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A climatological study of the wet and dry conditions in the pre-summer monsoon season of the Philippines

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Abstract
This study investigates the climatology of the wet and dry conditions in the pre-summer monsoon season of the Philippines that are less emphasized in previous works. Wet cases (Type W), which account for about 23% of the total pre-summer monsoon days from 1979 to 2015, are identified from April 1 to the monsoon onset defined by the Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA). The differences between the Type W and dry cases (Type D) are presented. The synoptic conditions associated with the Type W and Type D cases are sub-divided into two sub-types based on the wind conditions, the (a) westerly winds at 925 hPa (WINDS925hPa) intrusion over Luzon Island (120°–122.5°E, 12.5°–22°N) (Type WW and Type DW), and (b) enhanced easterly WINDS925hPa (Type WE and Type DE). The Type WE (Type WW) cases account for about 63.9% (36.1%) of the total Type W cases, while the Type DE (Type DW) cases account for about 88.1% (11.9%) of the total Type D cases. A subset of Type WE cases (Type WEDe), which features an eastward propagating cold front to the north of Luzon Island and an intensifying anticyclone to its west originating from the east of the Tibetan Plateau and their differences are also examined. These two opposing circulations interact with the subtropical high over the northern Pacific and the easterlies over Luzon Island, and form a deformation zone. The confluence region of this deformation zone, where the cold front interacts with the warm and humid air brought by the east-erly WINDS925hPa, lies over Luzon Island and contributes to the convective activities during the pre-summer monsoon over this region. This is the first attempt to clarify and document the role of deformation zones as another synoptic-scale convective system during the pre-summer monsoon season of the country.

KEYWORDS
cold front, deformation zone, monsoon onset, pre-summer monsoon

1 INTRODUCTION

The agricultural sector of the Philippines, especially those areas located on the western side of the country, relies heavily on the summer monsoon rainfall. While many studies have investigated the onset (Akasaka, 2010; Kubota et al., 2017), climatology (Cruz et al., 2013), long-term trends (Villafuerte et al., 2014), and variability...
(Akasaka et al., 2018; Olaguera et al., 2018) of the summer monsoon season (i.e., June to September), very few studies have examined the climatology and the different convective systems during the pre-summer monsoon season (i.e., March to May). Of course, the rainfall generated during this season is also important for the total annual rainfall of the country, besides the rainfall from the summer or winter monsoon seasons. Lohar and Pal (1995) recognized the importance of thunderstorms in the pre-monsoon rainfall of West Bengal in India from the rainfall data in one station for the period 1973–1992. They noted two types of thunderstorms over this area. One that is associated with the dry line, and another that is triggered by the sea breeze front. The dry line is a low-level mesoscale boundary that separates dry air mass from the moist air mass. According to Lohar and Pal (1995) this is locally referred to as “Northwesters” since they originate from the northwest. The air temperature behind a dry line is often much higher (i.e., due to the lack of moisture) than those ahead it. Due to the difference in the air densities, the dry air behind the dry line favours the lifting of the moist air ahead of it. This is favourable for the development of thunderstorms (ww2010.atmos.uiuc.edu/(Gh)/guides/mtr/af/frnts/dfdef.rxml). Lohar and Pal (1995) also found decreasing trends in the frequency of these thunderstorms over West Bengal from 1983 to 1992, which they attributed to the land-use change over this region. Ding (1992) and Chen et al. (2004) documented prominent double peaks in the annual mean rainfall in some stations over South China (SC) around May–June and in August, which they refer to as the typhoon season. Ding (1992) further noted that the pre-summer monsoon season over SC is initiated by the northward jump of the western North Pacific Subtropical High (WNPSH) and the onset of the summer monsoon over the South China Sea (the SCS). In addition, he also noted three rain-producing synoptic systems during the pre-summer monsoon season, and include cold fronts, convergence zones (i.e., shearlines, monsoon trough, low-level jet, etc.), and the middle to upper level synoptic scale systems (i.e., mid-latitude westerlies, WNPSH, etc.). Matsumoto (1997) found that the onset of the summer monsoon over the Indochina Peninsula commences in mid-May, almost concurrent with the onset timing over the SCS. However, pre-monsoon rainfall already occurs over the inland region of the Indochina Peninsula, while it is under the influence of mid-latitude westerlies. He also pointed out a potential problem in using the northward migration of the equatorial westerlies as an index for the summer monsoon onset such as those proposed by Orgill (1967) over this region, since southwesterly winds are already apparent over this region in early April. Kiguchi and Matsumoto (2005) examined the pre-summer monsoon rainfall over the Indochina Peninsula during the GEWEX Asian Monsoon Experiment-Intensive Observation Period (GAME-IOP) in 1998 and documented the intermittent rainfall episodes induced by the passage of an upper level trough that migrates along the southern edge of the Tibetan Plateau. This finding also revolutionizes the idea that the pre-summer rainfall over the Indochina Peninsula is not a localized phenomenon, but rather it is a synoptic-scale phenomenon. Kiguchi et al. (2016) confirmed the passage of the upper trough using a longer data set from 1979 to 2002. They further noted that this upper trough is associated with the mid-latitude cyclone over the Yangtze River basin and that the rainfall amount during the pre-summer monsoon period has no clear relationship with the onset timing of the summer monsoon over the Indochina Peninsula.

