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Lyndon Mark P. Olaguera

Jun Matsumoto

John A. Manalo

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RESEARCH ARTICLE

The contribution of non-tropical cyclone vortices to the rainfall of the Philippines

Lyndon Mark P. Olaguera[1,2,3] | **Jun Matsumoto**[3,4] | **John A. Manalo**[3,5]

[1]Department of Physics, Ateneo de Manila University, Quezon City, Philippines

[2]Regional Climate Systems Laboratory, Manila Observatory, Ateneo de Manila University, Quezon City, Philippines

[3]Department of Geography, Tokyo Metropolitan University, Tokyo, Japan

[4]Center for Coupled-Ocean-Atmosphere Research, Japan Agency for Marine Earth Science and Technology, Yokosuka, Japan

[5]Department of Science and Technology, Philippine Atmospheric, Geophysical and Astronomical Services Administration, Quezon City, Philippines

Correspondence

Lyndon Mark P. Olaguera, Department of Physics, Ateneo de Manila University, Loyola Heights, Quezon City 1108, Philippines.

Email: lolaguera@ateneo.edu

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Abstract

Weaker disturbances than tropical cyclones (TCs) such as tropical depressions and cold surges can significantly induce heavy rainfall and flooding events over the Philippines. However, the analysis of these disturbances including their rainfall contributions are often neglected in previous studies. As the first attempt to address this research gap, this study investigates the rainfall contribution of non-TC vortices over the Philippines from 1979 to 2020. Only those rainfall-producing non-TC vortices that formed and appeared within a 500-km radius from the Philippine coastline were examined in this study. A total of 7,686 non-TC vortex days (50% of the total days during the analysis period) were identified. The mean rainfall contribution of these non-TC vortices was found to be highest over the northeastern Mindanao Island (80–90% of the mean daily rainfall) and lowest over the central and western regions of Luzon Island (50–60%). Seasonal analysis of the occurrence frequency of these vortices shows that they are most frequent during the December–February (DJF) season. In this season, the rainfall contribution may increase to 50–80% of the mean daily rainfall over the whole country, while in the other seasons, the rainfall contribution may only increase to as much as 60%. Higher frequency of extreme rainfall days associated with these non-TC vortices were also found during the DJF season. The frequency of occurrence and percentage rainfall contribution of these non-TC vortices in relation to the different phases of the Boreal Summer Intraseasonal Oscillation (BSISO) during boreal summer (June–October) and the Madden–Julian Oscillation (MJO) during boreal winter (December–April) were also examined. Higher frequency and percentage rainfall contribution over the country were found during Phases 4–6 of both the BSISO and MJO, during which their respective active convections transition from the Maritime Continent to the western North Pacific.

KEYWORDS

Boreal Summer Intraseasonal Oscillation, cold surge vortex, low-pressure system, Madden–Julian Oscillation, tropical depression, tropical vortex

1 | INTRODUCTION

Tropical vortices in the Northern Hemisphere generally refer to cyclonic and rainfall-producing disturbances such as low-pressure systems including tropical cyclones (TCs) (Olaguera, Matsumoto *et al.*, 2021; You and Ting, 2021), cold surge vortices (CSVs) (Chen *et al.*, 2012a; 2012b; 2013; 2015a; 2015b), tropical depression (TD)-type disturbances (Yokoi and Matsumoto, 2008), and the Borneo vortex (Tangang *et al.*, 2008; Koseki *et al.*, 2014). The impact of these vortices, particularly those forming over the South China Sea (SCS), has been examined in earlier works of Cheang (1977) and Chang *et al.* (1979). More recent studies have elucidated the formation mechanism, westward propagation tendency, and preference in location and time of formation including those forming over the Philippine Sea (Chen *et al.*, 2012a; 2012b; 2013; 2015a; 2015b). These vortices were found to induce heavy rainfall and flooding (HRF) events and significantly contribute to the total rainfall over the tropical region (Cheang, 1977; Tangang *et al.*, 2008; Yokoi and Matsumoto, 2008; Chen *et al.*, 2012a; 2012b; 2013; 2015a; 2015b; Basconcillo and Moon, 2021). Chen *et al.* (2013) found that the CSVs contribute by about 33% to the total November–December rainfall over Peninsular Malaysia and about 34% to the total December–February rainfall over west Borneo. Hence, understanding their variability is not just important for disaster mitigation but also for the management of hydrological resources.

Nguyen *et al.* (2016) used the term Southeast Asian Sea-Maritime Continent vortices or SMVs to refer to these vortices within the Southeast Asia-Maritime Continent region (SEAMC; 10°S–25°N, 100°–120°E). They also quantified the rainfall induced by these SMVs and separated those induced by TCs and non-TCs over the SEAMC region. Their results showed that the contribution of non-TC vortices to the total rainy days during the period 1979–2010 is about 50–55%, while those related to TCs is about 10–20% over the southern coast of Vietnam. Chen *et al.* (2015a, 2015b) examined the formation mechanism of westward propagating CSVs, a non-TC vortex, over the SCS and the Philippine Sea. These CSVs are more common in winter and are formed by the interaction of the East Asian cold surges and easterly waves. Chen *et al.* (2015a) further classified these vortices to those forming over Borneo (in situ) and over the Philippine Sea. These vortices may propagate westward causing HRF events along their paths such as over the Indochina Peninsula and the Philippines, respectively. The presence of a surface island-chain trough and near-equatorial trough were found to be important for the formation location of these CSVs.

Heavy rainfall and strong winds associated with tropical vortices often lead to catastrophic damages to infrastructure, agriculture, and loss of human lives. For example, strong TCs (i.e., TCs with intensities of at least TS category and above) are more frequent during the June–October season. Tropical vortices that are weaker than TCs (i.e., TDs, low-pressure systems, CSVs, etc.) occur year-round but are more frequent during the boreal winter season (i.e., November–March). These weaker TCs also cause heavy rainfall and catastrophic damages (Rodolfo *et al.*, 2018; Olaguera, Matsumoto *et al.*, 2021; Olaguera, Caballar *et al.*, 2021). However, they are not well examined compared to stronger TCs. One reason is the uncertainty in the available TC track data sets. TDs and other less intense disturbances are often excluded due to lack of available wind information for these disturbances, while some meteorological agencies do not include them in their archives. These issues are further discussed by Hodges *et al.* (2017). Cheang (1977) examined the synoptic conditions during a heavy rainfall event in Peninsular Malaysia that is associated with westward propagating CSVs in December 1973. He found that the lateral shear is an essential factor for its formation, while its intensity is mainly dependent on its interaction with the cold surge. Yokoi and Matsumoto (2008) examined an HRF event over central Vietnam that occurred in November 1999. They found that the southerly anomalies from a westward propagating TD-type disturbance to the south of Vietnam interacted with the cold surge to the north of Vietnam, leading to the HRF event. A similar synoptic situation when a westward propagating vortex interacted with the northeasterly flow associated with a cold surge was found by Ogino *et al.* (2018) during their field observation campaign in December 2012 over the Philippine Sea. This westward propagating vortex and the cold surge formed a convergence region to the east of the Philippines and were found to have brought the rainfall along the eastern coast of the country. Olaguera, Matsumoto *et al.* (2021) examined an HRF event that occurred in January 2017 that led to urban flooding over Cagayan de Oro City in Mindanao Island, southern Philippines. This HRF event was caused by a westward propagating low-pressure system over the island that interacted with a cold surge. Olaguera, Manalo *et al.* (2022) examined the long-lasting flood events over the Philippines in relation to the different phases of the boreal summer intraseasonal oscillation (BSISO). One such flood event occurred in June 2011 over Mindanao Island, which has been associated with a continuous rainfall enhanced by a low-pressure system to its east (https://reliefweb.int/sites/reliefweb.int/files/resources/Full_Report_1263.pdf). This event coincidentally occurred during an active phase of the BSISO over Mindanao Island (i.e., Phases 4–6 of the BSISO). Yoshida *et al.* (2014) showed that the BSISO can modulate the

TC genesis frequency over the western North Pacific. During the boreal winter season (i.e., December–April), the Madden–Julian Oscillation (MJO) is the dominant eastward propagating ISO, which can interact with the cold surges and bring heavy rainfall to the east of the Philippines and the rest of Southeast Asia (e.g., Pullen *et al.*, 2015; Lim *et al.*, 2017, Olaguera, Caballar *et al.*, 2021). For example, Pullen *et al.* (2015) examined the unusual winter from November 2007 to March 2008 over the Philippines. They found that the multiscale interaction of the MJO, the existing La Niña condition, and a cold surge led to the extreme rainfall event over the country during this period. This example clearly demonstrates the complexity of extreme rainfall events in the country (Olaguera, Cruz *et al.*, 2022).

