Climatological seasonal changes of wind and rainfall in the Philippines

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Abstract
Climatological seasonal changes of rainfall and lower tropospheric circulation in and around the Philippines are analysed by utilizing the TRMM 3B42 to obtain the 5-day mean rainfall and ERA-Interim wind data for the period 1998–2013. In particular, climatological onset and withdrawal processes of the southwest (SW) and northeast (NE) monsoon are investigated. It is found that the onset of the SW monsoon occurs abruptly in mid-May almost simultaneously over the Philippines except in the southern region. The start of the SW monsoon in the Philippines occurs earlier in the north than in the south. In addition, a climatological increase in rainfall on the west coast precedes the SW monsoon arrival by approximately two pentads, due to tropical cyclone influences in some years. After the SW monsoon onset, the monsoon trough is located over the southern Philippines. In mid-June, the monsoon trough begins to deepen, and migrates northward to the central Philippines, and easterly winds intrude shortly to the northern Philippines. Then, the entire Philippines is covered by the summer monsoon westerly in early July, which is followed by the rainfall peak over the west coast region occurring in early August. The SW monsoon begins to retreat from the north in mid-September, and fully retreats from the Philippines rather suddenly in late September. In general, the rainfall amount in the west coastal region remains high for approximately 2 months after this wind reversal, showing relatively larger post monsoon rainfall due mainly to tropical cyclone effects. During the NE monsoon season, the rainfall centre in the east coast is located in the northern and central region until mid-December. Afterwards it is anchored in the southern region from late December to mid-March, indicating the fully established NE monsoon season.

[Correction added on 28 May 2020, after first online publication:
Citations of figures were previously incorrect and have been updated in this version.]
1 | INTRODUCTION

The monsoon climate is characterized by the seasonal reversal of prevailing winds between winter and summer, as shown by Ramage (1971) whose map includes the Philippines and part of the western North Pacific in the Asian monsoon region. Murakami and Matsumoto (1994) first defined the western North Pacific monsoon (WNPM) in which the Philippines is the only major landmass included.

The seasonal onset and retreat of monsoons have long been regarded as important seasonal change points dividing the dry winter and wet summer seasons, particularly in India (India Meteorological Department, 1943). Ramage (1971), and Tao and Chen (1987) showed isolines of the summer rainy season onset in the entire Asian monsoon region. However, these maps were drawn by compiling various sources of regional monsoons. Thus, their onset definitions were not uniform within the domain. In addition, in these maps, no isolines were drawn over the Philippines, probably because of the lack of data. However, Coronas (1920) identified precise climate regions over the Philippines based on monsoonal rainy seasons, and Flores and Balagot (1969) described that the Philippines is influenced both by the winter northeast (NE) monsoon and summer southwest (SW) monsoon. Although not well known, Asuncion et al. (1981) reported the climatological isolines of onset, peak, and retreat of the rainy seasons during both NE and SW monsoons based on the change of the angle tangential to the rainfall mass curve of 24 rainfall stations from 1951 to 1977. According to their figures, the seasonal onset and retreat progression patterns in these previous studies, although the timing is similar.