According to Flores and Balagot (1969), the summer monsoon over the Philippines originates as trades from the Indian Ocean anticyclone during the Southern Hemisphere winter. As these trades cross the equator, they are veered to the right and generally reach the country as southwesterly streams. There is strong spatial contrast in the rainy season of the Philippines because of its heterogeneous topography and the seasonal change of the Asian summer monsoon. Akasaka et al. (2007) noted that during the summer monsoon season (i.e., the months from May to September), the western coast experiences its rainy season, while the eastern coast experiences its dry season. The opposite occurs during the autumn and winter monsoon seasons, when the eastern (western) coast experiences its rainy (dry) season. Moron et al. (2009) found that the onset of the summer monsoon season over the Philippines occurs abruptly on the western coast between mid-to-late May, following the onset of the summer monsoon over the SCS, although rainfall may start to increase as early as in April (Flores and Balagot, 1969; Akasaka et al., 2007; Akasaka, 2010). Akasaka (2010) found that the northeastward shift of the WNPSH, evolution of the monsoon trough, and the approach of the easterly waves are important triggers for the summer monsoon onset over the Philippines.

The southward intrusion of mid-latitude fronts has been suggested as an important trigger for the summer monsoon onset over the SCS (Chang and Chen, 1995; Chan et al., 2000). For example, Chan et al. (2000) examined the summer monsoon onset over the SCS in 1998 and found a midlatitude trough/front (i.e., a cyclonic flow) that migrated southwards toward the SC coast and triggered the onset. They suggested that the northeasterly flow associated with the decaying winter monsoon during the late spring facilitate the increase of instability (i.e., the transfer of heat and moisture) over the SCS. The appearance of the cyclonic flow over
the SC coast induce enhanced ascent of warm and moist air over the SCS. The upper level divergence accompanying this change would then force the extension of rainfall in the upper troposphere and release of the convective available potential energy of the warm air mass. This results in the enhanced rainfall over the entire SCS, which indicates the onset of the rainy season over there. Knowing the proximity of the Philippines to the SCS, it can be inferred that the southward intrusion of these mid-latitude cold fronts can also induce rainfall over the country. In fact, the rainfall contours of about 5 mm·day⁻¹ during the summer monsoon onset over the SCS in Figure 15c of Chan et al. (2000) extends over the Philippines. Meanwhile, using the Geostationary Meteorological Satellite (GMS) data from 1982 to 1987, Hirasawa et al. (1995) found the appearance of deep convective clouds over Luzon Island in mid-to-late May, which is part of an eastward propagating cloud band along 30°N (see their Figures 2 and 4). This result indicates the impact of mid-latitude circulations on the pre-summer monsoon rainfall over the Philippines, which has not been examined in previous studies.

FIGURE 1  Spatial distribution of outgoing longwave radiation (OLR; shades; W·m⁻²) and winds at 925 hPa (WINDS₉₂₅hPa) and 200 hPa (WINDS₂₀₀hPa) (streams; m·s⁻¹) for (a,b) Type D, (c,d) Type W, and (e,f) their difference. Shaded areas in panel (e) and bold vectors in panels (e) and (f) indicate significant differences at the 95% confidence level by t-test. The scale of the unit vectors in panels (e) and (f) are 5 and 10 m·s⁻¹, respectively [Colour figure can be viewed at wileyonlinelibrary.com]
drought were previously reported during this season and this is further aggravated by the occurrence of El Niño, whose effects may persist until the succeeding summer season (e.g., Porio et al., 2019). Both hydrological and meteorological droughts are of great concern because of their profound socio-economic impacts. Hence, understanding the different convective systems during this season including their underlying mechanisms is of utmost importance.

The main objectives of this study are therefore to examine first the climatological characteristics of the wet and dry conditions during the pre-summer monsoon season in the Philippines and determine the major synoptic-scale convective systems during this period. The data and methodology used in this study are described in Section 2. The analysis of the pre-summer monsoon convection through case studies and composite analysis are presented in Section 3. A summary of the results is presented in Section 4.

