the Philippines into three regions: Luzon region (13°–22°N), Visayas region (10°–13°N), and Mindanao region (5°–10°N) [Colour figure can be viewed at wileyonlinelibrary.com]

the Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA), the country's official weather bureau. These stations have less than 20% missing data for the whole study period.

2. Daily reanalysis data, with 1.25° × 1.25° grid resolution, of zonal (U) and meridional (V) winds, specific humidity (SHUM) at multiple levels from the Japan Meteorological Agency (JMA) 55-year reanalysis (JRA55; Kobayashi *et al.*, 2015) from 1979 to 2018.
3. Daily bimodal ISO index from 1979 to 2018 developed by Kikuchi *et al.* (2012). The index can be downloaded at https://iprc.soest.hawaii.edu/users/kazuyosh/Bimodal_ISO.html. The BSISO encompasses a variety of timescales ranging from 10 to 70 days (Hsu *et al.*, 2016). As mentioned previously, the spatiotemporal patterns of the BSISO based on Kikuchi *et al.* (2012) were identified by applying an EEOF analysis on the band-passed filtered daily OLR with a time filtering of 25–90-days timescale. This mainly captures the 30–60-day mode of the northward propagating BSISO. The shorter timescale mode of the BSISO with 10–30-day periodicity is not be examined in this paper. The first two EEOF coefficients (hereafter, PC1 and PC2) are projected onto a phase-space diagram to depict the location of the active and suppressed phases of the BSISO. There are eight phases in this diagram and the propagation of the ISO is depicted in an anti-clockwise direction. The active convection of BSISO in Phases 1 and 2 is located over the eastern North Pacific and equatorial Indian Ocean, while it is located over the Bay of Bengal in Phases 2 and 3. In Phases 4 and 5 the active convection is located over India and the Maritime Continent, and in Phases 6 and 7, it is located over the western North Pacific.
4. TC best track data provided by the Joint Typhoon Warning Center (JTWC; www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/wpindex.php) from 1979 to 2018.
5. Historical flood events archived by the Dartmouth Flood Observatory (DFO; http://floodobservatory.colorado.edu/) from 1979 to 2018.

2.2 | Methodology

We defined the southwest monsoon months as the months from June to September (JJAS) following Cruz *et al.* (2013). Matsumoto *et al.* (2020) presented that the southwesterly wind climatologically prevails most of the Philippines during these 4 months. The analysis period extends from 1979 to 2018.

We divided the Philippines into three latitude regions: Luzon region (13°–22°N), Visayas region (10°–13°N), and Mindanao region (5°–10°N) as shown in Figure 1 to account for the spatial variation in the rainfall extremes. Yumul Jr *et al.* (2010) examined the dry weather condition that persisted over the Luzon region from June to early August 2007, while some areas over the Mindanao region were wetter than normal. Their results highlight the spatial difference in the extreme rainfall events between the two regions; hence, dividing the Philippines into three regions seems practical. There are 18, 12, and 12 stations in the Luzon, Visayas, and Mindanao regions, respectively.

Composites of rainfall were computed for each phase of the eight BSISO phases. Only the days with BSISO amplitudes greater than 1 were used for the composites. Otherwise, the days were used for the non-BSISO composites. The occurrence of the rainfall extremes was defined based on percentile thresholds following Hsu *et al.* (2016) and Ren *et al.* (2018). An extreme rainfall day was defined as the day when the daily rainfall amount exceeds the 95th percentiles (i.e., the 95th extreme) of all rainy days during JJAS. The changes in the frequency of occurrence of extremes were calculated as follows.

$$\Delta P_{\mathrm{BSISO}} = \frac{P_{\mathrm{BSISO}}(x \geq Xc) - P_{\mathrm{non-BSISO}}(x \geq Xc)}{P_{\mathrm{non-BSISO}}(x \geq Xc)}, \tag{1}$$

where $\Delta P_{\mathrm{BSISO}}$ is the percentage change in the cumulative probability of rainfall (x) exceeding a given threshold (Xc) due to BSISO. P_{BSISO} is the cumulative probability of rainfall exceeding a given threshold for a given BSISO phase, while $P_{\mathrm{non-BSISO}}$ is for the non-BSISO days. We used a bootstrapping procedure (Efron and Tibshirani, 1994) to assess the significance of the percentage change in the frequency of occurrence of extremes similar to those used by Matsueda and Takaya (2015) and Chen and Zhai (2017). The probability of occurrence of extreme events were calculated for each year from 1979 to 2018 for both the BSISO and non-BSISO days, producing 40 pairs. Then, these 40 pairs were randomly resampled and the average probabilities were calculated for both the BSISO and non-BSISO days. This was repeated for 1,000 times. We considered the probability of the extreme events during the BSISO days to be significantly higher than those during the non-BSISO days when the averaged probability of occurrence of extreme events during the BSISO days was higher than the non-BSISO days for more than 950 samples (95% of the 1,000 samples). This method was applied for each phase of the BSISO.

3 | RESULTS

3.1 | BSISO impact on rainfall extremes

To determine the dominant frequencies in the three regions, we perform a power spectral analysis using the fast Fourier transform (FFT) on their corresponding rainfall time series. This will also help clarify whether the BSISO significantly affects the rainfall in the three regions. The power spectra for the three regions are shown in Figure 2. The spectral analysis shows two dominant periods above the 95th percentile at intraseasonal (30–60 days) and synoptic (<10 days) scales over Luzon and Mindanao regions. Only the synoptic-scale variability is significant over the Visayas region. We also found that the 30–60-day BSISO mode explains about 15, 12, and 12% of the total seasonal variance over Luzon, Visayas,