The monsoon onset in the Philippines has been investigated by Akasaka et al. (2007), in which the Empirical Orthogonal Function (EOF) analysis was applied to 73 pentad mean rainfalls at 39 rainfall observing stations across the Philippines. They were able to identify the timing of the onset and withdrawal dates of summer rainy season in the country based on the sign change of the time coefficients of EOF1, which climatologically occur at P27 (May 11–15) and P62 (November 2–6) to P63 (November 7–11), respectively. Akasaka (2010) and Akasaka et al. (2018) further investigated the interannual variations of the monsoonal seasonal march based on the same criteria used by Akasaka et al. (2007). Moron et al. (2009) utilized station-based rainfall and CMAP data from all over the Philippines and defined the onset of rainy season, for both datasets, as the first wet day of a 5-day period receiving at least 40 mm without any 15-day dry spell receiving less than 5 mm in the 30 days following the start of that period. These studies first define the monsoon onset using rainfall data, then discuss its relationship with the large-scale atmospheric circulation. The local meteorological agency, the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) operationally defines the monsoon onset as the beginning of a five-day period (between April and July)
with total rainfall of 25 mm or more, and with three consecutive days having at least 1 mm of rainfall per day. This condition should be satisfied in at least six of the rainfall observing stations over the western coast of the country. By applying these criteria, Kubota et al. (2017) determined the monsoon onset over the Philippines for the period 1903–2013 and presented its decadal-scale variations. These aforementioned studies only provide one monsoon onset date for the entire Philippines. However, as shown by the previous larger-scale studies such as Asuncion et al. (1981), Moron et al. (2009), and Villafuerte et al. (2017), there are regional differences in the rainy season and monsoonal onset dates within the Philippines, which have not been fully documented yet. In addition, the circulation changes in the Philippines during the monsoon season or the seasonal transitions between the NE and SW monsoons have not been described well, although the stepwise large-scale changes in the WNPM (Wu and Wang, 2000, 2001; Wu, 2002; Ueda, 2005) and/or wider monsoon region (Matsumoto, 1990, 1992) have been pointed out and prominent climatological intraseasonal changes have been noted (Wang and Xu, 1997). Therefore, in this study we attempt to describe in detail the seasonal changes in the lower tropospheric winds and rainfall based on 5-day mean data.

The rest of the paper is organized as follows. The data and methodology used in this study are presented in Section 2. In Section 3, we describe and discuss the seasonal evolution of the climatological rainfall and low-level winds over the Philippines. Conclusions are given in Section 4.

2 | DATA AND METHODS

We utilized the TRMM3B42 Version 7 daily rainfall data (Huffman and Bolvin, 2013), with a horizontal resolution of 0.25° grid. As for the wind data, we utilized the 6-hrly (i.e., from 00Z to 18Z) zonal and meridional wind at 850 hPa from The European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis, with a horizontal resolution of 0.75° grid (Dee et al., 2011). We averaged the four 6-hrly data to obtain the daily zonal and meridional wind data. Both data are prepared for the period 1998–2013. Then, pentad means are calculated for the 16 years. The pentad number is defined from 1 (January 1–5) to 73 (December 27–31) excluding February 29 in leap years, and hereafter, denoted like P1 (Pentad 1). In order to see the seasonal change processes in and around the Philippines, we generate 5-day mean 850 hPa wind field and rainfall maps in each pentad and examine the remarkable features found between consecutive pentads. To further elaborate on the seasonal changes both in the west and east coast regions, north–south cross-sections along both coast lines are plotted using the grid point data shown in

3 | RESULTS AND DISCUSSIONS

3.1 | Climatological features of rainfall and low level circulation

The Philippines is affected by two monsoon systems, the SW monsoon and the NE monsoon in summer and
winter, respectively. Here, we utilize the term SW (NE) monsoon to be a large-scale wind exceeding approximately 1,000 km in horizontal scale from the south (north) to west (east) quadrant direction. The alternation of these two monsoon wind systems, and the location of monsoon trough, indicated by the maximum cyclonic curvature of the SW monsoon wind, are mainly discussed. Figures 2 and 3 presents some characteristics of

![FIGURE 2](image_url)
pentad mean rainfall and circulation at 850 hPa around the Philippines. Figure 2a presents the situation in February (February 20–24; P11) showing the typical condition in the NE monsoon season, locally known as Amihan. Wind from East-North-East direction is predominant all over the Philippines, except in northern Luzon Island where slight southerly component is found. This southerly flow in northern Luzon Island is commonly observed from the beginning of January, corresponding to the SW periphery of the western North
Pacific Subtropical High (WNPSH). Rainfall maximum is located along the east coast centered over Mindanao Island in the south, whereas rainfall is scanty in most part of the west coastal region, except Mindanao Island. These wind and rainfall patterns are commonly seen from mid-November to early April (not shown).