2 | DATA AND METHODOLOGY

2.1 | Data

In this study, we used the following data sets:

1. Daily rainfall data from the Asian Precipitation–Highly Resolved Observational Data Integration Towards Evaluation of Water Resources version 1901 (APHRODITE-V1901; Yatagai et al. 2012; www.chikyu.ac.jp/precip/english), with 0.25° x 0.25° grid resolution, from 1979 to 2015. This data set is only available over land.

FIGURE 2 As in Figure 1 but for the (a,b) Type D_E and (c,d) Type W_E cases [Colour figure can be viewed at wileyonlinelibrary.com]
2. To depict the large-scale change in rainfall, we used the daily outgoing longwave radiation (OLR; Liebmann and Smith, 1996), with 2.5° × 2.5° grid resolution, from 1979 to 2015 and provided by the National Oceanic and Atmospheric Administration (NOAA), as a proxy for convection.

3. Daily zonal ($U$) and meridional ($V$) winds, vertical velocity (OMEGA), relative humidity (RHUM), Temperature (TEMP) at multiple levels from 1979 to 2015 and from the National Centers for Environmental Prediction-Department of Energy (NCEP-DOE) Atmospheric Model Intercomparison Project (AMIP-II), with 2.5° × 2.5° grid resolution (Kanamitsu et al., 2002). Specific humidity (SHUM) and equivalent potential temperature ($\theta_e$) at multiple levels were also used and were derived from this data set.

4. Regional summer monsoon onset dates from the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA), the country’s official weather bureau. The summer monsoon onset is defined based on the stations located over the western coast of the Philippines due to their geographical exposure to the summer monsoon westerlies. PAGASA defines the onset as the beginning of a five-day period between April and July with total rainfall of about 25 mm or more, with three consecutive days having at least 1 mm of rainfall per day (Kubota et al., 2017). These conditions should be satisfied in at least five of the climate type 1 stations located over the western coast of the Philippines. PAGASA also has the disposition to include the changes in the large-scale circulations such as the reversal of the low-level winds from

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**FIGURE 3** As in Figure 1 but for the (a,b) Type $D_W$ and (c,d) Type $W_W$ cases [Colour figure can be viewed at wileyonlinelibrary.com]
easterly to westerly in the onset criteria. More information about the onset detection can be found in Kubota et al. (2017).

2.2 Methodology

We focused our analysis over Luzon Island (northern Philippines) since most of the stations used in defining the onset are located here. We defined Luzon Island and its vicinity as the region within 120°–122.5°E and 12.5°–22°N. We defined the pre-summer monsoon period as the period from April 1 to the onset day, defined by PAGASA, in each year. We excluded March in this definition since the eastern coast of Luzon Island is still under the influence of the northeasterly monsoon. In general, there are 2,103 days during the pre-summer monsoon period based on the aforementioned conditions. We used the 240 W·m⁻² as the threshold for OLR in depicting the active convection following Kiguchi et al. (2016). Values below (above or equal to) this threshold indicates enhanced (suppressed) convection.

3 RESULTS

3.1 Climatological characteristics of the pre-summer monsoon convection

In order to examine the climatological characteristics of the convective activities during the pre-summer monsoon, first, we classified the pre-summer monsoon days into two types: (1) wet days (Type W), when at least 10% of the total grid points over Luzon Island (300 grid points) from the APHRODITE data set have rainfall above 0 mm·day⁻¹ and the area averaged OLR over Luzon Island is below 240 W·m⁻², and (2) dry days (Type D), for the remaining days that do not satisfy (1). This definition is almost similar to those in Kiguchi et al. (2016). Henceforth, the number of days in each type will

![FIGURE 4](https://wileyonlinelibrary.com)
be referred to as cases. Following these criteria, there are 1,618 cases (76.9% of the 2103 pre-summer monsoon cases from 1979 to 2012) that belong to Type D and 485 cases (23.1%) to Type W. We also found that the pre-summer monsoon period contributes by about 7.34% (151.8 mm) to the total annual rainfall over Luzon Island (2067.4 mm), indicating that the pre-summer monsoon period is relatively dry. To further clarify their difference, the composites of OLR, winds at 925 hPa (WINDS$_{925hPa}$), and 200 hPa (WINDS$_{200hPa}$) for both types, are shown in Figure 1.