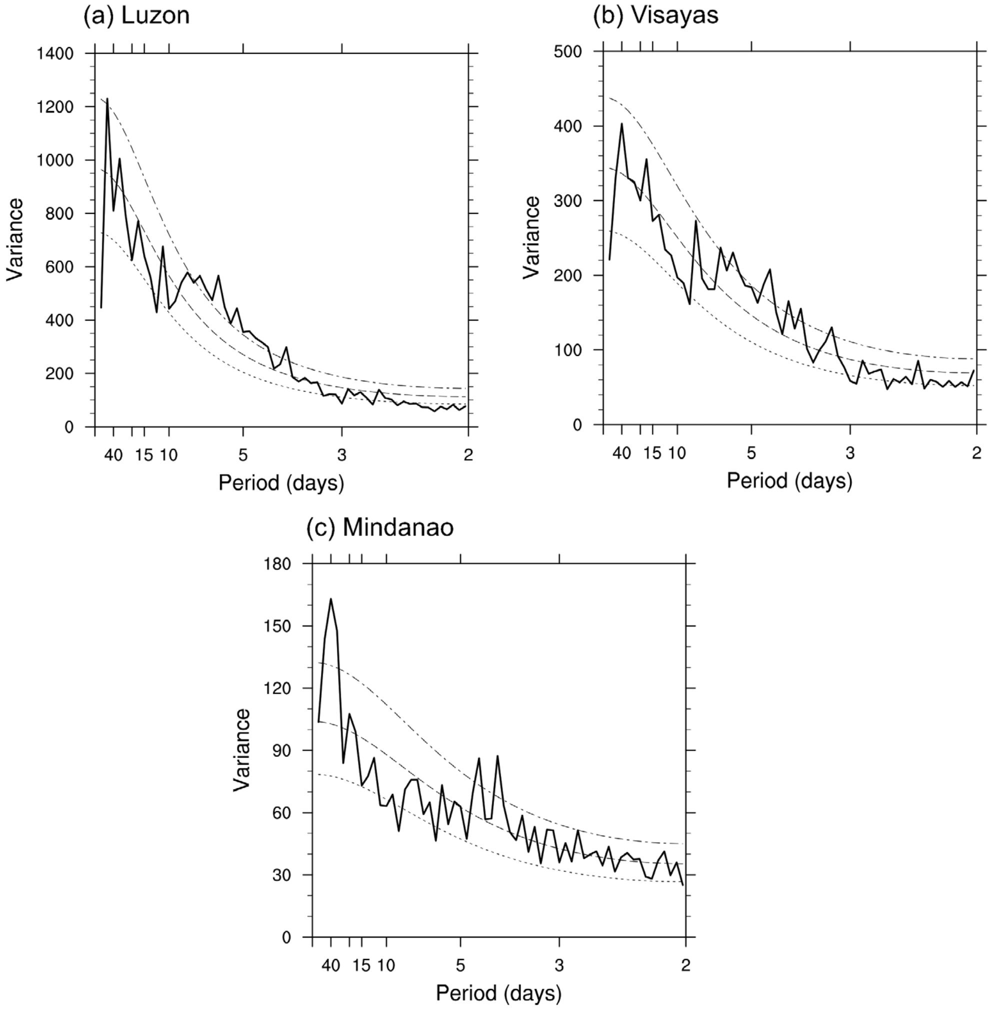

FIGURE 2 The mean power spectra (solid line) of JJAS rainfall from 1979 to 2018 over the (a) Luzon, (b) Visayas, and (c) Mindanao regions. The dashed line indicates the Markov red noise spectrum. The dotted and dot-dashed lines indicate the 5th and 95th percentile confidence levels, respectively, estimated using the lag -1 autocorrelation

and Mindanao regions, respectively. This indicates that the rainfall variability accounted by the BSISO is larger over the Luzon region than those over the Visayas and Mindanao regions. Also notice that the peaks at the 10–30-day timescale are less pronounced compared to the 30–60 and 2–10-day variabilities.

To clarify further how the BSISO affects the rainfall extremes in the Philippines, we illustrate the probability density functions (PDFs) of rainfall amounts during the different phases of the BSISO days relative to the non-BSISO days, as shown in Figure 3. The PDFs are illustrated as box plots consisting of the 5th (minimum), 25th (lower quartile), median, 75th (upper quartile), and 95th (maximum) percentiles. The PDFs are based on the average daily rainfall from all stations that fall within each region. Although the western coast stations over the Luzon region experience higher rainfall amounts during the southwest monsoon season compared to the eastern coast stations, we found that the PDF over the Luzon region is not sensitive to the selection of stations. Specifically, the PDF is the same whether we generate it using the western coast stations only or from the average of all stations in the region (not shown).

Over the Luzon region, the median and 75th percentile of rainfall are skewed towards higher amounts between Phases 6 and 8 relative to the PDF of the non-BSISO days. The median and the 25th percentile of rainfall are skewed towards lower values between Phases 1 and 4. As previously mentioned, Olaguera *et al.* (2021) found that about 59% of the monsoon break cases over Luzon occurred between Phases 1 and 4 of the BSISO. Hence, the results of this study are consistent with their study. For the Visayas region, the median values and the 75th percentile are skewed towards higher values between Phases 5 and 7, while the median and the 25th percentile are skewed towards lower values between Phases 1 and 3 and during Phase 8 relative to the non-BSISO days. As for Mindanao region, the median and the 75th percentile are skewed towards higher values between Phases 4 and 6, while the median and the 25th percentile are skewed towards lower values between Phases 1 and 3, and Phases 7 and 8 relative to the non-BSISO days.