While Chen *et al.* (2012a, 2012b, 2013, 2015a, 2015b) examined the formation mechanism and preferred locations of winter time CSVs, only the rainfall contributions of these CSVs to the total winter time rainfall over the Indochina Peninsula, Peninsular Malaysia, and Borneo have been quantified in these studies. Chen *et al.* (2015a) identified cases of westward propagating CSVs that formed over the Philippine Sea and eventually led to HRF events over the Philippines, some of which stagnated to the east of SCS due to the strong northerly cold surges in this region that prevented them from propagating further westward. On the other hand, Nguyen *et al.* (2016) only examined the tropical vortices over the SEAMC region, which excludes the Philippines. The contribution of TCs to the total daily mean rainfall of the Philippines was quantified by Bagtasa (2017). However, this study excludes weaker TCs (i.e., TDs and below). Rodolfo *et al.* (2018) pointed out that TDs that are often ignored in most TC analysis can also bring catastrophic damages, especially to the southern Philippines. Nevertheless, about 50% of the total daily mean rainfall is induced by TCs over the northwestern portion of the country. The southern portion of the country experience less TC influence; thus, the TC rainfall contribution is also small (about 14%) (Bagtasa, 2017).

Based on the abovementioned literature, the contribution and impact of tropical vortices, particularly those with weaker intensities than TCs to the rainfall of the Philippines remains a research gap. Therefore, this study aims to examine the effect of tropical vortices, especially those that are not TC related to the rainfall of the country. Specifically, our main research questions are: (a) Which locations in the Philippines are mostly affected by these tropical vortices? and (b) What fraction of the total rainfall is associated with tropical vortices? The rest of the paper is organized as follows. Section 2 describes the different data sets and methodology used in this study. The main findings of the study are presented in section 3. A summary and discussions are provided in section 4.

2 | DATA AND METHODOLOGY

2.1 | Data

The following data sets from 1979 to 2020 were used in this study.

1. Daily rainfall data from 43 stations and provided by the Philippine Atmospheric Geophysical and Astronomical Services Administration (PAGASA). These stations have less than 20% missing data during the whole analysis period. These stations are shown in Figure 1.
2. Daily reanalysis data, with 1.25° × 1.25° grid resolution, of zonal (*U*) and meridional (*V*) winds at multiple levels from the Japan Meteorological Agency (JMA) 55-year reanalysis (JRA55; Kobayashi *et al.*, 2015). The relative vorticity was calculated from the *U* and *V* winds at 850 hPa using spherical harmonics, while the surface winds were derived from the *U* and *V* at 10-m from this reanalysis data set.
3. TC tracks from the Joint Typhoon Warning Center (JTWC), which can be accessed at https://www.metoc.navy.mil/jtwc/jtwc.html.
4. Daily bimodal index for the MJO and BSISO by Kikuchi (2020), which can be accessed at http://iprc.soest.hawaii.edu/users/kazuyosh/Bimodal_ISO.html. This index mainly captures the 30–60-day mode of the intraseasonal oscillations (ISOs) during the Northern Hemisphere summer and winter. The MJO index was used for the analysis during the December–April (DJFMA) season, when it is predominant, while the BSISO index was used for the analysis during June–October (JJASO) season.

2.2 | Methodology

The analysis period spans from 1979 to 2020. The days when a TC is located within 1,110 km from the coastline of the country (i.e., the TC days) were removed first. Bagtasa (2017) found that TCs can induce rainfall over the Philippines when their distance is at most 10° (∼1,110 km) from the Philippine landmass. This optimal radius was statistically determined from the relationship between the TC centre distance and total rainfall over the country. TCs were defined as those disturbances with intensities from tropical storm (TS) and above. Then, another spatial filter was applied to isolate the non-TC rainfall-inducing vortices in the country. The accurate centre positions of non-TC vortices are difficult to determine. Hence, the 1,100-km radius cannot be used. Nguyen *et al.* (2016) used a 500-km radius relative to the coast to filter

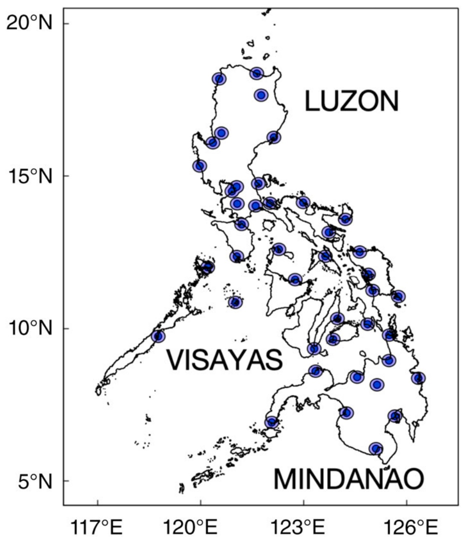

FIGURE 1 The three major island groups of the Philippines (Luzon, Visayas, and Mindanao) and the location of the 43 weather stations from PAGASA [Colour figure can be viewed at wileyonlinelibrary.com]

those non-TC vortices that could induce rainfall over Vietnam. The same radius in determining the impact of the non-TC vortices on rainfall was used in this study.

The non-TC vortex days were obtained using a modified methodology of Nguyen *et al.* (2016) from the daily JRA-55 data set. In their study, a non-TC vortex is said to exist at a particular grid point when the relative vorticity at 850 hPa is at least 1×10^{-5} s^{-1} and the 10-m wind speed at that grid point in the reanalysis data is at least 5 $m \cdot s^{-1}$. The average vorticity and wind speed of the four closest grid points should also meet these criteria. Hoskins and Hodges (2002) noted that relative vorticity is less sensitive to changes in the largescale fields, which makes it more suitable for weak and strong TC detection compared to mean sea level pressure and geopotential height.

In this study, we found that the 1×10^{-5} s^{-1} resulted in detected vortices that are difficult to distinguish from noise. Hence, the sensitivity of the detection method to the relative vorticity threshold was tested first. Previous studies that used relative vorticity for detecting TCs set the thresholds to 5×10^{-5} s^{-1} (e.g., Fudeyasu *et al.*, 2006). However, such high threshold cannot detect less intense TCs (e.g., Takahashi and Yasunari, 2008). We carefully checked the spatial maps of relative vorticity and winds, and checked the number of detected vortices using different thresholds between 1×10^{-5} and 5×10^{-5} s^{-1}. We found that the 3×10^{-5} s^{-1} threshold gave the most reasonable result (not shown). Finally, we used the 3×10^{-5} s^{-1} for the 850 hPa relative vorticity threshold and the 5 $m \cdot s^{-1}$ criteria for 10-m wind speed in detecting the non-TC vortices. When any grid point within 500 km from the Philippine coastline satisfies the abovementioned criteria in any day, then those days were considered as vortex days.

3 | RESULTS

3.1 | Seasonal and annual distribution of non-TC vortices

About 7,686 days (∼50% of the total days during the analysis period) were identified as non-TC vortex days from 1979 to 2020. Based on the JTWC best track data, about 186 (∼2%) of this non-TC vortex days are TD days (i.e., maximum sustained wind speed is lower than 34 knots) that came within 500 km from the coast of the country. This indicates that most of the non-TC vortices detected in this study maybe weaker disturbances such as low-pressure areas (LPAs) or CSVs. To further depict the location where these vortices are more frequent, the spatial distribution of the seasonal frequency of their occurrences relative to the total number of days in each season and within 500-km from the coastline of the country are shown in Figure 2.

It appears that the DJF season has the highest frequency of vortices with about 8–10% occurrences to the east of Mindanao Island and over the SCS. The northwestern part of Luzon Island also has the highest percentage of occurrence of about 18–20%. These vortices during the DJF season may be related to CSVs as discussed by Chen *et al.* (2012a, 2012b, 2013, 2015a, 2015b) that form over the Philippine Sea and SCS. During JJA, more vortices appear to the west and east of the country, with fewer occurrences over land. This means that most of these vortices do not make landfall over the country but may enhance the southwest monsoon flow (e.g., Cayanan *et al.*, 2011). The MAM season has the lowest percentage of occurrence with only about 4% occurrence to the east of Mindanao Island and about 6% to the northwest of Luzon Island. During SON, the percentage of occurrence of vortices increases again over the country, particularly to the west and eastern coasts. On the annual time scale, it is evident that more vortices appear to the west, northwest, and southeast of the country.