Easterly WINDS$_{925hPa}$ are apparent over the Philippines in the composite of the Type D cases (Figure 1a) and the entire country is relatively dry, with OLR values above 240 W m$^{-2}$. The WNPSH is centred around 155°W, 30°N and its western ridge is located over the Indochina Peninsula. A narrow convergence region, with enhanced convection, can be seen over the Indochina Peninsula along 105°E, where the monsoon westerlies from the Bay of Bengal converge with the easterlies from the southern flank of the WNPSH. This feature is one of the triggers for the monsoon onset over the Indochina Peninsula, as noted by Zhang et al. (2004; see their Figure 12). At 200 hPa, an upper-level anticyclone is located over the SCS in the Type D composite (Figure 1b). This upper-level anticyclone is associated with the developing South Asian Anticyclone (SAA; Yanai et al., 1992). On the other hand, southeasterlies are apparent over the Philippines in the Type W composite and the WNPSH retreats eastward and centred around 140°W, 30°N (Figure 1c). This is accompanied by the enhanced convection over the Indochina Peninsula, the SCS, and the Philippines. The monsoon southwesterlies converge with the southeasterlies from the southern flank of the WNPSH over the SCS. At 200 hPa, the SAA is located around 100°E, 18°N in the Type W composite (Figure 1d).

The differences of the composites of OLR and WINDS$_{925hPa}$ and WINDS$_{200hPa}$ are shown in Figures 1e,f, respectively. Significant anomalous southwesterly WINDS$_{925hPa}$ can be seen over the western Indochina Peninsula, the SCS, and the Philippines (Figure 1e) that extends to the dateline along 20°N. This is also accompanied by a significant increase in convection, as indicated by the negative OLR in the aforementioned regions. This suggests that the enhanced southwesterly WINDS$_{925hPa}$ significantly contribute to the convection in the Type W composite. At 200 hPa (Figure 1f), although the Philippines is under the easterly conditions, the difference is not significant, indicating that the convection enhancement over this region is largely influenced by the low-level circulations. Nevertheless, significant easterlies can also be seen along 20°–40°N between the northern Luzon Island and Japan, indicating the weakening of the westerly jet in the region.

### 3.2 Classification of the pre-summer monsoon rainfall based on the zonal wind reversal

The convection enhancement during the summer monsoon onset over the Philippines is usually accompanied by the reversal of WINDS$_{925hPa}$ from easterly to westerly (e.g., Akasaka, 2010). Hence, we further classify the Type W cases into two types based on the reversal of the zonal winds at 925 hPa ($U_{925hPa}$) over Luzon Island. We classified the Type W cases as Type W$_E$, when easterlies ($U_{925hPa} < 0$) are apparent over Luzon Island, and Type W$_W$, when westerlies ($U_{925hPa} > 0$) are apparent over Luzon Island. Note however, that easterly to southeasterly winds can be depicted over the Philippines for both the Type W and D cases in Figures 1a,c. Hence, we also classified the Type D cases into Type D$_E$ and Type D$_W$, following the aforementioned notations. The results are summarized in Table 1. It is found that about 63.9% of the Type W cases (310 cases) belong to Type W$_E$ cases, while 36.1% (175 cases) belong to Type W$_W$ cases.

This indicates that most of the rainfall over Luzon Island during the pre-summer monsoon period is brought by easterlies. On the other hand, 88.1% (1,426 cases) of the Type D cases belong to Type D$_E$, while only 11.9% (192 cases) belong to Type D$_W$ cases, indicating that easterly winds also bring more dry weather conditions over Luzon Island. We also found that the Type W$_E$ cases contribute by about 75% (113.8 mm) to the total pre-summer monsoon rainfall over Luzon Island, while the Type W$_W$ cases account for about 25% (38.0 mm).

To further elucidate the spatial structure of the convection and winds during the pre-summer monsoon period based on the above classifications, we illustrate the OLR and WINDS$_{925hPa}$ for the Type W$_E$ and Type D$_E$, and Type W$_W$ and Type D$_W$, in Figures 2 and 3, respectively. The OLR and WINDS$_{925hPa}$ composites for the Type D$_E$ (Figure 2a) are almost similar to those in the Type D composite, as shown in Figure 1a, where a convergence region can be seen over the Indochina Peninsula and the SAA is located over the SCS. The OLR and WINDS$_{925hPa}$ composites for the Type W$_E$ are also almost similar to the Type W cases except that the convergence region between the southeasterly WINDS$_{925hPa}$ and westerly WINDS$_{200hPa}$ is located over the eastern Indochina Peninsula (Figure 2b). The differences among the composites (Figures 2e,f) also resemble the difference between the Type W and Type D cases, as shown in Figures 1e,f, but with significant change in the upper
level easterlies between 15°–20°N (Figure 1f). As for the Type D_N, southwesterly winds can be seen along 10°–20°N and convection is enhanced over the Indochina Peninsula (Figure 3a). In the upper level, the SAA is located around 100°E, 12°N (Figure 3b). For the Type W_W cases, southwesterly WINDS_925hPa stretches from the Bay of Bengal to the North Pacific and convection is enhanced over the Indochina Peninsula, SCS, and the Philippines. In addition, enhanced convergence between the southerly WINDS_925hPa and the easterly WINDS_925hPa can be depicted along the equatorial region in the Type W_W composite. In the upper level, the SAA is located around 100°E, 20°N. The differences in the composites, as shown in Figures 3e,f, show enhanced convection and westerly WINDS_925hPa along 10°–20°N, and enhanced easterly WINDS_200hPa along 20°–30°N.