Figure 3 shows the spatial distribution of the changes in the frequency of extreme rainfall occurrence for the 95th percentile extreme by the BSISO phases. From Phases 1–4, the frequency of extreme rainfall occurrence decreases by about 20–80% in most parts of the Philippines relative to the non-BSISO days. The largest percentage decrease in the probability of extremes is more apparent between Phases 3 and 4 over the Luzon region. The probability of extreme rainfall occurrence apparently increases between Phases 4 and 8, starting from the south of 15°N, where it increases by about

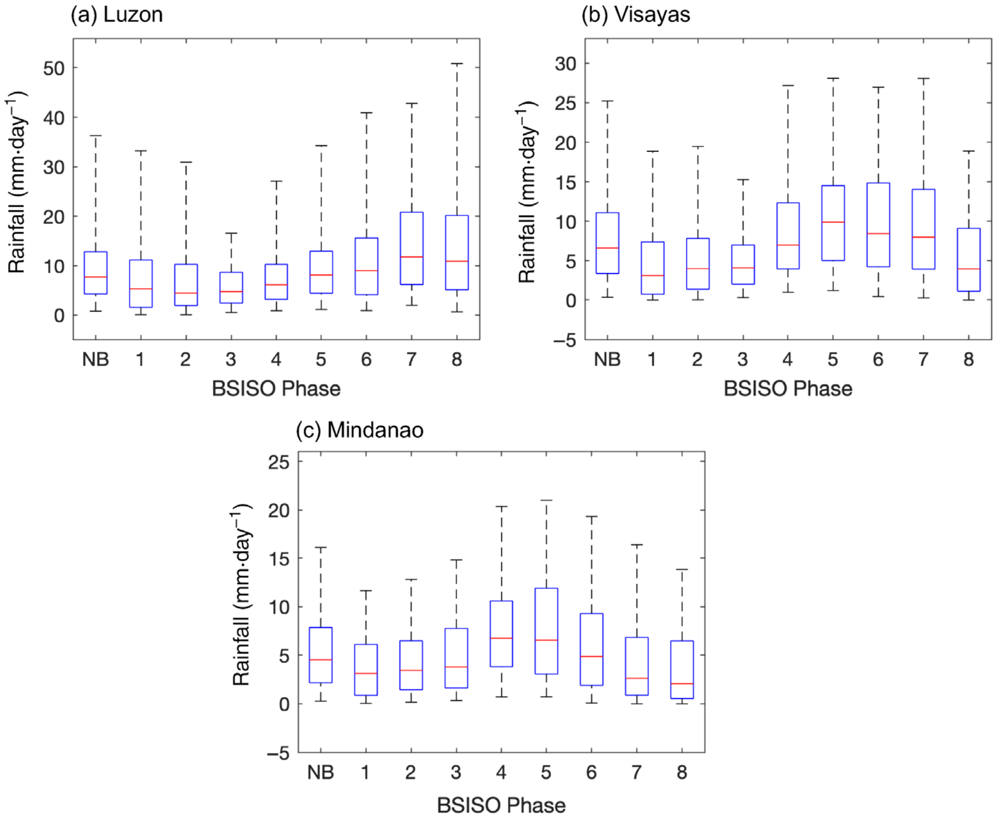

FIGURE 3 Probability distribution functions of average rainfall (mm·day^{-1}) over (a) Luzon, (b) Visayas, and (c) Mindanao regions for the eight BSISO phases and non-BSISO (NB) days [Colour figure can be viewed at wileyonlinelibrary.com]

20–60% in Phases 4 and 5. Between Phases 7 and 8, the probability of extreme rainfall occurrence increases by about 60–80% in stations located to the north of 12°N, especially along the west coast stations, and decreases to its south by about 20–60%. The spatial variation in the probability of extreme rainfall occurrence clearly demonstrates the overall northward/northwestward propagation characteristics of the BSISO as noted by Kikuchi *et al.* (2012) as well as the spatial differences in the timing of extreme heavy rainfall events in the Philippines.

3.2 | Relationship between BSISO and long-lasting flood events

On September 15–27, 2005, the central Luzon region including the areas along the Pampanga river experienced flooding due to heavy monsoon rains (https://earthobservatory.nasa.gov/images/15579/flooding-in-the-philippines) and further aggravated by the passage of Tropical Storm Damrey. There were 16 reported deaths and thousands of families displaced. The BSISO phase space diagram for this event (Figure 4) shows that it coincidentally occurred during Phases 6–8. Based on Figure 3, the extreme events are favoured over the Luzon region in these phases. Over the Mindanao region, we also found multiple heavy rainfall/flood events that coincidentally occurred during the active phase of the BSISO. One such case occurred on June 5–21, 2011 (Figure 5) and flooding was reported in some parts of Mindanao region (https://reliefweb.int/sites/reliefweb.int/files/resources/Full_Report_1263.pdf). This flood event was triggered by continuous rain and a low-pressure area to the east of Mindanao region. Coincidentally, this flooding event occurred during Phases 4–6.

We also checked all the flooding events over the three regions from 1979 to 2018 based on the DFO archive. We only selected those events that lasted for at least seven consecutive days. We plotted the reported starting dates listed in the DFO archive together with their corresponding BSISO phases and amplitudes in Figure 6, separately for Luzon (a), and Visayas and Mindanao (b). Only the flooding cases that coincidentally occurred during the strong phase of the BSISO are discussed. The two flooding cases discussed previously are also included in this figure.

TCs are one of the synoptic systems that induce extreme rainfall and flooding events over the Philippines. To determine the possible relationship between TCs and flooding events under the different phases of the BSISO in the three regions, we classified the flooding cases from the DFO archive into TC and non TC-related cases, as