3.2 | Rainfall contribution of non-TC vortices

Figure 3 shows the percentage contribution of non-TC vortices to the mean daily rainfall from 1979 to 2020. On average, most stations to the east of the country receive higher rainfall amounts (6–10 $mm \cdot day^{-1}$) compared to the western coast stations because the rainfall in the former stations are brought by the southwest and northeast

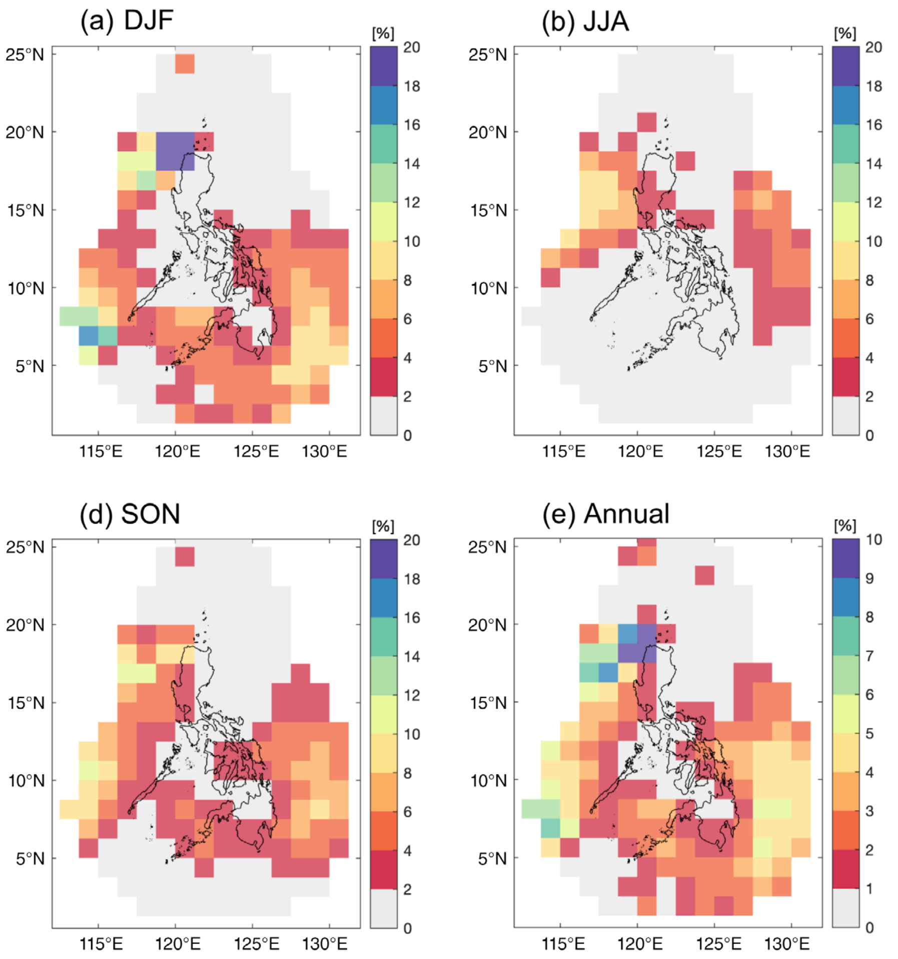

FIGURE 2 Spatial distribution of the seasonal frequency of occurrence of non-TC vortices relative to the total number of days in each season (%) for the (a) DJF, (b) MAM, (c) JJA, (d) SON, and (e) annual total. Only those vortices that came within 500-km from the Philippine coastline are shown here [Colour figure can be viewed at wileyonlinelibrary.com]

monsoons, and synoptic disturbances (Flores and Balagot, 1969). The rainfall contribution from non-TC vortices appears to be higher (4–10 mm·day^{-1}) on the eastern coast stations (Figure 3b). In general, non-TC vortices contribute by about 70–80% to the mean daily rainfall over the Visayas and Mindanao stations and 40–60% over most parts of Luzon Island.

We also quantified their contribution per season, as shown in Figure 4. Higher percentage contribution (60–80%) is more evident during the DJF season, particularly over the eastern coast stations. Their contribution in other seasons is about 20–60%, with larger contributions over the Visayas and Mindanao stations.

3.3 | Contribution of non-TC vortices to extreme rainfall

As previously mentioned, non-TC vortices may also cause heavy rainfall and flooding events over the country. These disturbances may bring rainfall amounts that are higher than the 95th percentile extreme rainfall thresholds (e.g., Olaguera, Manalo *et al.*, 2022). During boreal winter, it has been noted in section 1 that CSVs are the common disturbances that induce heavy rainfall and flooding events over the country in this season. During boreal summer, on the other hand, LPAs forming and appearing in the vicinity of the Philippines may bring heavy rainfall and flooding events. These LPAs may further develop into TDs and TCs. One flooding case identified by Olaguera, Manalo *et al.* (2022) occurred from June 5–21, 2011 (https://ndrrmc.gov.ph/2-uncategorised/1669-flooding-incidents-in-region-x-region-xi-region-xii-and-armm) that is associated with non-TC vortices. This flooding event was also recorded in the Dartmouth Flood Observatory Archive (https://floodobservatory.colorado.edu/Archives/index.html) and was caused by consecutive LPAs that later developed into TDs and TCs in the vicinity of the Philippines. In total, there were three LPAs during June 2011 that developed into TCs, which are TSs

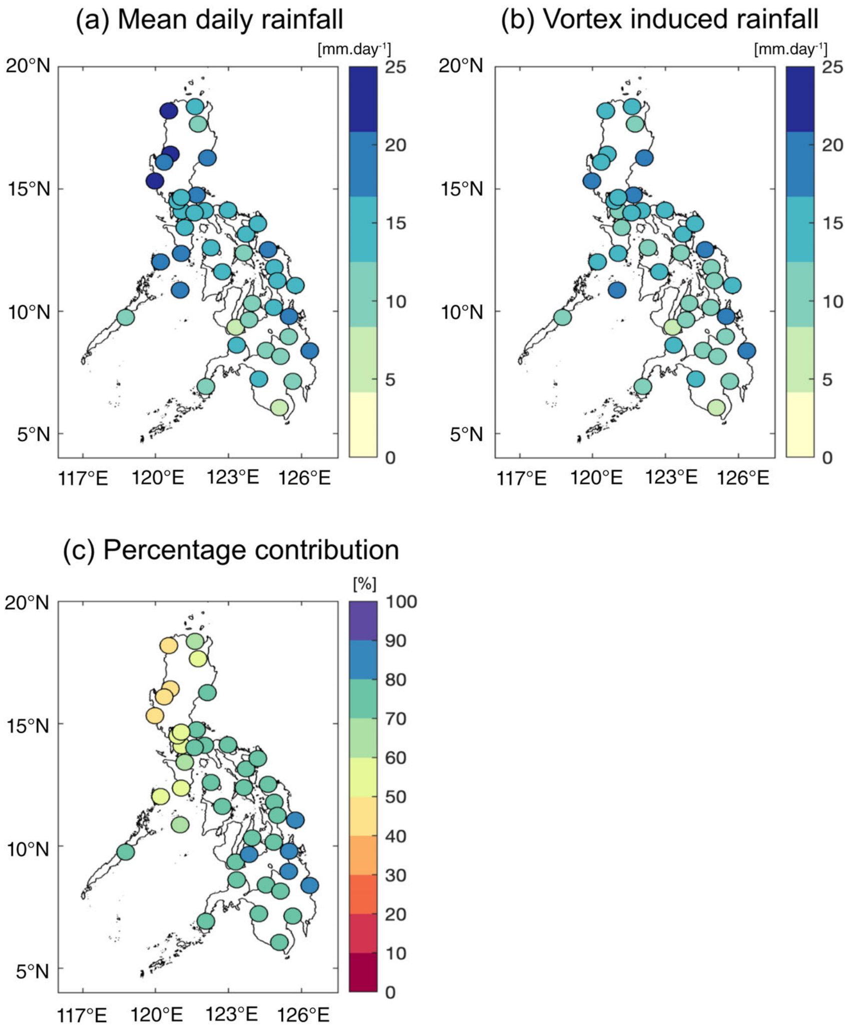

FIGURE 3 (a) Mean daily rainfall (mm·day^{-1}), (b) rainfall induced by the non-TC vortices (mm·day^{-1}), (c) percentage rainfall contribution by these vortices (%) [Colour figure can be viewed at wileyonlinelibrary.com]

Sarika, Haima, and Meari. The other LPAs during this period were short-lived but still brought rainfall over the country (not shown). Motivated by the abovementioned case, we examined the contribution of non-TC vortices to the extreme rainfall over the country in this section.