### 3.3 Impact of deformation zone on the rainfall over the Philippines

We further analysed the cases that belong to Type W_E and found cases when a cold front pass along 20°–30°N. As an illustrative example, we show the composites of OLR and WINDS_925hPa and rainfall for the May 18, 1981 case in Figures 4a,b. It is worth mentioning that this day was only chosen arbitrarily and similar features can be observed in other Type W_E cases with a passing cold front to the north of Luzon Island. The historical weather charts from the Japan Meteorological Agency are shown in Figure S1. An eastward propagating cold front originating from southwestern Japan can be depicted from 12 UTC May 16, 1981 to 00 UTC May 18, 1981 (Figures S1a–d). The daily composites of OLR and WINDS_925hPa show enhanced convection and a confluence zone is located over Luzon Island. The APHRODITE rainfall shows that the average daily rainfall on this day reached by about 30 mm day⁻¹ over Luzon Island. The mean position of the cold front on this day can also be depicted as the lower boundary of the negative meridional equivalent potential temperature gradient (\( \frac{\partial \theta_e}{\partial y} \); https://www.wpc.ncep.noaa.gov/sfc/UASfcManualVersion1.pdf), as shown in Figure 4c. The mean position of the cold front can be seen just to the north of Luzon Island. The shearline is also characterized by enhanced vertically integrated moisture flux convergence (VIMFC), as shown in Figure 4d. Other remarkable features are the two cyclonic circulations centred around 115°E, 15°N (SCS) and 140°E, 38°N (mainland Japan) that are juxtaposed in a southwest-northeast orientation and two anticyclonic circulations centred around 180°, 25°N (the WNPSH) and 115°E, 40°N (northern China) that are adjacent to the aforementioned cyclonic circulations. Together, these circulation features form a deformation zone (Mak, 2011). The col/saddle point of this deformation zone is centred around 135°E, 20°N. The confluence zone (henceforth referred to as shearline) over Luzon Island lies along the axis of dilatation of this deformation zone. According to the glossary of the American Meteorological Society, a shearline is defined as a line or narrow region of maximum horizontal wind shear (i.e., \( \frac{\partial U}{\partial x} \) > 0).

From the kinematic properties of the horizontal wind field in the natural coordinates, the deformation zone (total deformation; TDef) can be represented by the combination of the stretching (STD) and shearing deformation (SHD). These are calculated as follows:

\[
STD = \frac{\partial U}{\partial x} - \frac{\partial V}{\partial y},
\]

\[
SHD = \frac{\partial U}{\partial y} + \frac{\partial V}{\partial x},
\]

\[
TDef = \sqrt{STD^2 + SHD^2},
\]

where \( U \) and \( V \) are the zonal and meridional wind components. As an example, we illustrate these parameters for the May 18 case in Figures 5a–c. At 925 hPa, the shearline to the north of Luzon Island coincides with a region of positive STD_925hPa that stretches from the Indochina Peninsula to the southeast of Japan (Figure 5a). On the other hand, the SHD_925hPa is negative along 15°N and stretches over Luzon Island (Figure 5b). We confirmed that this negative SHD_925hPa term is mainly due to the more negative \( \frac{\partial U}{\partial y} \) term in Equation 2, which is favourable for the cyclonic circulation over the SCS (i.e., this is important for the relative vorticity; not shown). The total deformation (TDef_925hPa) is about 2 \times 10^{-5} s⁻¹ over Luzon Island and the positive values coincide along the shearline. According to Mak (2011), the values of STD and SHD depend on the coordinate system used in depicting the fluid flow, suggesting that they have no unique physical significance. On the other hand, the TDef does not depend on the coordinate system and have physical significance.