After April (Figure 2b), the easterly flow gradually weakens and rainfall peak in the eastern coast becomes obscure. Between mid-April (Figure 2b) and early May (P26: Figure 2c), rainfall gradually increases over the central mountainous region in Luzon Island. Wind condition is still similarly from the east in most part of the Philippines north of 8°N until mid-May (P27: Figure 2d). However, it is noted that rainfall substantially increases over the South China Sea including the western part of the Philippines at P26 (Figure 2c). Another remarkable feature worthy of note is that the northwesterly wind begins to invade the southern Philippines south of the monsoon trough around 8°N (indicated by a red dashed line) over Mindanao Island. The rainfall maximum in most of the Philippines has shifted to the west coast in P27 although wind direction is mostly from southeast (Figure 2d). This situation will be elaborated on in the next section. One pentad later in P28 (Figure 2e), the whole wind system in the north of 10°N abruptly changed from easterly to westerly, which clearly marks the onset of summer SW monsoon wind regime in the Philippines. The timing is almost the same as the first transition of the Asian monsoon (Matsumoto, 1997; Hsu et al., 1999; Ueda, 2005), or the climatological monsoon onset of the Philippines defined by Akasaka (2010), Akasaka et al. (2007, 2018), and Moron et al. (2009). In the east of Luzon Island is the southwestern periphery of the WNPSH anticyclonic flow, and the convergence between the southwesterly and southeasterly is located in the east of the northern Philippines, while it is over Visayas. On the other hand, the rainfall maximum around the Philippines is located over the ocean in the south of Taiwan, where southweste rly flow is predominant. This rainfall peak is related with the establishment of the Mei-yu/Baiu front over Taiwan/Okinawa region (Hirasawa et al., 1995; Chen et al., 2004) and concurrent with the onset of the South China Sea monsoon (Kajikawa and Wang, 2012). Similar rainfall features are also seen in rainfall distribution on the 1–10 days before the Philippines rainy season onset date in Moron et al. (2009), their Fig. 4b. It is also noted that although the wind has already shifted to southwesterly in the northern Philippines, it is still southeasterly in the south between 8 and 12°N. The Philippines is located near the converging region between the southwesterly and southeasterly. This is because of the cyclonic circulation centered at 8°N, 127°E in P28 indicating the monsoon trough being located in the southern part of the Philippines, and northwesterly is predominant over the western part of Mindanao in the south of this trough. Such situation continued until P33 (June 10–14; Figure 2f).

In P34 (Figure 2g), the easterly wind in the southern part of the Philippines changes to westerly. The wind over the Philippines tends to have more southerly component in this season. This indicates that the confluence zone between the westerly and easterly shifts eastward in the east of the Philippines due to the eastward retreat of the WNPSH (Olaguera et al., 2018a, 2018b, 2020b, submitted). The monsoon trough is located in the central part of the Philippines. It is noted in some pentads in this period, southeasterly flow from the WNPSH covers the northern part of Luzon Island. Such conditions continue until early July (P37; Figure 2h).

Then, in P38 (July 5–9), the westerly wind region in the north of the Philippines expands eastward and northward and southwesterly wind covers the entire Philippines, indicating SW monsoon, locally known as Habagat, has fully established. Subsequently, the axis of the monsoon trough has migrated to the NE of the Philippines, as typically shown in Figure 2i (P38; July 5–9).

Although not so obvious from the streamline chart in Figure 3a, SW monsoon flow strengthen from late July, as will be shown later in Figure 4, and the Philippines sets in the mature stage of SW monsoon season. The peak of both rainfall in the west coast and westerly wind speed occurs in early August in P44 (Figure 3b), which is somewhat earlier than the period shown in Wang and LinHo (2002). The rainfall peak in the west coast and its relationship with the South China Sea monsoon was elaborated on by Chen et al. (2017b). The wind regime around the Philippines is not changed much with the West-North-West to East-South-East oriented monsoon trough located in the north of the Philippines until early September in P51 (August 29–September 2; not shown).