Extreme rainfall days were defined as the days with rainfall amounts above the 95th percentile in each station. We obtained the percentage contribution of non-TC vortices to the total extreme rainfall per season as shown in Figure 5. Higher percentage contribution of non-TC vortices to the extreme rainfall can be found during the DJF season. Some stations over Mindanao Island, particularly those located to the northeast and south as well as the northwestern most station in Luzon Island have about 90–100% of their extreme rainfall attributed to these vortices. The central and eastern coast stations of the country experience about 60–80% of their extreme rainfall due to these vortices in this season. During MAM season, about 20–50% of the extreme rainfall along the western coast of the country can be attributed to these vortices. The rest of the country experience at most 70% of their extreme rainfall due to these vortices in this season. As for JJA and SON, these vortices account for no more than 60% of the extreme rainfall over the whole country.

We further classified non-TC vortices into TDs and other weaker disturbances. TDs often cause catastrophic damages to the country (e.g., Rodolfo *et al.*, 2018). A very recent catastrophic event associated with TD 35 W (locally known as Usman) in late December 2018 demonstrates such case. This TD did not make landfall over the country but brought copious amounts of rainfall, particularly in CALABARZON (Cavite, Laguna, Batangas, Rizal, and Quezon), MIMAROPA (Mindoro, Marinduque, Romblon, and Palawan), Bicol Region, and eastern Visayas (NDRRMC, 2019). The estimated damage cost is more than 5.4 billion PhP (∼102 million USD), while there were 156 reported deaths and 26 missing people. Based on the JTWC best track archive, there are 84 TDs that came within 500 km from the coastline and induced extreme rainfall in any station over the country. The tracks of these TDs per season are shown in Figure S1.

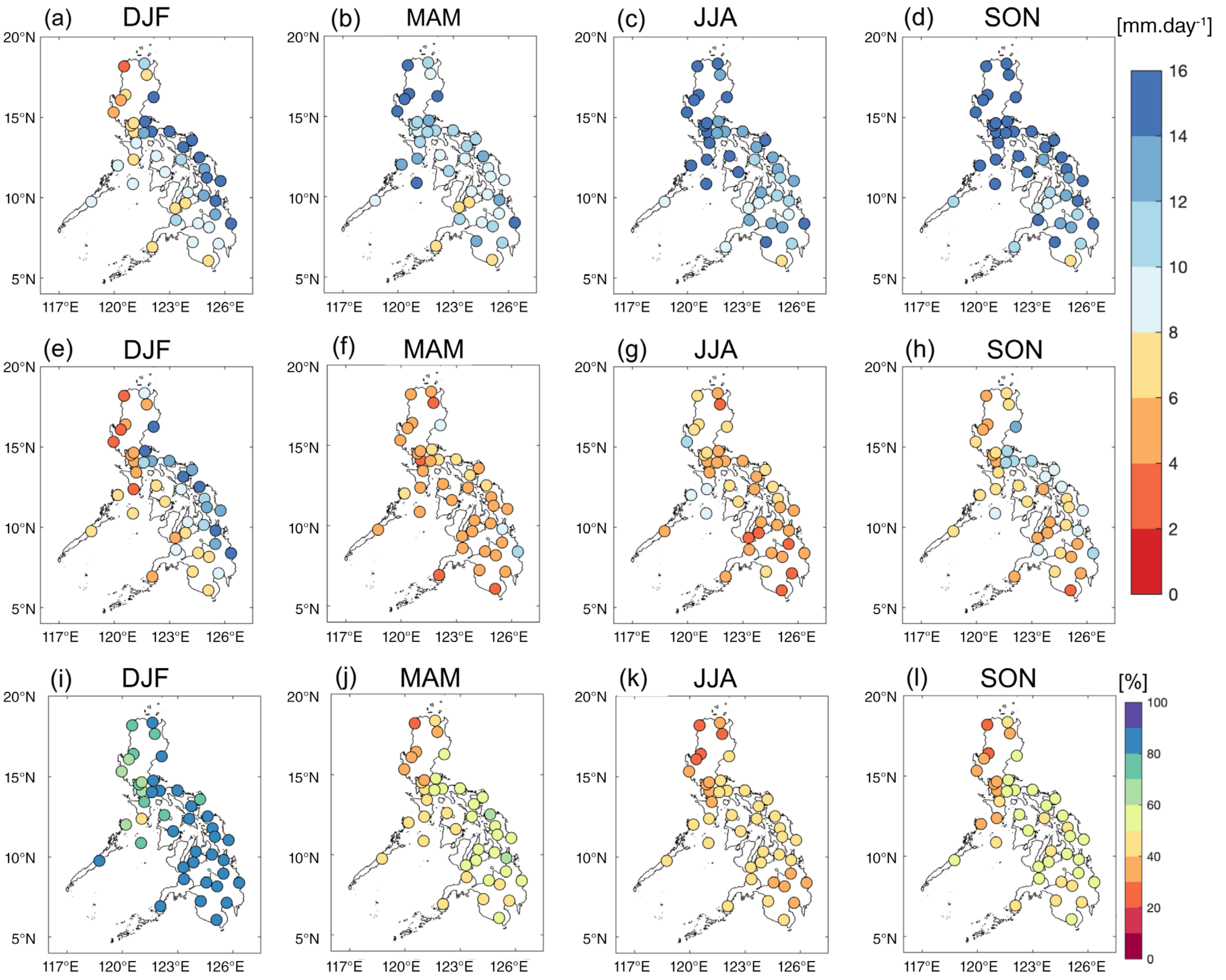

FIGURE 4 Seasonal distribution of mean daily rainfall (mm·day^{-1}) (a–d), rainfall induced by the non-TC vortices (mm·day^{-1}) (e–h), and the corresponding percentage contribution by these vortices (mean vortex rain/mean daily rainfall; %) (i–l) [Colour figure can be viewed at wileyonlinelibrary.com]

About 28 of these TDs made landfall over the country. The total number of TDs are 23, 16, 18, and 27 for the DJF, MAM, JJA, and SON seasons, respectively, indicating higher frequency of TDs towards the end of the year. As for the landfalling TDs there are 7, 6, 5, and 10 for the same respective seasons.

Figure 6 shows the number of extreme rainfall days (i.e., days with rainfall above the seasonal 95th percentile of rainfall) induced by TDs and other weaker disturbances (i.e., the rest of non-TC vortex days after removing the TD days) in the PAGASA stations. During the DJF season (Figure 6a), more TDs appear over the central and southern Philippines, while during JJA, they are mainly located to the north (Figure S1). During the DJF season, more extreme rainfall days can be depicted over Luzon Island (>15 days) compared to Mindanao Island. The TDs located to the central and southern Philippines may enhance the interaction between the Philippine landmass and the prevailing northeast monsoon flow in this season, which can explain why the number of extreme rainfall days in this region is higher compared to the south. The spatial distribution of extreme rainfall days during the MAM appears similar to those during the SON season, with more extreme rainfall days over the central and southern Philippines. The lowest number of extreme rainfall days associated with TDs can be found during the JJA season. During this season, most of TCs are stronger (i.e., TS and above); hence, less extreme rainfall days are associated with TDs.

As for the extreme rainfall days associated with other disturbances aside from TDs, the results show higher frequency of extreme rainfall days during the DJF season