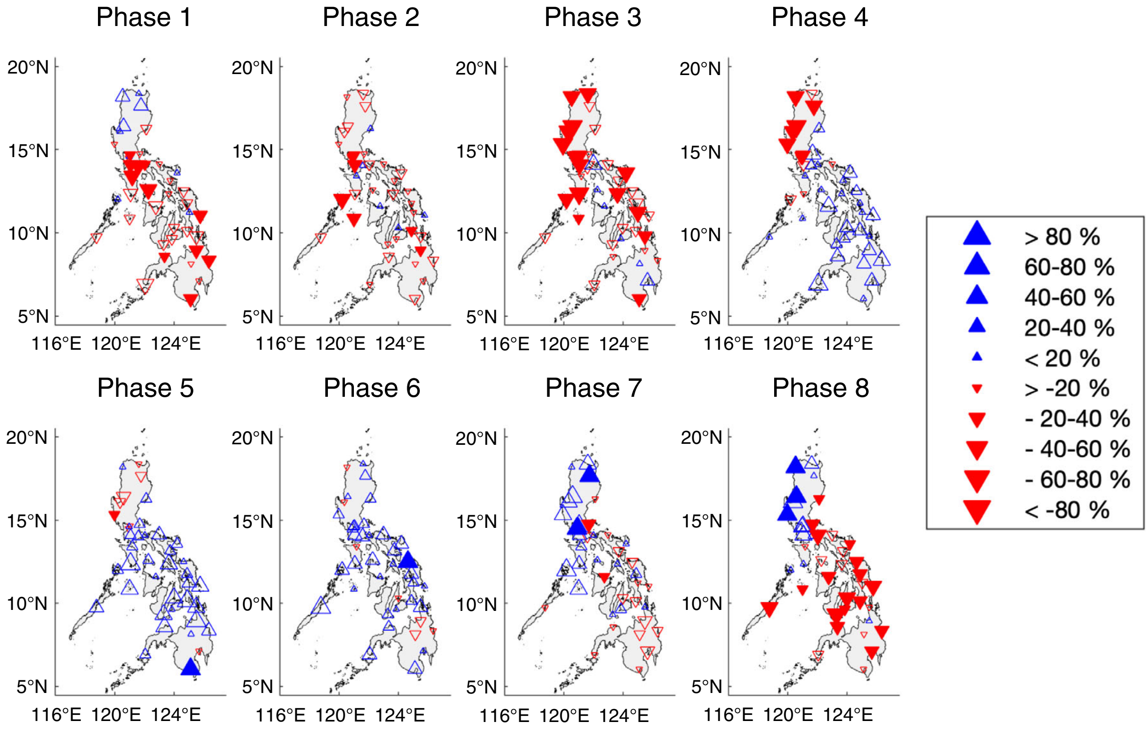

FIGURE 4 Percentage changes in the probability of rainfall at the 95th percentile extremes for the eight phases of the BSISO. Upwards (downwards) triangles indicate increase (decrease). Shaded triangles indicate stations that exceed the 95% confidence level [Colour figure can be viewed at wileyonlinelibrary.com]

shown in Figure 6. The contribution of TCs to the extreme rainfall events under different phases of BSISO are further examined in section 3.4.2.

There are 13 cases that are associated with TCs and 10 cases that are non-TC-related (i.e., due to torrential rain, heavy rain, or monsoonal rain) in the long-lasting flooding events over the Luzon region (Figure 6a). There are five TC-related and four non-TC-related flooding cases that occurred between Phases 6 and 8. These accounts for about 39% of the total flooding cases (23) over the Luzon region. On the other hand, there is one TC-related flooding case during Phase 2 and two non-TC-related flooding cases that occurred during Phase 1. It is worth mentioning that some parts of northern Luzon region still experience higher probability of extreme rainfall occurrence during Phase 1 as shown in Figure 4. The single TC case that occurred during Phase 2 is associated with Typhoon Fung-Wong (2002) that developed over the western North Pacific on July 19, 2002, moved westward/northwestward towards the northeastern Philippines, and dissipated over southern Japan on July 27, 2002. The flooding event over the Luzon region started on July 20, 2002 according to the DFO archive when the TC was located to the east of 140°E (not shown). Hence, this illustrates the TC–monsoon interaction, as examined by Cayanan *et al.* (2011). There is no reported flooding case over the Luzon region during Phase 3, which is consistent with Figure 4, when the probability of extreme rainfall occurrence is very low. There are two TC-related and one non-TC-related flooding cases that occurred between Phases 4 and 5. Note that during these phases, the probability of extreme rainfall occurrence starts to increase again over the Luzon region (Figures 3 and 4).

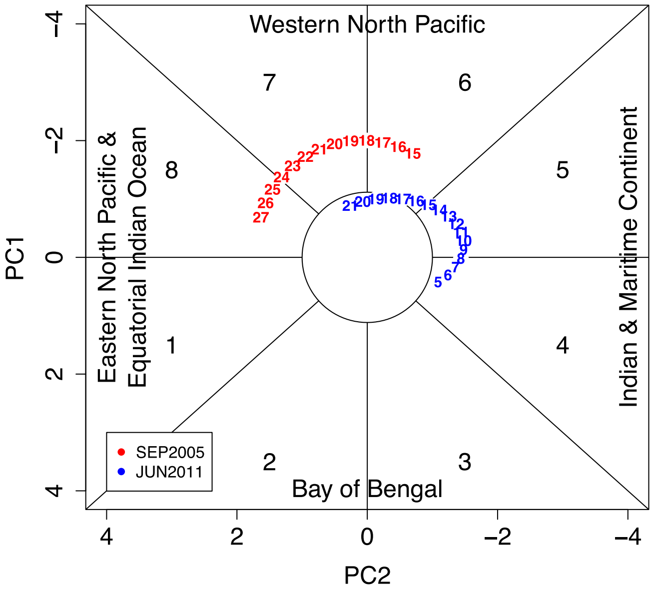

FIGURE 5 Flood events that occurred on September 2005 over the Luzon region and June 2011 over the Mindanao region. The numbers indicate the days when the flood occurred [Colour figure can be viewed at wileyonlinelibrary.com]

Over the Visayas region, only one long-lasting flood event case was reported but under a weak BSISO. Over the Mindanao region (Figure 6b), there are about five non-TC-related cases, three of which occurred between Phases 4 and 5, which is consistent with those in Figures 3 and 4. These flooding cases over the Mindanao