To examine the climatological impact of these deformation zones on the rainfall over Luzon Island, we further classified the Type W_E cases into Type W_EDef cases. Additional criteria were added on the conditions for detecting the Type W_E cases. These include (a) \( \frac{\partial \theta_e}{\partial y} > 0 \) over the north of Luzon Island (120°–122°5'E, 20°–25°N), (b) \( \frac{\partial U}{\partial y} > 0 \) and TDef_925hPa > 0, (c) VIMFC > 0 over Luzon Island. The first condition ensures the passage of a cold front to the north of Luzon Island, while the second
the other hand, show that the SAA is centred around Luzon Island (Figure 6b). The upper level winds, on the other hand, show a clear anticyclonic circulation centred around 130°E, 32°N and a deformation zone to the northeast of Luzon Island (Figure 6a). The confluence zone is also located over Luzon Island. The APHRODITE rainfall composite shows that the enhanced convection corresponds to about 5–15 mm day$^{-1}$ over Luzon Island (Figure 6b). The upper level winds, on the other hand, show that the SAA is centred around 108°E, 15°N (Figure 6c).

How does the deformation zone influence the rainfall variability over Luzon Island? The shearline, which lies along the axis of dilatation of the deformation zone, may be associated with heavy rainfall events. As we have noted previously, the shearline is characterized by enhanced moisture convergence. In addition, to the north of the shearline are northeasterly winds that carry cold air, while to its south are easterly winds that carry warm air. The cold air to the north of the shearline may force the warm air to its south to ascend which is favourable for the enhancement of rainfall. This can also be depicted from the latitude-height cross section of $\frac{\partial \theta}{\partial Y}$, vertical velocity, and meridional wind in Figure 6d. Note the enhanced vertical ascent between 12°–20°N and descent to its north.

Based on the above results, it can be inferred that the mid-latitude disturbances such as shearlines associated with deformation zones besides the easterlies along the southern periphery of the WNPSH, also contribute to the pre-summer monsoon rainfall over the Philippines. To the best of our knowledge, this is the first attempt to clarify such phenomenon and document the role of deformation zones as another convective system during the pre-summer monsoon season of the Philippines.

The impact of deformation zones on the rainfall of the Philippines is more frequent during the winter monsoon season. In fact, some heavy rainfall events during this season are associated with shearlines, which is locally referred to as the effect of the “tail-end of the cold front” (Faustino-Eslava et al., 2011; Yumul et al., 2013; Olaguera et al., 2020). Olaguera et al. (2020) examined a winter heavy rainfall event case on January 16, 2017 over Mindanao Island in the southern Philippines and associated it with a shearline that was formed by the interaction of a low-pressure area over Mindanao Island and the enhanced northeasterlies to its north. They further noted that a cold front associated with these northeasterlies interacted with the warm and humid tropical air mass and resulted in the heavy rainfall event.

### 3.4 Daily evolution of the deformation zone

In this section, we examine the formation mechanism of the deformation zone through composite analysis of the long-lasting Type WEDef cases. We only selected one case in each year that lasted for at least two consecutive days

<table>
<thead>
<tr>
<th>Type</th>
<th>Conditions</th>
<th>No. of cases (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type D (Dry days)</td>
<td>OLR ≥ 240 W m$^{-2}$</td>
<td>1,618</td>
</tr>
<tr>
<td></td>
<td>Rainy grid points &lt; 10%</td>
<td></td>
</tr>
<tr>
<td>Type W (Wet days)</td>
<td>OLR &lt; 240 W m$^{-2}$</td>
<td>485</td>
</tr>
<tr>
<td></td>
<td>Rainy grid points &gt; 10%</td>
<td></td>
</tr>
<tr>
<td>Type W (Wet days)</td>
<td>U_{925hPa} &gt; 0 m s$^{-1}$</td>
<td>175</td>
</tr>
<tr>
<td></td>
<td>U_{925hPa} &lt; 0 m s$^{-1}$</td>
<td>310</td>
</tr>
<tr>
<td>Type W_{EDef}</td>
<td>U_{925hPa} &lt; 0 m s$^{-1}$</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>VIMFC &gt; 0 kg m$^{-2}$ s$^{-1}$</td>
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<tr>
<td></td>
<td>$\frac{\partial u}{\partial z}$ &gt; 0 s$^{-1}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T_{Def925hPa} &gt; 0 s$^{-1}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\frac{\partial q}{\partial y}$ &lt; 0 K m$^{-1}$ over 120°–122.5°E, 20°–25°N</td>
<td></td>
</tr>
</tbody>
</table>
out of the 70 Type WEDef cases from 1979 to 2015. Hence, we came up with 13 cases that are summarized in Table 2. Lag 0 indicates the first day of each of these 13 cases and the preceding and succeeding lag days are denoted by a “−” or “+” sign, respectively. The average duration of these 13 cases is about 3 days.