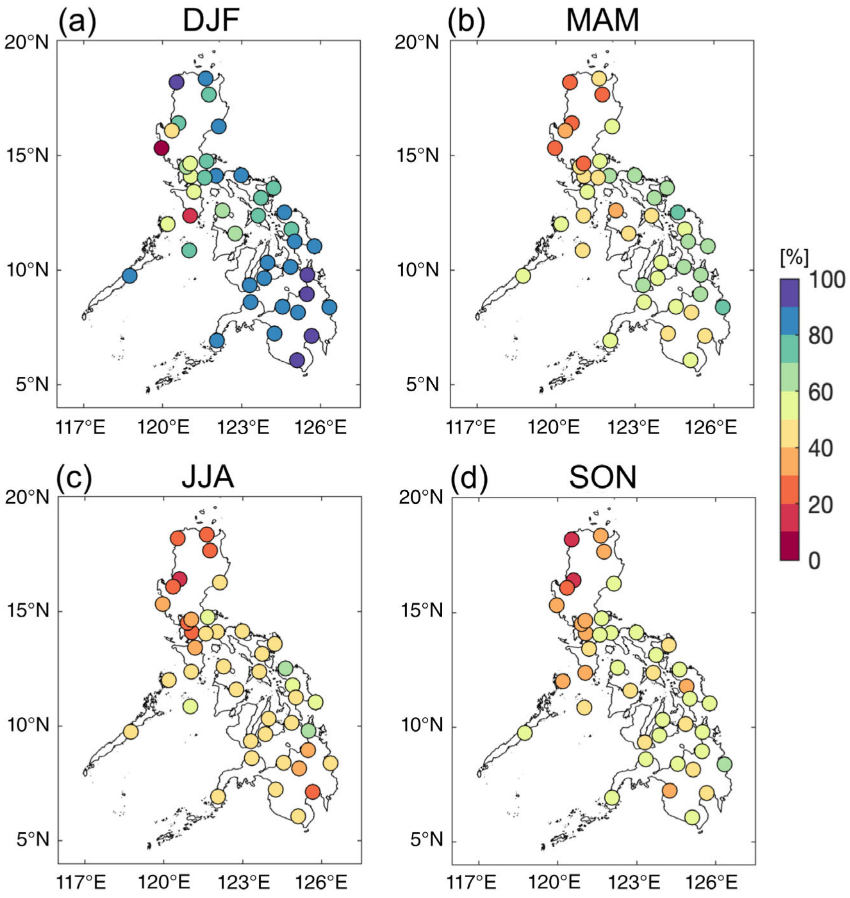

FIGURE 5 Percentage rainfall contribution of the non-TC vortices to the total extreme rainfall (>95th percentile) during (a) DJF, (b) MAM, (c) JJA, and (d) SON seasons [Colour figure can be viewed at wileyonlinelibrary.com]

(Figure 6e), particularly to the northeast of Mindanao Island where there are above 140 days of total extreme days associated with these disturbances. During the MAM season (Figure 6f), higher frequency of extreme rainfall days is more evident to the east coast of the country. On the other hand, the number of extreme rainfall days during the JJA and SON season (Figure 6g,h) appears comparable (below 100 days).

The mean rainfall associated with TDs and other disturbances including their percentage rainfall contribution relative to the mean daily rainfall of all non-TC vortex days are shown in Figures 7 and 8, respectively. During DJF and SON (Figure 7a,d), TDs induce higher rainfall amounts to the east coast of the country. During the JJA season (Figure 7c), higher rainfall amounts are more evident to the west coast of Luzon Island, which indicates that the TDs during this season also enhance the southwest monsoon (e.g., Cayanan *et al.*, 2011). In terms of percentage rainfall contribution, TDs contribute by about 30% in some stations on the west coast of Luzon and Visayas Islands. For the rest of the country the percentage rainfall contribution is below 10%. During MAM, JJA and SON (Figure 7f–h), the percentage rainfall contribution of TDs is less than 10% in most parts over the country.

Similar to the TDs, the induced rainfall of other weaker disturbances is also evident to the eastern coast of the country during the DJF and SON seasons, and to the west coast of Luzon during the JJA season (Figure 8a,c,d). In terms of percentage rainfall contribution, some parts of Luzon and Visayas Islands receive about 70–80% of their rainfall associated with these disturbances. As for the other seasons, the percentage rainfall contribution is about 90%. This indicates higher rainfall contribution from these weaker disturbances than from TDs.

3.4 | Impact of BSISO and MJO

Previous studies have shown that the BSISO during the boreal summer season (i.e., JJASO) (e.g., Yoshida *et al.*, 2014; Moon *et al.*, 2018; Olaguera, Manalo *et al.*, 2022) and MJO during boreal winter (DJFMA) (e.g., Bagtasa, 2020; Kikuchi, 2020) can modulate the formation of tropical vortices that eventually develops into TCs. The presence of these ISO modes changes the background circulation that are favourable for the formation of TCs (e.g., Yoshida *et al.*, 2014). Bagtasa (2020) found that TCs are more frequent around the country including those landfalling TCs during Phases 5 and 6 of MJO.

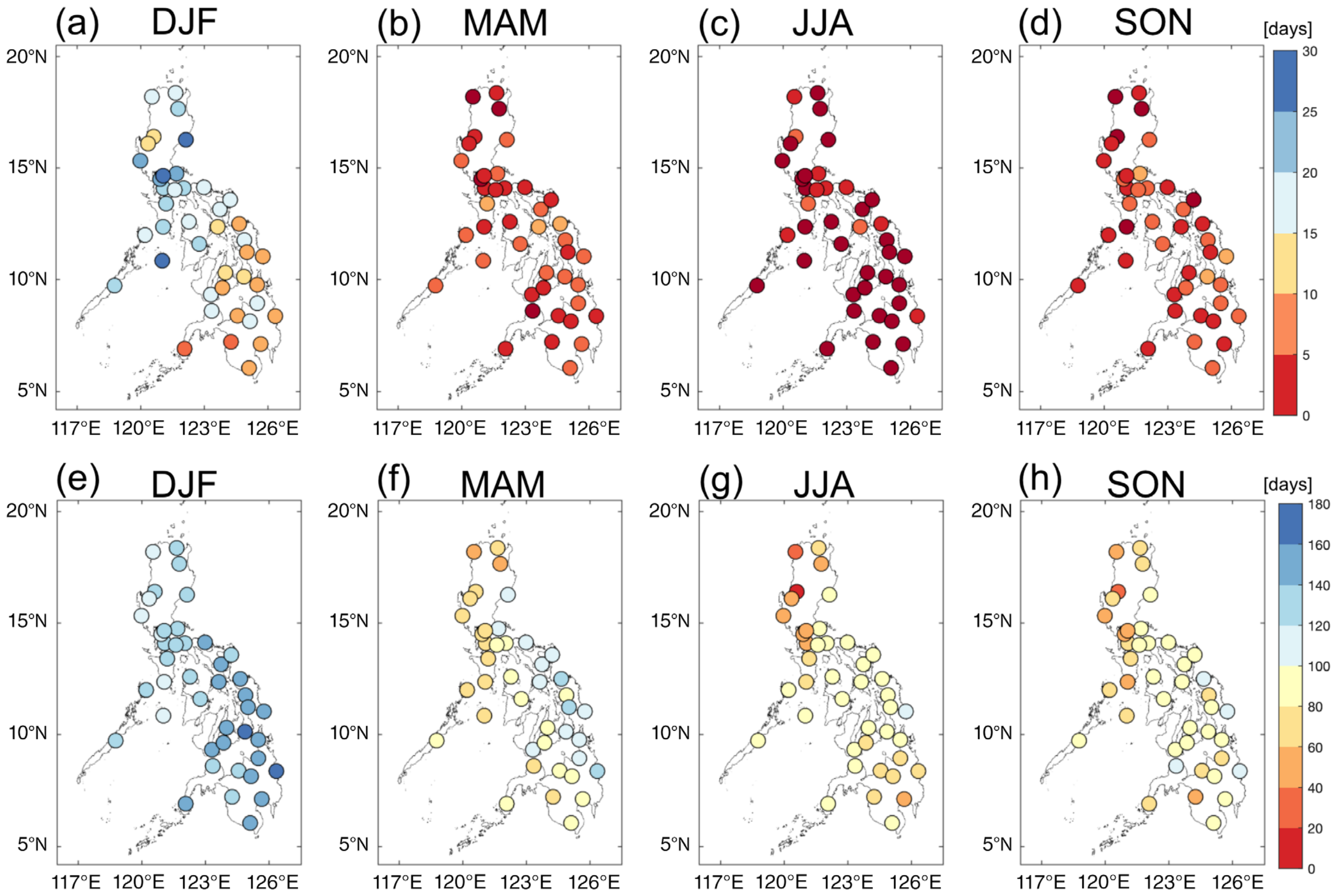

FIGURE 6 Total number of extreme rainfall days (days >95th percentile) per season associated with TDs (a–d) and other disturbances (e–h) [Colour figure can be viewed at wileyonlinelibrary.com]

In these phases, the active convection associated with MJO transitions from the Maritime Continent to the western North Pacific. The mean daily rainfall of all the days with significant MJO events (i.e., amplitude >1) in the eight phases of MJO are shown in Figure S2. The region along the east coast of the Philippines generally receives more rainfall during boreal winter. From Phase 4 to Phase 6, most stations along the east coast receive about 10 $\text{mm}\cdot\text{day}^{-1}$ of rainfall compared to the other phases. As for the BSISO, TC genesis over the western North Pacific is enhanced during Phases 5 to 8 of the BSISO. Olaguera, Manalo *et al.* (2022) examined the extreme rainfall events over the Philippines associated with the BSISO and found that most TC induced extreme events over the country also occur in these phases. The mean daily rainfall of all days with significant BSISO events in the eight phases of the BSISO are shown in Figure S3. The mean daily rainfall starts to increase in most of the stations across the country between Phases 4 and 6. In Phases 1–3 of the BSISO, rainfall amounts in most stations across the country is rather small (<2 $\text{mm}\cdot\text{day}^{-1}$). In Phases 7–8, only the stations located over Luzon Island receive more than 3 $\text{mm}\cdot\text{day}^{-1}$ of rainfall compared to the central and southern stations, which is indicative of the northward propagating characteristics of the BSISO. In this section, we examined the percentage contribution of those non-TC vortices that induced rainfall over the country and occurred during significant phases of the BSISO and MJO (i.e., amplitude >1).