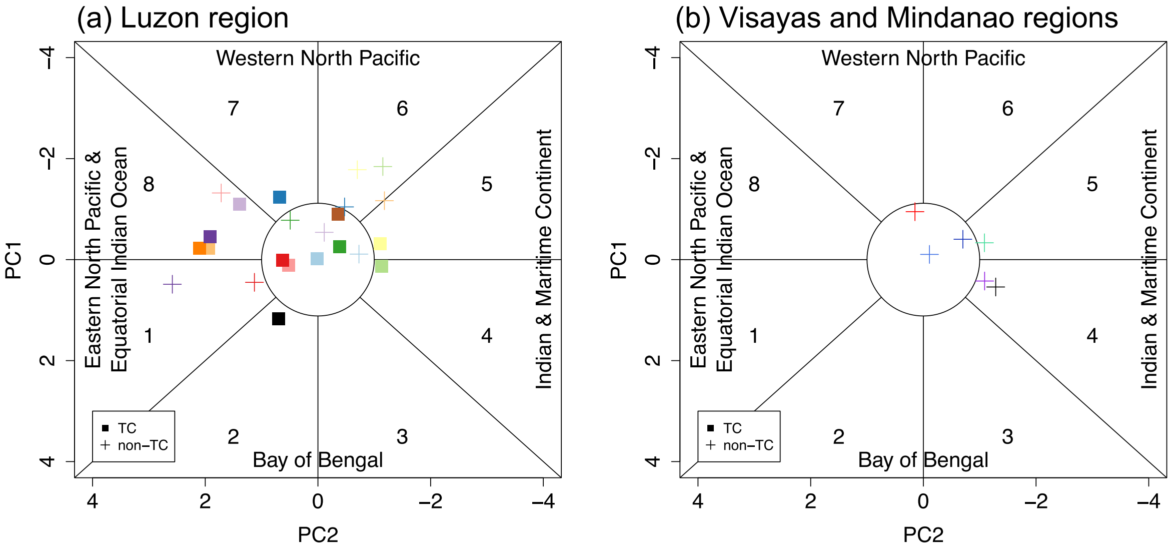

FIGURE 6 As in Figure 5 but for all the long-lasting flood events (≥7 days) recorded by the Dartmouth Flood Observatory from 1979 to 2018 over (a) the Luzon region (cross marks: non-TC-related; shaded squares: TC-related) and (b) the Visayas (red) and Mindanao (blue, purple, light blue, orange, cyan, and black) regions. Only the first days of the flooding events are shown. The colours of the symbols indicate unique events. All days in (b) are not TC-related [Colour figure can be viewed at wileyonlinelibrary.com]

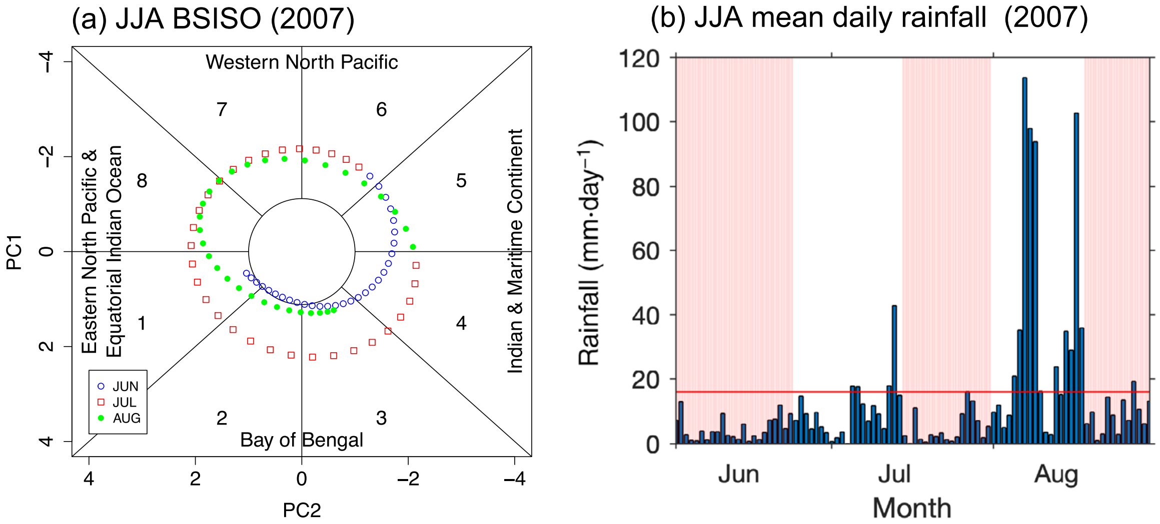

FIGURE 7 (a) Phase-space diagram from June 1, 2007 to August 31, 2007 (JJA) and the corresponding (b) daily rainfall (mm·day^{-1}) time series averaged across the eight PAGASA stations located on the western coast of the Luzon region (Laoag, Vigan, Dagupan, Iba, Science Garden Ambulong, Coron, and Baguio stations). The horizontal line in (b) is the climatological southwest monsoon daily rainfall across the eight PAGASA stations from 1981 to 2010 (JJAS; mm·day^{-1}). Shaded days in (b) indicate Phases 1–4 of the BSISO [Colour figure can be viewed at wileyonlinelibrary.com]

region account for about 30% of the total flooding cases over the Visayas and Mindanao regions.

3.3 | Relationship between BSISO and the June–July 2007 dry spell over Luzon region

As previously noted, Yumul Jr *et al.* (2010) examined the dry weather condition that persisted for 2 months (i.e., a dry spell) over the Luzon region from early June to July 2007. They suggested that this is due to the westward extension of the WNPSH that suppressed convective activities and TCs over the Luzon region and non-northward migration of the Inter Tropical Convergence Zone. Olaguera *et al.* (2021) examined the monsoon breaks following the southwest monsoon onset over Luzon region from 1979 to 2017 and found that most of their identified breaks coincided with the suppressed phase of the BSISO (Phases 1–4). Motivated by these findings we therefore examined the possible role of the BSISO in inducing the dry weather condition during the southwest monsoon season of 2007.