Then, the monsoon trough dividing the monsoon westerly in the south and easterly in the north over the eastern South China Sea and north of the Philippines in P52, as shown in Figure 3c, starts to migrate southward across the Philippines from mid-September (Figure 3d). This indicates the commencement of the retreat of SW monsoon from the South China Sea, as shown in Matsumoto (1997). In turn, northeasterly flow begins to proceed into the Philippines from the north, indicating the start of the NE monsoon season. In P53, the monsoon trough further migrate southward and begins to enter the northern part of the Philippines (Figure 3d). The monsoon trough gradually and continuously moves southward, as shown in Figure 3e (October 3–7) and Figure 3f (October 13–17), when it is located in Visayas.
Due to this wind change, the rainfall peak in Luzon Island shifts to the east coast in this period. However, rainfall amount in the west coast is not dramatically decreased for approximately 2 months even after this wind change. It is also noted that the westerly flow in the south of the monsoon trough begins to have northerly component from early October. Based on our definition, it indicates the termination of the SW monsoon. This circulation feature seems to be influenced by the cyclonic flow centred off the east coast of the Philippines.

The northeasterly flow fully covers the entire Philippines, except its southern most portion in the south of 8°N in P60 (October 23–27; Figure 3g). Monsoon trough stagnates for approximately 3 weeks until early November in the southern part of the Philippines over Mindanao Island. Then from mid-November in P64 (Figure 3), the NE monsoon prevails over the whole Philippines until the end of the year.

3.2 Spatial contrasting features of rainfall and low-level circulation along the west and east coasts

In the previous subsection, some abrupt changes in the wind field are observed between the two consecutive pentads (e.g., P27–P28; see Figures 2), which may indicate the seasonal change turning point. In order to elaborate on the abrupt changes in rainfall and wind fields, the time-latitude cross-sections along the west (Figure 4a) and the east coasts (Figure 4b) of the Philippines (see, Figure 1 for the location of grids used in defining the east and west coasts) are shown. An abrupt change of wind regime from the easterly to westerly monsoon is obvious in mid-May over most part of the Philippines except in the south of 8°N where the change occurs in early May along the west coast (Figure 4a). If we look more closely, this shift in the north of 8°N occurs earlier in the north by one pentad than in the south, and the latest occurrence is seen around 10°N. In addition, as observed in Figure 2, the rainfall increases along the west coast begins from early May, 1–2 pentads earlier than the wind shift. Rainfall in the west coast is in general below 2 mm day$^{-1}$ before mid-March in the north of 15°N, indicating a prominent dry season. While the rainfall gradually increases from mid-March, and from mid-April, the rainfall exceeds 2 mm day$^{-1}$ (Figure 4a).

In the east coast, the wind shift from easterly to westerly occurs almost simultaneously with the west coast in mid-May in the north of 13°N. While, easterly wind remains until early June in the southern part of the country (Figure 4b). It is also noted, although the rainfall is relatively abundant along the east coast during the easterly monsoon flow, the rainfall in the north of 15°N is somewhat less from the beginning of January until mid-April compared with that in the south. In this period, rainfall peak in the east coast is located between 8 and 10°N over the northern Mindanao Island. In particular, rainfall is scanty in the north of 13°N from early to mid-April. It should be noted that even after the wind shift from easterly to westerly in mid-May, the rainfall amount in the east coastal region remains high exceeding 4 mm day$^{-1}$, although amount-wise less than the west
coast, as will be shown later in Figure 9. This is because the mountain ranges in the Philippines are not high enough to block rainfall induced by SW monsoon. Therefore, in the westerly monsoon season, rainfall is abundant both in the west and east coastal regions.