Figure 9 shows the percentage rainfall contribution of non-TC vortices in the eight phases of the MJO during DJFMA. The mean daily rainfall induced by the non-TC vortices are shown in Figure S4. The non-TC vortices contribute by about 10–80% of the mean daily rainfall over the Visayas and Mindanao stations in Phases 1–3. Their percentage contribution increases to 90–100% from Phases 4 to 6 and decreases again to below 80% from Phases 7 to 8. This is consistent with the results of Bagtasa (2020). The rainfall in the Philippines increases from Phases 4 to 6 as the MJO traverses the Maritime Continent to the western Pacific (Figure S2). TC activity around the country is also enhanced in these phases. According to Bagtasa (2020), an anomalous cyclonic circulation is

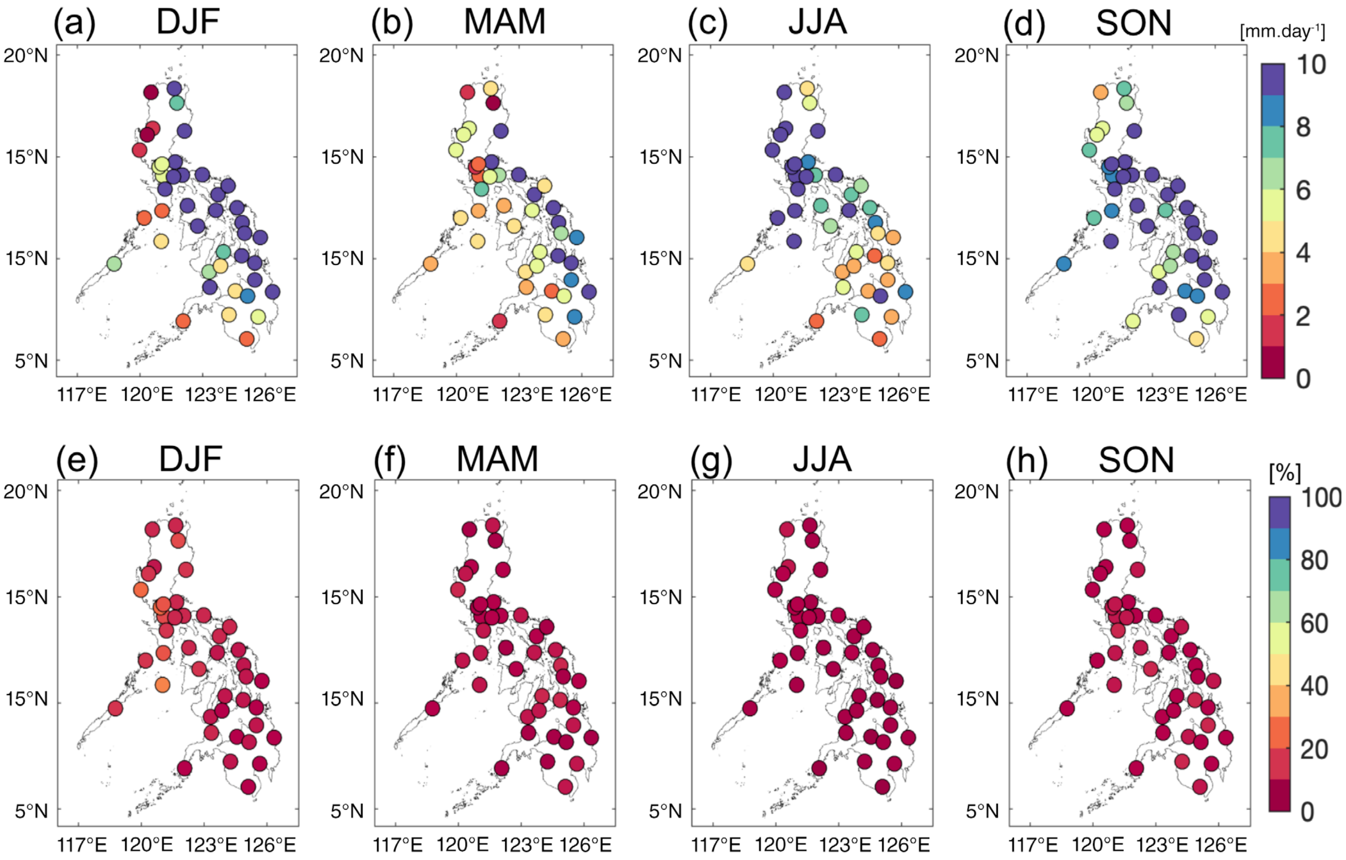

FIGURE 7 Mean daily rainfall (mm·day^{-1}) induced by TDs per season (a–d) and the corresponding percentage rainfall contribution (%; e-h) relative to the accumulated rainfall of all non-TC vortex days [Colour figure can be viewed at wileyonlinelibrary.com]

established over the Philippine Sea in these phases. At Phase 5, the northeasterlies associated with this cyclonic circulation anomaly converges with the cyclonic disturbances off the eastern coast of Mindanao Island, which is one of the factors contributing to the heavy rainfall events in the region (e.g., Ogino *et al.*, 2018; Olaguera, Matsumoto *et al.*, 2021). At Phase 6, the anomalous cyclonic circulation reaches its peak strength and enhanced rainfall can be seen over the central-eastern Philippines. Enhanced TC activity was also found in these phases (Bagtasa, 2020).

Figure 10 shows the percentage rainfall contribution of non-TC vortices during the eight phases of the BSISO during JJASO. It is evident that these vortices contribute by about 40–60% in Phases 4 and 5 of the BSISO, particularly in the Visayas and Mindanao region. For the other phases, the rainfall contribution remains below 50%. Yoshida *et al.* (2014) examined the five circulation patterns that affect TC genesis over the western North Pacific during boreal summer. These five circulation patterns are the shear line, confluence region, easterly wave, monsoon gyre, and pre-existing TCs (Ritchie and Holland, 1999). How these circulations flow patterns help in the development of TCs are discussed further by Ritchie and Holland (1999) and Yoshida *et al.* (2014). During Phase 5, they found that the easterly wave and monsoon gyre are the dominant patterns that may significantly contribute to TC formation. In this phase, the BSISO transits from the eastern Indian Ocean to the Maritime Continent and convection becomes active along its path. Yoshida *et al.* (2014) further noted that westerly winds appear over the equatorial western Pacific and that the cyclonic horizontal wind shear is enhanced between the westerly wind and trade wind. This creates favourable conditions for TC formation in the region.

Figure 11 shows the frequency of the non-TC vortices in the different phases of BSISO and MJO. The highest number of vortices occurs from Phases 4 to 6, which peaks at Phase 5 for both MJO and BSISO. This corroborates the high rainfall percentage contribution in these phases as shown in Figures 9 and 10. The high frequency of non-TC vortices from Phases 4 to 6 of the BSISO also corroborates the results of Zhao *et al.* (2015, see their fig. 8), who examined the relationship between TC genesis frequency and the different phases of the BSISO over the western North Pacific.