Figure 7a shows the BSISO phase-space diagram from June 1, 2007 to August 31, 2007, while Figure 7b shows the average daily rainfall from the eight PAGASA stations (Laoag, Vigan, Dagupan, Iba, Science Garden Ambulong, Coron, and Baguio stations) located on the western coast of the Luzon region. These stations are similar to those used by Cruz *et al.* (2013) and Olaguera *et al.* (2021) in characterizing the southwest monsoon season of the Philippines. From June 1–24, the active convection of the BSISO is located over the Bay of Bengal and convection is suppressed over the western North Pacific. In these days, the rainfall over the Luzon region is lower than 20 mm·day^{-1}. An increase in rainfall occurs between June 25 to July 14, when the active convection of the BSISO is located over the western North Pacific (Phases 5–8). One TC (Typhoon Man-Yi (2007); not shown) developed between these dates and traversed over the eastern Philippines. However, the rainfall brought by this TC was not sufficiently large and still below the climatological rainfall values (Figure 7c). A decrease in rainfall occurs from July 15 to August 1 when the active (suppressed) convection of the BSISO is over the Bay of Bengal (western North Pacific) again. These results indicate that the suppressed phases (Phases 1–4) of the BSISO over the western North Pacific may lead to suppressed rainfall over the Luzon region. In addition, higher rainfall amounts were only observed when the active convection of the BSISO is located over the Indian/Maritime Continent and western North Pacific regions (Figure 7a). These results are consistent with Figures 3 and 4.

3.4 | Possible mechanisms for the occurrence of rainfall extremes

3.4.1 | The role of moisture convergence and divergence

Hsu *et al.* (2016) noted the importance of moisture convergence (divergence) in providing favourable (unfavourable)

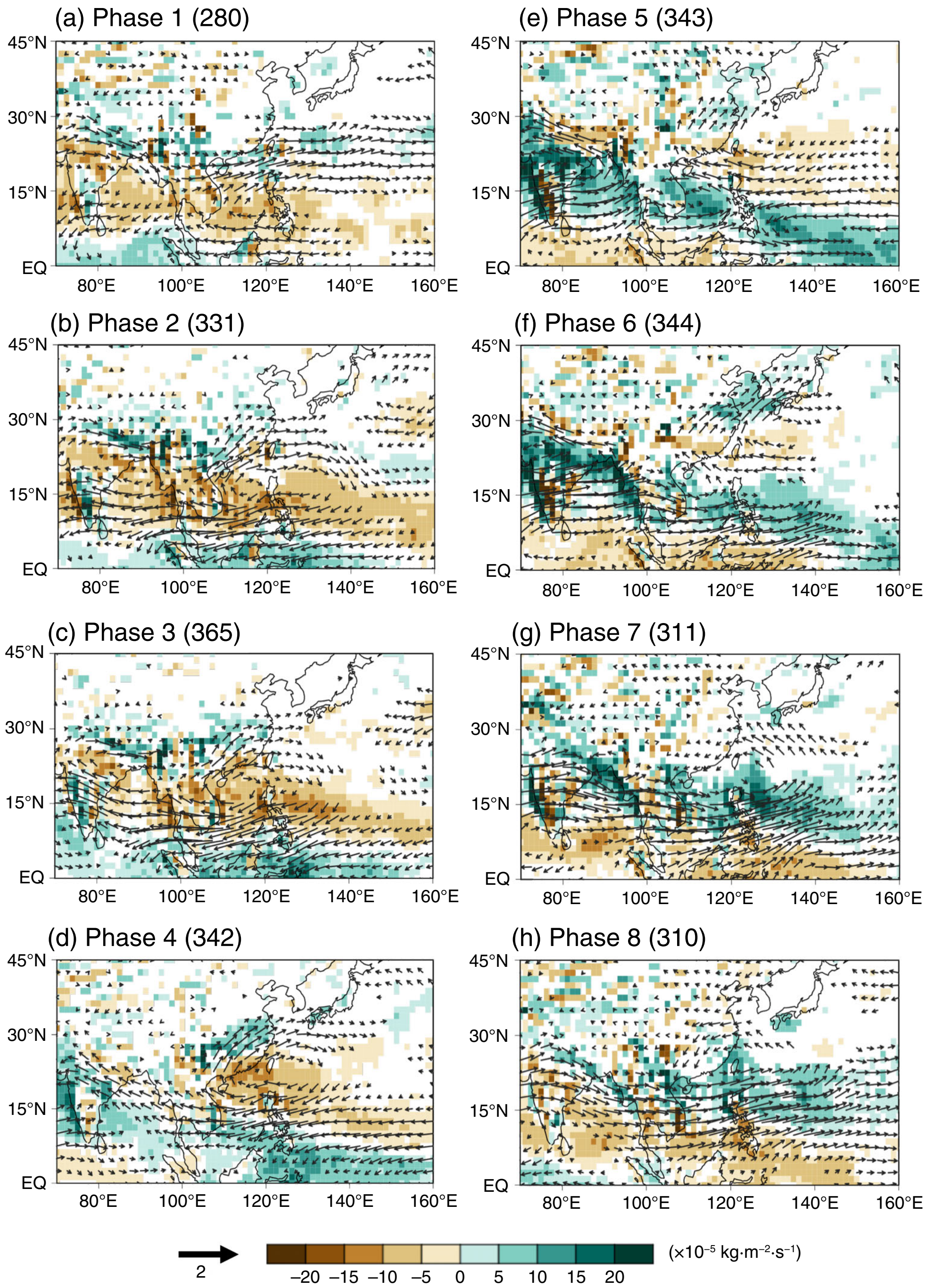

FIGURE 8 Composites of vertically integrated moisture flux convergence (VIMFC; shades; $\times 10^{-5}$ kg·m^{-2}·s^{-1}) and 850 hPa winds (vectors; m·s^{-1}) in the eight phases of the BSISO relative to the non-BSISO days. The scale of the wind vectors is 2 m·s^{-1}. Only the fields that exceeded the 95% confidence level using *t*-test are shown. The number of days used for the composites are shown in the figure titles [Colour figure can be viewed at wileyonlinelibrary.com]

conditions for the occurrence of extreme rainfall events. Therefore, in this section we examined the changes in column-integrated (from 1000 to 300 hPa) moisture flux convergence (VIMFC) during the different BSISO phases, as shown in Figure 8.