The discrepancy between the rainfall seasonal changes and monsoonal wind shift presented here is one of the important findings of the present study. As noted previously in Matsumoto (1997) for the rainy season over the Indochina Peninsula, sometimes earlier rainy season onset can be recognized in the Asian monsoon region. As for the rainfall increase in the Indochina Peninsula, Kiguchi and Matsumoto (2005) and Kiguchi et al. (2016) attributed to the influence of mid-latitude westerly trough to the occurrence of rainfall before the monsoon circulation onset. On the other hand, Akasaka (2010) and Akasaka et al. (2007, 2018), and Moron et al. (2009) did not present such discrepancy between the rainy season onset and monsoonal wind changes. In order to investigate the reason for this discrepancy, we have plotted the similar time-latitude sections of rainfall and wind in each year, as in Figure 2, and found that in 9 years (1999, 2000, 2001, 2004, 2005, 2007, 2008, 2009, and 2011) the increase of rainfall occurs earlier than the wind shift from easterly to westerly, while in other years, they change almost simultaneously. The composite of rainfall and zonal wind at 850 hPa for these years are shown in Figure 5. It is clearly seen that in the former years, the rainfall peak is observed in P26–27 prior to the wind shift from easterly to westerly (Figure 5a), on the other hand, in the latter years, rainfall peak appears after the wind shift (Figure 5b).

One of the main factors for these differences may be the existence of TCs. Chen et al. (2010) noted that the Philippines summer monsoon onset in 2008 is preceded by the twin TCs in the South China Sea and the Philippines Sea, and Chen et al. (2017a) presented that TC genesis often occur over the South China Sea in May accompanied by the South China Sea monsoon onset. Therefore, we have plotted the location of the TCs in P26 and P27, prior to the climatological monsoonal wind shift in Figure 6. It is clearly seen that in the years when rainfall increase prior to the wind shift, TCs are located near Luzon Island, while in the latter years, no TCs are located near the Philippines. Although the local rainfall prior to the monsoonal wind change may contribute some for these differences, Figures 5 and 6 imply that the TC induced rainfall strongly influence the increase of rainfall on the west coast of Luzon Island prior to the SW monsoon onset in the west coast. Kubota et al. (2017) have already noted the influence of TCs on the monsoon onset over the Philippines. Except 2001, our TC existent years are all coincide with TC related onset years identified by Kubota et al. (2017). Kubota et al. (2017) showed for the case year 2013 that during the onset induced by TC, the wind in the southern (northern) Philippines is southwesterly (southeasterly), which is consistent with this result, and we newly find that in these years, the SW monsoon circulation establishes later after the rainfall increase induced by TCs. It is also noted our targeting years are corresponding to the higher probability of TC existence (PTCe) period.

The opposite change from westerly to easterly, on the other hand, starts from the north in mid-September, and gradually migrates southward until mid-November with

![Figure 5](image-url)
some clear stagnations in early October in 15°N, mid-October in 13°N, and late October to early November in the south of 8°N. From early October, the westerly wind begins to show northerly component, thus it cannot be regarded as SW monsoon by our definition. These features are obvious along both coasts but the late October to early November change is only obvious along the west coast (Figure 4). It is also noted that although the rainfall amount decreases, it is still higher than 4 mm day⁻¹ after the wind shift along the west coast in the north of 15°N and 10°N until mid-November and mid-December, respectively. This is the peculiar post-SW monsoon rainfall over the west coast region. In contrast, the rainfall amount along the east coast region, in general, increases substantially associated with the monsoonal wind shift from westerly to easterly.

Figure 7 presents the location of TCs in every 9 pentads between P54 and P62, between P63 and P71, and between P72 and P10. These periods are corresponding to the rainfall situations. When rainfall is abundant in the whole Philippines along the west coast, decreased along the west coast in Luzon Island between 14°N and 18°N, and decreased along the west coast in the north of 10°N. It can be observed, that in Figures 7, the main course of TCs is passing across Luzon Island from P54 to P62 (Figure 7a). On the other hand, the main course of TCs shifts southward to the Visayas from P63 to P71 (Figure 7b). After P72, number of TCs dramatically decreases, and several TCs are located in the PAR without passing over the Philippines (Figure 7c). This indicates that the effect of TCs is minimal in this period, and rainfall over the west coast is substantially decreased. Although more precise analysis is needed to quantify the influence of TCs on the rainfall, it can be inferred that the relatively abundant rainfall after the monsoonal wind shift on the west coast can be attributed mainly to the TCs.