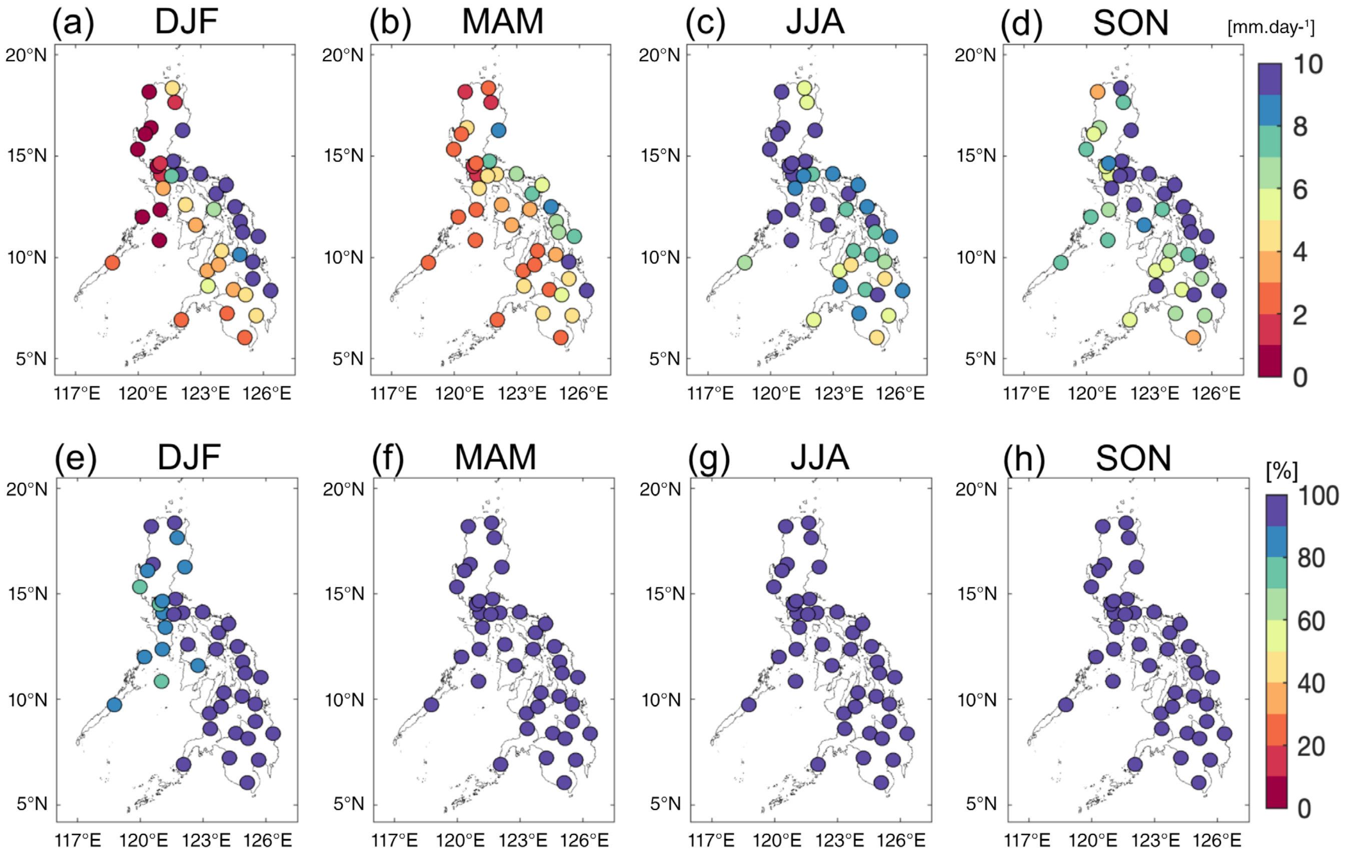

FIGURE 8 As in Figure 7 but for the other disturbances aside from TDs [Colour figure can be viewed at wileyonlinelibrary.com]

4 | SUMMARY AND DISCUSSION

This study examined the rainfall contribution of non-TC-related tropical vortices over the Philippines from 1979 to 2020. An objective index based on relative vorticity at 850 hPa and surface winds was used to detect these vortices. About 7,686 days or 50% of the total days during the analysis period were found to be associated with these non-TC vortices that occurred within 500-km from the coast of the country.

The largest rainfall contribution of these non-TC vortices was found over the northeastern region of Mindanao Island, where they contribute by about 80% to the mean daily rainfall. The lowest rainfall contribution was found over Luzon Island and to the west of the country, where they only contribute by about 40–50% to the mean daily rainfall. The high rainfall contribution to the northeast of Mindanao region may be related to the westward propagating cold surge vortices, which were found by Chen *et al.* (2012a, 2012b, 2013, 2015a, 2015b), Ogino *et al.* (2018), and Olaguera, Caballar *et al.* (2021) that usually causes heavy rainfall and flooding events in this region.

The seasonal analysis of the spatial distribution of the non-TC vortices revealed that they are most frequent during the DJF season, particularly over the SCS and eastern Mindanao Island. The lowest percentage of occurrence was found during the MAM season, which is the driest season in the country and when synoptic disturbances are fewer compared to the other seasons. Fewer vortices were also found over land across all seasons. However, the vortices appearing over the eastern, western, and northern parts of the country could enhance the prevailing southwest monsoon flow during JJA and northeast monsoon flow during the DJF season, which further increases the rainfall amounts over land.

The contribution of the non-TC vortices to the extreme rainfall over the country was also examined per season. The results revealed that about 90% of the extreme rainfall events particularly over the northeastern and southern Mindanao Island could be attributed to these vortices during the DJF season. This confirms that even non-TC vortices could induce extreme rainfall events over the country. During the MAM season, about 60–70% of the extreme rainfall along the east coast of the country could be attributed to these vortices. During JJA and SON, the contribution of these vortices to extreme rainfall does not exceed 50% across the country. This may be related to the fact that intense TCs are more frequent in these two seasons and are the primary sources of extreme rainfall events than those during DJF and MAM seasons.

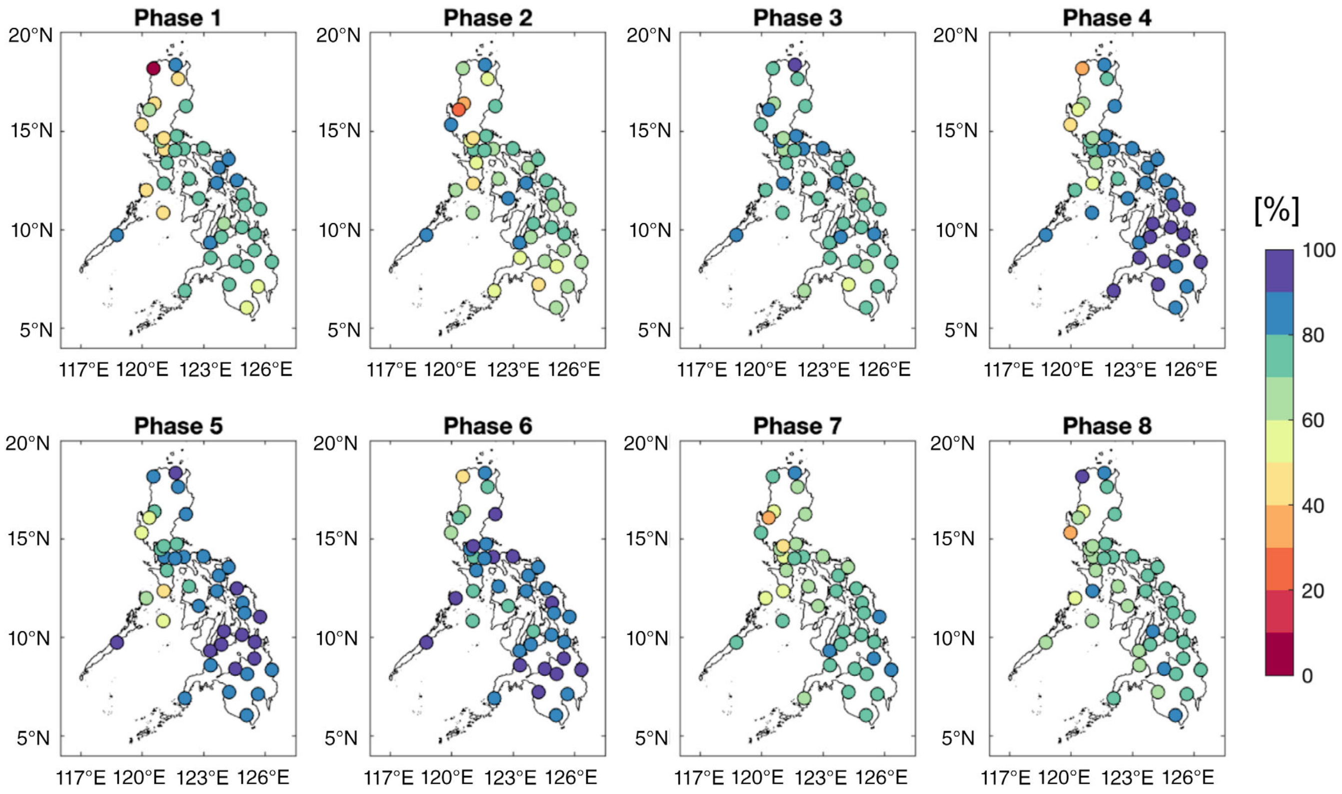

FIGURE 9 Percentage rainfall contribution of non-TC vortices in the eight phases of the MJO during DJFMA season [Colour figure can be viewed at wileyonlinelibrary.com]