Figure 7 shows the composites of OLR and \( W_{925hPa} \) for the Type WEDef cases, while Figure 8 shows the APHRODITE rainfall composites. At Lag −4 (Figure 7a) easterly to southeasterly \( W_{925hPa} \) are apparent over the country. These easterlies are associated with the southern flank of the WNPSH that is centred around 140°W, 30°N (A₁). The WNPSH remains stationary in the same location throughout the composites. Two cyclonic circulations are located to the north of Japan along 50°–60°N and propagates eastward in the succeeding lag days. The rainfall increases by about 15 mm-day\(^{-1}\) over the northern Luzon Island and to the south is about 5 mm-day\(^{-1}\) (Figure 8a). An anticyclonic circulation (hereafter, A₂) can be seen in the east of the Tibetan Plateau and a deformation zone is formed over mainland China. At Lag −3 (Figure 7b), A₂ moves eastward, while the deformation zone moves southeastward and centred around 125°E, 30°N. The confluence region on the western side of the deformation zone appears over mainland China. The rainfall over Luzon Island appears to increase on the western coast (Figure 8b). At Lag −2, the deformation zone is now centred at 130°E, 28°N, while A₂ is now centred at 120°E, 35°N (Figure 7c). Note that the mainland China is under the influence of an anticyclone in the east of the Tibetan Plateau. At Lag −1 (Figure 7d), the northerly/northeasterly \( W_{925hPa} \) associated with A₂, expand southward over the northern SCS. Another cyclonic circulation develops along 55°N and its southern flank extends further south along 25°N. The rainfall increases to the northeast of Luzon Island (Figure 8c). At Lag 0 (Figure 7e), A₂ proceeds southeastward and accompanied by the southeastward progression of the deformation zone around 130°E, 25°N. Rainfall starts to increase to about 15 mm-day\(^{-1}\) over Luzon Island, especially on the eastern coast (Figure 8e). This rainfall distribution appears

\[
\begin{align*}
\text{(a) } & STD_{925hPa} \\
\text{(b) } & SHD_{925hPa} \\
\text{(c) } & TDef_{925hPa}
\end{align*}
\]
until Lag +2 over Luzon Island. At Lag +1 (Figure 7f), A₂ is now located over eastern China and convection over Luzon Island is enhanced. The confluence region along the deformation zone is located over northern Luzon Island. At Lag +2 (Figure 7g), A₂ proceeds eastward around 130°E, 30°N, while the deformation zone is located to the east of 140°E. Rainfall over the Philippines starts to weaken (Figure 8g). In the succeeding lag days (not shown), A₂ merges with A₁, the deformation zone dissipates, and the convection decreases again over Luzon Island.

4 | SUMMARY AND DISCUSSION

This study investigated the climatological characteristics of the wet/dry conditions in the pre-summer monsoon period of the Philippines. We defined the pre-summer monsoon period as the period from April

Table 2: List of deformation cases that lasted for at least two consecutive days from 1979 to 2015