The time-longitude cross-sections of pentad mean rainfall and zonal wind speed at 850 hPa along 16–17°N, representing central Luzon Island in the north, and along 8–9°N (to represent the northern Mindanao Island), are shown in Figure 8, respectively. Easterly winds are predominant observed over the central Luzon Island until mid-May. Such dominance of easterly wind is associated with rainfall maxima around 122–123°E (along the east coast of the Philippines), which lasts until early May. Also noted is the systematic westward extension of high rainfall area represented by 4 mm isohyet in these rainfall peak events in the intraseasonal time-scale from January to May. In early May, just before the change of the monsoonal wind, two rainfall peaks appear around 120°E and 122°E indicating more abundant rainfall in both west and east coastal areas, respectively. Easterly wind revival episode in the northern part between mid-June and early July is clearly seen in both western and eastern coasts, while it is more obvious in the east coast. Such east–west slight differences are well observed in the time-longitude cross-sections in Figure 8a along central Luzon Island. Another feature worthy of note in Figure 8a is the shift in the location of maximum rainfall during the SW and NE monsoon seasons. In particular, rainfall is more abundant around 122°E from January to April and from October to December, while it is more abundant between May to September around 120°E. This regional contrast in rainfall is induced by orographic effect. Over the northern part of Mindanao Island (southern region of the Philippines), there is a delay in the shifting of the winds from easterly to westerly in the east of 124°E until mid-June just before the revival of easterly in the north (Figure 8b). Abrupt change of zonal wind from wintertime easterly to summer westerly is obvious in all region in this area in mid-May. The rainfall peak in the east coast area is also observed in the winter monsoon season along 126°E from January to mid-May and mid-October to December. The wind shift from easterly to westerly occurs in early May, somewhat earlier than the north in the west of 120°E. The abrupt change in mid-May is not obvious in this zone, but can be recognized between 122°E and 125°E. After that easterly wind
to the east of 125°E continues until mid-June, almost simultaneously with the easterly wind revival in the north. Summer-time rainfall peak in the west coast around 122°E becomes a bit obvious from that period with some peaks in the intraseasonal time-scale in late June and early August. The latter is almost simultaneous with the westerly wind peak. The wind shift from west to east occurs widely in late October, almost 1 month later than in the northern Luzon region (see, Figure 8a). As seen in the north, the rainfall peak in the east coast area becomes obvious later from mid-November. Rainfall amount in the west of 121°E suddenly increases including the South China Sea. This event can be regarded as an important turning point from winter monsoon to summer monsoon regime in the northern Philippines.

As discussed earlier, the entire Philippines is almost fully dominated by the summer monsoon westerlies after early July. It is interesting to note, however, that the rainfall centre shifts from the east coast to the west coast in mid-May in the northern Luzon region (Figure 8a). To clarify this further, the time-latitude section of the rainfall differences between the west and east coasts of the Philippines are shown in Figure 9. This highlights the rainfall contrast between the west and east coasts in a wider region of Luzon. The west coast of the country is wetter than the east coast over the regions extending from 10 to 18°N in early May, where rainfall amounts sometimes exceed 8 mm day\(^{-1}\). This rainfall contrasts between the west and east coasts change the sign from positive (more rainfall in the west) to negative occurring in mid-November in the south of 9°N, and then the whole country is covered by winter monsoon/rainfall regime. It should also be noted that before mid-December easterly wind peak is located at 14.5°N, while it shifts southward to 12.5°N in late December and then in 10–11°N after January along the west coast (Figure 4a). Wind alternation from west to east occurs widely in late September with slight east–west time differences. On the other hand, rainfall is still abundant including the west coastal area until mid-October as shown in Figure 8. This discrepancy of the wind regime and rainfall distribution is probably due to the activities of TCs.