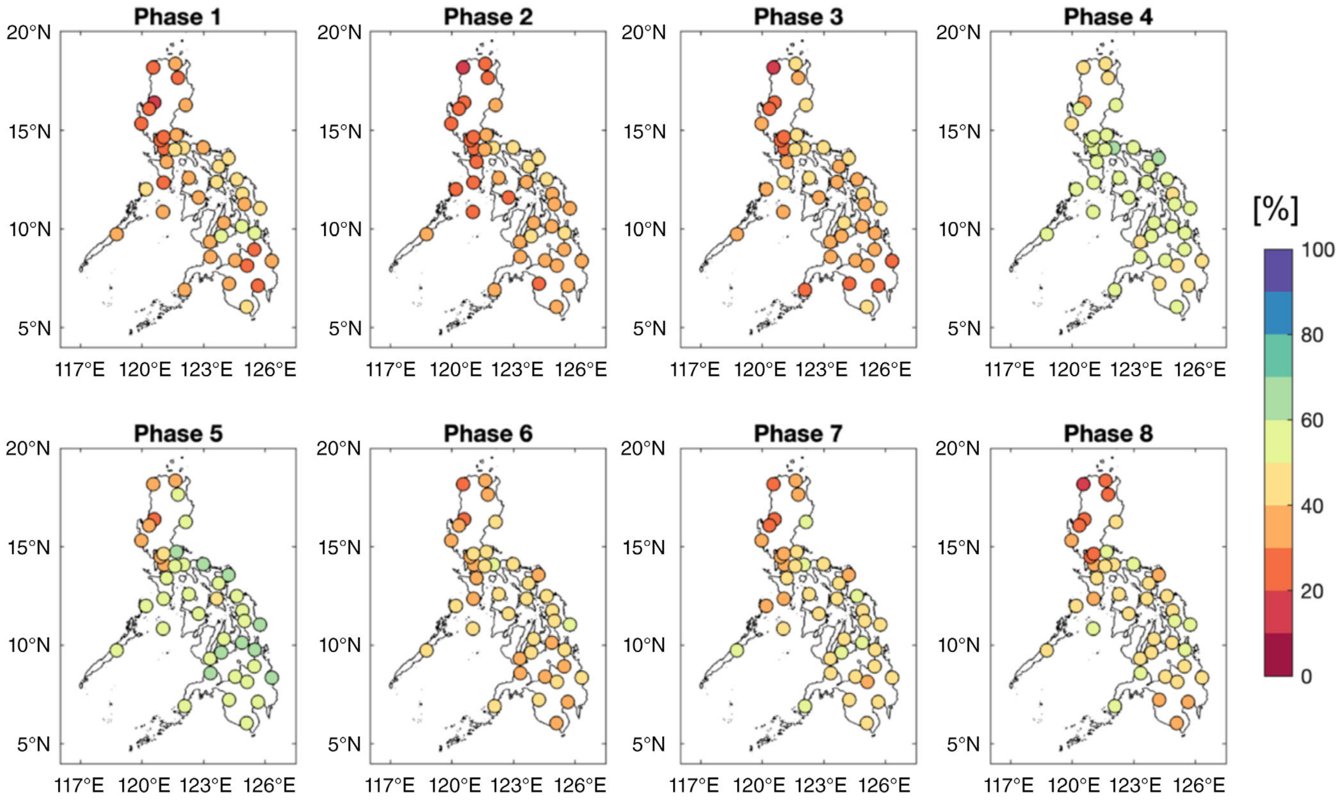

FIGURE 10 As in Figure 9 but for the BSISO during the JJASO season [Colour figure can be viewed at wileyonlinelibrary.com]

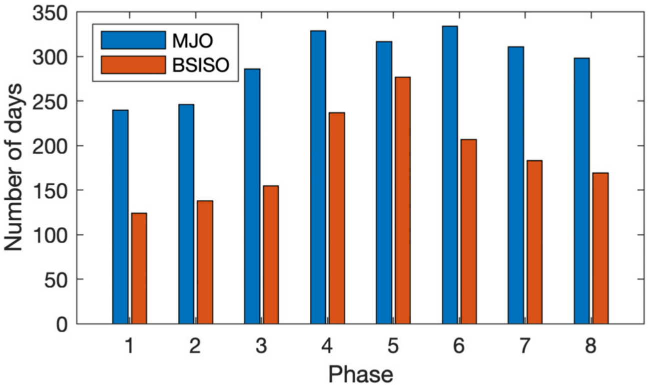

FIGURE 11 Total number of non-TC vortex days in each phase of the MJO (blue) and BSISO (orange) [Colour figure can be viewed at wileyonlinelibrary.com]

The total non-TC vortex days were further classified into TDs based on those listed in the JTWC best track archive and other weaker disturbances. The percentage rainfall contribution associated with TDs relative to the mean daily rainfall of all non-TC vortex days is only about 10% in most parts of the country except during the DJF season, where they contribute by about 30%, particularly in some stations located on the west coast of Luzon and Visayas Islands. On the other hand, the other weaker disturbances induced more rainfall (~70–90%) than TDs. The number of extreme rainfall days (i.e., days with rainfall above the 95th percentile per season) was also examined. Although the total number of extreme rainfall days associated with weaker disturbances is higher than TDs, the results showed that the number of extreme rainfall days induced by these disturbances is highest during the DJF season compared to the other seasons. These weaker disturbances during the DJF season may include westward propagating CSVs (e.g., Ogino *et al*., 2018; Olaguera, Matsumoto *et al*., 2021). On the other hand, weaker disturbances in the other seasons may include short-lived LPAs, LPAs at the initial stage of developing TCs, or LPAs from dissipating TCs.

The occurrence of these non-TC vortices was also examined in relation to the different phases of the BSISO and MJO during the boreal summer (JJASO) and boreal winter (DJFMA), respectively. The results showed that these non-TC vortices are more frequent between Phases 4 and 6 of both MJO and BSISO. During Phase 5 of MJO, these vortices contribute by about 90% to the mean daily rainfall during boreal winter, particularly over the central and southern Philippines. On the other hand, they only contribute by about 60% in the same phase of the BSISO during boreal summer over the same region. The active convections of these two ISOs were found to provide favourable conditions for the formation and development of weak and strong TCs (Yoshida *et al*., 2014; Moon *et al*., 2018; Bagtasa, 2020; Basconcillo and Moon, 2021). As mentioned previously, Ritchie and Holland (1999) identified five large-scale patterns that affects tropical cyclone genesis over the western North Pacific, which are the shear line, confluence region, easterly wave, monsoon gyre, and pre-existing TCs. Zhao *et al*. (2015) examined the relationship between TC genesis over the western North Pacific in each of these five circulation patterns and BSISO. In their study, TC genesis is defined as the time when the disturbance is first classified as a TD. Their results show that the shearline pattern mostly contribute to the TC genesis during the active phases (i.e., Phases 4–7) of the BSISO. According to Zhao *et al*. (2015) the shearline pattern is characterized by a cyclonic shear of the horizontal wind along the monsoon trough, which favours the development of TCs through barotropic instability along the shearline and sustained moist convection. They also assessed the genesis potential index (GPI) and its components in relation to the different phases of the BSISO. They found that the low-level relative vorticity and mid-level relative humidity contributes more to the positive GPI anomalies during the active phases of the BSISO.

There are a lot of issues left unaddressed in the present work. For example, the tracks of the non-TC vortices examined in this study were not characterized. A more sophisticated tracking algorithm is needed to detect these vortices in the reanalysis data set as demonstrated by Hunt and Fletcher (2019) and You and Ting (2021). Such tracking algorithm may also be utilized in detecting weaker TCs in future works.

AUTHOR CONTRIBUTIONS

Lyndon Mark P. Olaguera: Conceptualization; investigation; visualization; validation; methodology; writing – original draft; formal analysis. **Jun Matsumoto:** Investigation; writing – original draft; funding acquisition; methodology; validation; formal analysis; supervision. **John A. Manalo:** Conceptualization; investigation; writing – original draft; methodology; validation; visualization; formal analysis; software; data curation.

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ORCID

Lyndon Mark P. Olaguera https://orcid.org/0000-0002-1603-9255
Jun Matsumoto https://orcid.org/0000-0003-1551-9326
John A. Manalo https://orcid.org/0000-0001-8710-5347

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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