An anticyclonic circulation anomaly can be depicted over the entire Philippines between Phases 1 and 3 (Figure 8a–c), which is accompanied by a northwest–southeast oriented region of enhanced divergence, extending from 20°N over the Indian subcontinent to the near equatorial region in the western Pacific. During Phase 1 (Figure 8a), significant VIMFC can be seen over the northern tip of Luzon Island associated with the enhanced southwesterlies in this region. These results are consistent with those depicted in Figure 4, with suppressed probability of occurrence of extreme rainfall events in most parts of the country, while enhanced probability of occurrence of extremes are confined to the north of Luzon region. The anticyclonic circulation anomaly over the Philippines is replaced by a cyclonic circulation anomaly and enhanced VIMFC begins to appear from the Mindanao region from Phase 4 to Phase 6

TABLE 1 Percentage (%) of days that are induced by TCs for the eight phases of the BSISO and for the three regions in the Philippines

	BSISO TC days			Total TC days (BSISO + non-BSISO)		
Phase	**Luzon**	**Visayas**	**Mindanao**	**Luzon**	**Visayas**	**Mindanao**
1	20.00	10.71	10.71	50.00	41.67	46.15
2	16.01	9.67	5.44	55.79	44.44	32.14
3	9.04	6.30	5.75	36.26	31.08	32.81
4	15.50	14.62	13.16	45.69	52.63	47.37
5	25.95	23.32	20.41	48.90	62.02	61.40
6	29.65	23.55	18.90	53.68	53.64	56.52
7	35.37	22.19	12.54	50.23	50.36	48.15
8	36.45	14.52	14.19	52.31	45.00	51.16

Note: Columns 2–4 are for the BSISO TC days relative to the total BSISO days. Columns 5–7 are for the BSISO TC days relative to the total TC days (BSISO TC days + non-BSISO TC days).

(Figure 8d–f). Notice that this cyclonic circulation anomaly favours the enhancement of monsoon southwesterlies over the Philippines. During Phase 7 (Figure 8f), this cyclonic circulation anomaly progresses northwards and the Visayas and Mindanao regions experience weakened VIMFC and suppressed probability of extreme rainfall occurrence. During Phase 8 (Figure 8h), enhanced VIMFC is only confined around the Luzon region, especially on the west coast, which is induced by the southern edge of the cyclonic circulation anomaly to the north. During Phases 7 and 8, there are weakened VIMFCs over the central and eastern Luzon region, although there are enhanced mean rainfall and extremes in these phases in some stations, as shown in Figure 4. This discrepancy maybe associated to the limitation of the reanalysis data used in this study and local processes interacting with the BSISO circulation regardless of the weakened VIMFCs. This discrepancy warrants further clarification using higher resolution data sets in future works. In general, the increase in the probability of extreme rainfall occurrence appears to follow the regions of enhanced VIFMC and northward progression of the associated cyclonic circulation anomalies.

3.4.2 | The contribution from tropical cyclones

It was demonstrated in section 3.2 that TCs are one of the causes of extreme rainfall events in the country. In this section, we examined the contribution of TCs in each phase.

The following two criteria based on Wang *et al.* (2020) should be satisfied in order for an extreme rainfall day to be considered as TC-induced: (a) the distance between the station and TC centre is less than 1,000 km (e.g., Kubota and Wang, 2009) and (b) the difference between the date of the TC tracks and the occurrence time of the extreme rainfall is within ±1 day. This methodology was applied in each station. The consolidated dates for each region were then matched with those dates in each phase of the BSISO and non BSISO days. The percentage of BSISO days that were identified as TC-induced (i.e., BSISO TC days) are summarized in Table 1. We included the percentage of BSISO TC days relative to the total TC days (i.e., BSISO + non-BSISO TC days) to further elucidate how much the 30–60-day mode of the BSISO account for the total TC influence on rainfall.

More than 25% of the extreme rainfall days over the Luzon region are TC-induced between Phases 5 and 8. The lowest percentage occurred on Phase 3 (~9%). Over the Visayas region, the highest percentage also occurs between Phases 5 and 7 (~22–23%), while is it is between Phases 5 and 6 over the Mindanao region (~18–20%). The lowest percentage can be seen between Phases 2 and 3 over the Visayas and Mindanao regions (<10%), respectively. Another interesting result is that the contribution of TCs appear to be more dominant over the Luzon region compared to the Visayas and Mindanao regions, where the total TC-related extreme rainfall days do not exceed 24% in all phases. Relative to the total TC days, about 50–55% are accounted by the BSISO between Phases 6–8 and 1–2 over the Luzon region, while 50–62% between Phases 4 and 7 over the Visayas region. On the other hand, 50–60% of the total TC days are accounted by the BSISO between Phases 5 and 6 and in Phase 8 over the Mindanao region.

All long-lasting flooding events over the Mindanao region depicted in Figure 6b are not TC-related. Kubota and Wang (2009) showed that TC rainfall contribution during July–September exceeds 40% in northern Luzon, while it decreases southwards and is less than 10% over

Mindanao region according to their Fig. 4. The higher TC contribution over Luzon found in this study is consistent with their results.

4 | SUMMARY AND DISCUSSION

This study examined the statistical relationship between the northward/northwestward propagating 30–60-day mode of the BSISO and the probability of occurrence of rainfall extremes over the Philippines. Previous studies have demonstrated the impact of the BSISO on the diurnal cycle of rainfall (e.g., Natoli and Maloney, 2019; Riley-Dellaripa *et al*., 2020) and monsoon break occurrence (e.g., Olaguera *et al*., 2021) in the Philippines. In this study, we found that the BSISO can also modulate the occurrence of large-scale heavy rainfall events and dry weather conditions in the country.