Based on the above description, schematic diagrams on the seasonal changes of the Philippines monsoon and rainy season along the west and east coastal regions are presented in Figure 10, respectively. In this figure, the relatively rainfall abundant regions exceeding approximately 4 mm/day, and their core rainy seasons exceeding 16 mm/day are shown in bluish colour. It is noted that in the west coast, the rainy season is confined in the boreal summer to autumn, while in the east coast, rainfall decrease in the boreal summer season is not very conspicuous except the minimum rainfall period in April in the northern part. This is consistent with the seasonal rainfall variations on both coastal regions shown by Moron et al. (2009). In Figure 10, the monsoonal wind changes are indicated by thick lines. It indicates rather complicated monsoonal and rainfall seasonal changes in the Philippines, and the monsoonal wind changes do not directly related with the rainfall changes. The NW monsoon is predominant in the south of 16°N from January to the end of April. The wind transition occurs in early to mid-May, and the SW monsoon first invades into the

![Figure 7](image-url)
Philippines to the north of 10°N in mid-May. On the other hand, rainfall along the west coast region suddenly increases approximately 2-pentads earlier in early May (May 6–10) corresponding to the end of the NE monsoon season. In this short period, the wind in the northern Philippines is southeasterlies, and this rainfall increase is mainly due to the TC affects prior to the SW monsoon onset in some years (Figure 6). The prevailing southeast-erly wind during the onset of summer rainy season is consistent with the result of Moron et al. (2009). After mid-June, the SW monsoon basically prevails over the whole Philippines. Even after the SW monsoon onset, easterly wind sometimes invades into the Philippines in the east coast region in the south until mid-June, and in the north until early July when it also invades in the west coast. After mid-July, SW monsoon fully covers the Philippines accompanied with northward shift of the monsoon trough in the western Pacific, indicating its full establishment. The peak rainy season in the west coast occurs in August. During the SW monsoon season, rainfall is relatively smaller on the east coast compared with the west coast, still the rainfall amount is not scanty over the east coast region, indicating that the whole country is influenced by the SW monsoon.

The retreat of the SW monsoon starts from the northern tip in mid-September, and it shifts southward to the southern tip rather abruptly in late September on both coasts almost concurrently. After the termination of the SW monsoon, northwesterly flow in the north of monsoon trough prevails in the central and southern regions on both coasts, which can be regarded as an autumnal transition. Then the NE monsoon gradually proceeds from the north. It is noted that rainfall in the west coast region remains high approximately for 2 months after the wind reversal. This is also the effect of TCs as shown in Figure 7. Compared with the spring transition, it is
characterized by the gradual southward shift until mid-December. This gradual southward shift of the NE monsoon was first pointed out by Kubota et al. (2017), and will be strongly related with TC activities, although further analysis is needed. After mid-December, the rainfall in the west coast region north of 9°N becomes scanty because of the much less affection of TCs and monsoonal wind shade. On the other hand, the rainfall is peaking along the east coast in early to middle December due probably to the NE monsoon.

It is noted that the region in the south of 9°N, over Mindanao Island, rainfall in the west coast region is abundant almost in the whole season. Therefore, although from the perspective of wind reversal, this region is within the monsoonal regime from the prevailing wind direction, but from the rainfall perspective, it is excluded as monsoonal rainfall regime. This is roughly in agreement with the delineation of the WNPM region by Murakami and Matsumoto (1994) and/or Wang and LinHo (2002). In addition, it is noted that the rainfall over the east coast is abundant (exceeding 4 mm/day) almost whole year except from January to April in the northern part, although the rainfall amount is relatively less during the SW monsoon season compared with the west coast (Figure 9). Therefore, simple alternation of wet and dry seasons according to the monsoonal wind cannot be applied to the rainfall regimes in the Philippines. The discrepancies between the monsoonal wind shift and rainfall during the monsoon transitional seasons are mainly attributed to the effect of TCs. Murakami and Matsumoto (1994) have noted that the effect of short term (about 5-day) disturbances are predominant during the onset and retreat phases of the WNPM. Here we confirm the effect of TCs on rainfall over the Philippines during the monsoon transitions.

4 CONCLUSIONS

Climatological seasonal changes of rainfall and lower tropospheric circulation in the Philippines are analysed by
utilizing the TRMM 3B42 rainfall and ERA-Interim wind data covering the period from 1998 to 2013. The climatological pentad means of rainfall and 850-hPa wind fields were derived and used to describe the onset and withdrawal processes of the SW and NE monsoons in the country. It is found that the grand onset of SW monsoon occurs abruptly in mid-May almost simultaneously over the Philippines except in the southern region south of 8°N where westerly monsoon arrives earlier by approximately 2 pentads in early May. After the mid-May grand onset, SW monsoon starts from the north in the Philippines. This slight difference of onset between sudden rainfall increase and monsoonal wind shift is newly found in this study. The differences observed in the long-term climatology are mainly attributed to the TC influences before the summer monsoon onset in approximately the half years of analysis.