<table>
<thead>
<tr>
<th>Year</th>
<th>Month-day</th>
<th>Duration (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>May 18–21</td>
<td>4</td>
</tr>
<tr>
<td>1981</td>
<td>May 18–19</td>
<td>2</td>
</tr>
<tr>
<td>1985</td>
<td>April 22–24</td>
<td>3</td>
</tr>
<tr>
<td>1988</td>
<td>April 8–9</td>
<td>2</td>
</tr>
<tr>
<td>1994</td>
<td>May 18–19</td>
<td>2</td>
</tr>
<tr>
<td>1995</td>
<td>May 9–11</td>
<td>3</td>
</tr>
<tr>
<td>1996</td>
<td>April 11–12</td>
<td>2</td>
</tr>
<tr>
<td>1999</td>
<td>April 5–6</td>
<td>2</td>
</tr>
<tr>
<td>2000</td>
<td>April 15–16</td>
<td>2</td>
</tr>
<tr>
<td>2006</td>
<td>May 13–14</td>
<td>2</td>
</tr>
<tr>
<td>2007</td>
<td>May 7–9</td>
<td>3</td>
</tr>
<tr>
<td>2009</td>
<td>April 25–May 1</td>
<td>7</td>
</tr>
<tr>
<td>2013</td>
<td>May 25–26</td>
<td>2</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6: Composites of (a) outgoing Longwave radiation (OLR; shades; W m⁻²) and winds at 925 hPa (WINDS₉₂₅hPa; streams; m s⁻¹), (b) APHRODITE rainfall (shades, mm day⁻¹), (c) 200 hPa winds (WINDS₂₀₀hPa; streams; m s⁻¹), and (d) pressure-latitude cross-section of meridional gradient of equivalent potential temperature (∂θₑ/∂y; contours; K m⁻¹) between 120°–122.5°E superimposed with the meridional circulation (vectors; V, m s⁻¹; OMEGA, Pa s⁻¹) (vectors). The scale of the unit vector in (d) is 5 m s⁻¹ and 5 Pa s⁻¹ [Colour figure can be viewed at wileyonlinelibrary.com]
1 to the onset date in each year. The onset dates are based on simultaneous and persistent rainfall occurrences over the western coast of the country and are provided by PAGASA, the country's official weather bureau. Based on the APHRODITE rainfall data set, the pre-summer monsoon rainfall only contributes by about 7.3% to the total annual rainfall over Luzon Island.
First, we classified the pre-summer monsoon period into wet cases (Type W; at least 10% of the grid points from the APHRODITE data set over Luzon Island have rainfall greater than 0 mm $\text{day}^{-1}$ and the area averaged $\text{OLR}$ is less than 240 W $\text{m}^{-2}$) and dry cases (Type D; $\text{OLR} \geq 240$ W $\text{m}^{-2}$ and rainy grid points from the APHRODITE data set is less than 10%). The Type W (Type D) cases account for about 23.1% (76.9%) of the total pre-summer monsoon cases from 1979 to 2015, suggesting that the pre-summer monsoon period over the Philippines is relatively dry. At 200 hPa, the SAA is already located over the Indochina Peninsula and northeasterly $\text{WINDS}_{200\text{hPa}}$ on its eastern edge are apparent over the Philippines for the Type W composite. The differences in the Type W and Type D composites feature an enhanced southerly $\text{WINDS}_{200\text{hPa}}$ that significantly contribute to the convection in the Type W composite. No significant difference in the $\text{WINDS}_{200\text{hPa}}$ are found between the composites over the Philippines, suggesting that the low-level circulations largely affected the pre-summer monsoon rainfall and $\text{OLR}$ fields over the country.

Next, we further classified the Type W cases into two sub-types based on the wind conditions, (a) wet conditions associated with westerlies (Type $\text{WW}$), and (b) easterlies (Type $\text{WE}$), and created composites. The Type $\text{WW}$ (Type $\text{WE}$) account for about 63.9% (36.1%) of the total Type W cases. The Type $\text{WW}$ composites show apparent southerly winds over the Philippines and the WNPSH that is located to the east of the Philippines, indicating that the summer monsoon over the Indochina Peninsula and the SCS has already started. In contrast, the Type $\text{WE}$ composite show enhanced convection over the Philippines, with apparent southeasterlies that converge with the summer monsoon westerlies over the Indochina Peninsula.

We also classified the Type D cases into Type $\text{DE}$, which account for about 88.1%, and Type $\text{DW}$, which account for about 11.9% of the total Type D cases. Another classification is analysed, which is a subset of Type $\text{WE}$ cases, when a deformation zone develop to the north of Luzon Island that is accompanied by an eastward propagating cold front, an anticyclone to its west, and another stationary anticyclone over the north Pacific. These cases are denoted as Type $\text{WEDef}$. There are only 70 of such cases from 1979 to 2012. The interaction of the cold front to the north of the deformation zone and the warm and humid air from the prevailing easterlies induce enhanced convergence and rainfall over Luzon Island.

In general, the results of this study reveal that aside from the convective activity brought by the easterly $\text{WINDS}_{200\text{hPa}}$ along the southern flank of the WNPSH, mid-latitude disturbances may also contribute to the pre-summer monsoon convection over the Philippines. For the first time, the role of deformation zones as another convective system during the pre-summer monsoon season over the country is presented. There are still many

**FIGURE 8** As in Figure 7 but for the APHRODITE rainfall (mm $\text{day}^{-1}$) [Colour figure can be viewed at wileyonlinelibrary.com]
issues left unaddressed in the present study. For instance, we only showed that the intermittent convective events during the pre-summer monsoon season is a synoptic-scale phenomenon. The contribution of the localized thunderstorms on the pre-summer monsoon convection have yet to be investigated. Also, the contribution of all these aforementioned factors on the pre-summer monsoon convection should be quantified. The role of cold fronts in triggering the onset of the summer monsoon over the SCS has long been recognized (Chan et al., 2000). In fact, it is one of the factors that makes the onset detection of the summer monsoon over the SCS more complicated (Wang et al., 2004). The current available indices in detecting the onset over the SCS such as those proposed by Wang et al. (2004) are oversimplified and exclude the impact of these cold fronts. Finally, how these cold fronts can also affect the onset of the summer monsoon over the Philippines is also an interesting issue.

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CONFLICT OF INTEREST
The authors declare that they have no competing interests.

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**SUPPORTING INFORMATION**

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

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