We divided the Philippines domain into three regions: Luzon region (13°–22°N), Visayas region (10°–13°N), and Mindanao region (5°–10°N), to account for the regional differences in the occurrence of extreme rainfall events. The changes in the circulation patterns, moisture processes, and TC activities were analysed to explain how the BSISO modulates the occurrence of extreme rainfall events. The results show that the probability of occurrence of extreme rainfall events for the 95th percentile extremes increase first in some parts of the Mindanao region by as much as 60% during Phases 4 and 5, relative to the non-BSISO days. The median of the PDFs of rainfall are above those during the non-BSISO days between Phases 4 and 6 (with the peak in Phase 4) in this region. On the other hand, the median values of the PDFs of rainfall are above those during the non-BSISO days between Phases 4 and 7 (with the peak in Phase 5) over the Visayas region. The probability of occurrence of extreme rainfall events increases by as much as 80% during Phase 5 in some of the stations in this region. Over the Luzon region, the PDFs of rainfall are above those during the non-BSISO days between Phases 5 and 8, with the peak occurring in Phase 7. The probability of occurrence of extreme rainfall events increases by as much as 80% in some of the stations in this region between Phases 7 and 8. The decrease in the probability of extreme rainfall occurrence occurs first over the south of 15°N during Phase 8 (20–60%) and progresses northwards until Phase 4. The analysis of the large-scale circulation features and moisture processes reveal that the BSISO can modulate the moisture convergence (divergence) fields that provides favourable (unfavourable) environment for the occurrence of extreme rainfall events. As the cyclonic (anticyclonic) circulation anomalies associated with the BSISO propagate northwards from the equatorial region to the north of the Philippines, moisture convergence (divergence) also propagates northwards and the regions with increased (decreased) extreme rainfall events appear accordingly. Similar spatial patterns in the moisture convergence and divergence fields over the Philippines found in this study were also observed during the active phases of the eastward propagating MJO (i.e., Phases 5–7 in Fig. 3 of Bagtasa, 2020). In these phases of the MJO, the WNPSH weakens, a cyclonic circulation anomaly cantered to the north of the Philippines is established, enhanced southwesterly flow is apparent to the south of this cyclonic circulation anomaly, and enhanced rainfall can be found over the Philippines (see Bagtasa, 2020, Fig. 3). During the inactive phases of the MJO, an anomalous anticyclone cantered to the north of the Philippines is established, enhanced moisture divergence, and suppressed rainfall can be found over the country. He further noted that the leading edge of the MJO also provides favourable conditions for TC activity and contributes to the enhanced rainfall over the northwestern region of the Philippines.

We examined the long-lasting (i.e., ≥7 days) historical flood events documented by the DFO in each phase of the BSISO. About 39% (9 out of 23) of these long-lasting flood events occurred between Phases 6 and 8 over the Luzon region. No long-lasting events associated with a strong BSISO phase occurred over the Visayas region. Over the Mindanao region, about 30% of the long-lasting flood events occurred from Phases 4 to 6.

We also examined the June–July 2007 dry spell over Luzon region and found that the days with low rainfall amounts coincided with the suppressed BSISO phases (Phases 1–4) over the western North Pacific. This result corroborates the results found by Olaguera *et al*. (2021) who demonstrated that the majority of the post onset monsoon break cases over the Luzon region occur during the suppressed phases of the BSISO over the western North Pacific.

TCs are one of the synoptic systems that contribute to the extreme rainfall events in the Philippines (e.g., Cinco *et al*., 2016; Bagtasa, 2020). Further examination of all the extreme days in each phase shows that about 25–36% of the extreme days between Phases 5 and 8 were TC-induced. The total TC-induced extreme rainfalls days over the Visayas and Mindanao regions are both less than 24% of the total BSISO days, indicating less TC influence in these regions. Moon *et al*. (2018) showed that the TC genesis frequency over the western North Pacific is enhanced in these phases (see their fig. 1). They found that the mid-tropospheric vertical motion is the most dominant large-scale factor that controls TC genesis frequency during the Northern Hemisphere summer in these phases. Other important factors are the vertical wind shear and low-level relative vorticity. Previous studies such as those by Ritchie and Holland (1999) and Yoshida and Ishikawa (2013) identified five large-scale patterns that affects TC genesis over the western North Pacific. These are the monsoon shearline (SL), monsoon confluence region (CR), monsoon Gyre (GY), easterly wave (EW), and pre-existing TC (PTC). Yoshida and Ishikawa (2013) examined about 908 TC genesis cases from 1979 to 2008 and found that the SL has the largest contribution to the TC genesis in their study period. Yoshida *et al*. (2014) examined the impact of the BSISO on the TC genesis frequency over the western North Pacific in relation to these five large-scale flow patterns. They found that the Phases 5–8 of the BSISO provided favourable conditions for more TC generation over the western North Pacific, with the highest number of TCs generated during Phase 7. These results are consistent with Table 1 in this study, with more TC-induced extreme events over Luzon Island between Phases 5 and 8. The results of Yoshida *et al*. (2014) further show different dominant flow patterns in each phase. The EW and GY flow patterns were found to be the dominant flow patterns between Phases 5 and 6, while the SL and CR flow patterns are the dominant patterns between Phases 7 and 8. They also found that the large-scale westerly wind is enhanced to the west of the mean TC genesis position between Phases 7 and 8 during the active BSISO. They suggested that stronger SL and CR are induced around the mean TC genesis location due to the enhanced westerly winds.

Some studies found that the BSISO can also modulate temperature extremes (e.g., Chen and Zhai, 2017; Hsu *et al*., 2017). For example, Chen *et al*. (2017) found that enhanced rainfall extremes occur over the central-eastern China, while a simultaneous fourfold to fivefold increase in temperature extremes occur in southeast China during the active phases of the BSISO. They suggested that this is related to the vertical cells induced by the BSISO, with its ascending branch located over the central-eastern China and descending branch to the south. Whether the BSISO induce similar changes in temperature over the Philippines requires further investigation. Ren *et al*. (2018) demonstrated that the BSISO modulation on rainfall extremes can be predicted up to 2 weeks in advance using the Climate Forecast System and suggested the possibility for developing a medium-to-extended-range probabilistic forecast. This aspect is also of great interest and importance and will be explored in future studies.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

AUTHOR CONTRIBUTIONS

John Asaula Manalo: Conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; writing – original draft; writing – review and editing. **Jun Matsumoto:** Supervision; writing – original draft; writing – review and editing.

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