After the onset, confluence zone between summer monsoon westerly in the south and easterly from the North Pacific high is located in the east of the Philippines in the north, while in the south it is located almost in the Philippines, thus, in the east coast of the Philippines in the south, easterly wind continues to be predominant until mid-June (P33). After mid-June (P34), the WNPSH shifts northward and the whole southern Philippines is covered by westerly wind. This period corresponds well to the second abrupt seasonal change analysed by Wu and Wang (2001). Afterwards, due to the strengthening of the WNPSH, easterly flow prevails over northern Philippines until early July (P37). Then SW monsoon flow covers the whole country from early July (P38) and peaks in early August (P44), both for the low-level wind and rainfall. It is noted that during the SW monsoon season, rainfall is relatively smaller on the east coast compared with the west coast, still the rainfall amount is not scanty over the east coast region, indicating that the whole country is influenced by the SW monsoon. The SW monsoon begins to retreat from the north in mid-September, and fully retreats from the southern tip of the Philippines in mid-November. Even after the change of wind regime, rainfall amount remains higher along the west coast for approximately 1 month, which is also attributed to the TC activities. According to Akasaka et al. (2007) and Akasaka et al. (2018) the end of rainy season in the Philippines occurs in late December. As such monsoon wind regimes alone cannot explain the seasonal rainfall regimes, since in the Philippines, rainfall contribution from the TCs is relatively high (approximately 37–55% at central and northern Luzon Island stations from July to October, as shown by Kubota and Wang, 2009).

The wind fields are presented only at 850 hPa, while if we see the situation at 925 and 1,000 hPa, similar features are found (not shown). Anyway, in monsoon climatology, wind direction relative to the monsoon wind has been so far regarded as one of the most important climatological features in Asian monsoon region (e.g., Chang et al., 2005). Here, we show the clear discrepancies between the rainfall increase or decrease and monsoonal wind change both of which occur in rather abrupt nature in both onset and retreat of SW monsoon over the Philippines. Here, we have regarded SW and NE monsoon flow simply from the wind directions, and do not consider the origin of these winds. In particular, for the NE monsoon, as noted in Flores and Balagot (1969), easterly flow sometimes originated from the North Pacific subtropical high, and sometimes from the Siberian High. More precise analysis is needed on the differences between these circulation fields on the rainfall situation along the east coast. In addition, as for the influence from the TCs we only present the TC track maps for presenting their influence. More quantitative analysis are needed to firmly present the effect of TCs on the rainfall over the Philippines. Moreover, in addition to TCs, some other synoptic systems, such as mid-latitude front or disturbances (e.g., Olaguera and Matsumoto, 2019; Olaguera et al., 2020a), or local rain systems such as diurnally driven local circulation are also contributing to the rainfall. The contribution from these systems on climatological rainfall seasonal changes should also be studied in future.

This study presents only climatological mean fields for 16 years. As noted by a number of previous studies (e.g., Hattori et al., 2005; Akasaka, 2010; Kubota et al., 2017; Chen et al., 2017a; Akasaka et al., 2018; Olaguera et al., 2018a, 2018b), there are large interannual and inter-decadal variations both on the onset timing as well as seasonal evolution and strength of monsoon. How the climatological seasonal march is modulated by these variations should be investigated further in the future by utilizing longer period data. In addition, this study presents the wind fields only utilizing the ERA-Interim data. Since the main target region is near the Philippines where the local station observation data are added to the initial field of the reanalysis, we guess the differences by the different reanalysis maybe not very big. However, this should be examined in future. Furthermore, how climate models can reproduce these minute seasonal change features will be important for investigating the local climate projections, in particular, related with rainfall.

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