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Changes in intensity and tracks of tropical cyclones crossing the central and southern Philippines from 1979 to 2020: an observational study

Clint Eldrick R. Petilla[1,2], Leia Pauline S. Tonga[1,2], Lyndon Mark P. Olaguera[1,2,3*] and Jun Matsumoto[3,4]

Abstract

Observational studies on the characteristics of tropical cyclones (TCs) crossing Mindanao and Visayas Islands, in the southern and central Philippines, respectively, remain limited. To address this research gap, this study investigates the changes in the translational speeds, the direction of motion, and intensities of 8 and 39 landfalling TCs crossing Mindanao and Visayas Islands, respectively, from 1979 to 2020. The intensities, translational speeds, and direction of motions of the TCs were characterized by their position before (approaching point; AP), during (landing point; LP), and after (departing point; DP) traversing through Mindanao and Visayas Islands. The results show a significant linear relationship in the intensity change between AP and DP, indicating a general weakening of TCs as they traverse both island groups. About 5 (29) TCs showed a decrease in intensity based on the maximum sustained wind speed (MSW) after crossing Mindanao (Visayas). The intensity of TCs with at least Typhoon category upon landfall, decreased on average (percentage) by about 23.33 kts (− 25.4%) and 24.29 kts (− 45.5%) after crossing Mindanao and Visayas, respectively. The MSW of weaker TCs decreased on average by about 6.67 kts (− 25.0%) and 8.13 kts (− 20.5%) after traversing Mindanao and Visayas, respectively. Cases with increased (1 TC for Mindanao and 6 TCs for Visayas) and no change in intensities (2 TCs for Mindanao and 4 TCs for Visayas) after crossing the island were also found. Landfalling TCs over Mindanao exhibited a characteristic where those deflected rightward (leftward) at AP tend to be deflected rightward (leftward) at DP, while no pattern was found for the TCs traversing Visayas. Furthermore, TCs moving across Mindanao and Visayas tend to decelerate as they approach and move away from the island. The findings of this study are essential for disaster mitigation and a greater understanding of the TCs behavior in terms of intensity, translational speed, and deflection.

Keywords Tropical cyclone, Tracks, Topography, Mindanao, Visayas

*Correspondence:
Lyndon Mark P. Olaguera
lmolaguera@observatory.ph
Full list of author information is available at the end of the article

1 Introduction

Tropical cyclones (TCs) remain one of the most destructive natural phenomena that induce heavy rainfall events, flooding, and strong wind damages in many tropical and subtropical coastal regions around the globe, including the Philippines (Kubota and Chan 2009; Cayanan et al. 2011; Fudeyasu et al. 2014; Cinco et al. 2016; Corporal-Lodangco and Leslie 2016; Kubota et al. 2017). The Philippines is located along the corridor of TCs over the western North Pacific and ranks 2nd in terms of TC landfall, following China (Wu et al. 2004; Kubota and Chan 2009; Fudeyasu et al. 2014). Recent studies showed that damage costs associated with TCs in the Philippines have been increasing in recent decades (Cinco et al. 2016; Basconcillo and Moon 2021). In particular, Basconcillo and Moon (2021) showed that the damage cost associated with TCs during the December to February season, which is the less active TC season in the Philippines, and in annual terms have increased after 2012. After this year, the estimated annual damage cost has been more frequently exceeding USD 500 million (see their Fig. 1). Therefore, it is crucial to analyze the characteristics such as tracks, landfall patterns, changes in the eye wall structure, and multi-scale spatio-temporal variability of TCs because of their profound socioeconomic impacts and for improving the country's disaster mitigation efforts.

As TCs traverse complex terrain after landfall, the topography affects their characteristics. Recent observational and numerical studies show that as a TC interacts with the land surface, its track and associated rainfall may change depending on the initial behavior of the TC. For example, the slow movement of Typhoon (TY) IN-FA (2021), when it made landfall in Zhejiang, South China, together with the terrain effects under continuous north/northeasterly air flow resulted in extreme precipitation. Other factors include topography providing vertical transport of water vapor and the development of low-level vertical circulation along with the terrain effects, resulting in prolonged intense rainfall (Yang et al. 2022). Idealized numerical experiments by Huang et al. (2011) on the influence of Taiwan's topography on the track of TY KROSA (2007) showed that the terrain height of Taiwan played a crucial role in the looping motion of the typhoon at its landfall, while the topographic shape and cloud microphysics only played secondary roles, while for TY ROANU (2016), the Rakhine mountain influenced its movement toward Myanmar; without it, the TC would have moved northwestward with more rainfall (Maw and Min 2017). In Luzon Island, northern Philippines, numerical experiments showed that the Sierra Madre Mountain Range might decrease the translational speed of TCs, allowing precipitation to accumulate over the island (Racoma et al. 2016). Idealized numerical simulations of Tang and Chan (2014) showed terrain-induced gyres that caused a northward deflection of TC tracks when they crossed the Philippines and Taiwan. Brand and Blelloch (1973) examined the effects of the Philippine landmass on TC tracks from 1960 to 1970. They showed an evident impact of the Philippines on the speed, movement, and size parameters of TCs. In addition, they found a reduction in the average maximum sustained wind speed (MSW) of TCs by about 33% and a northward deflection as they pass through the islands. Moreover, they noted that the influence of the landmass on TCs is directly proportional to the area of the terrains. The Philippines has a complex topography with two major island groups to the north and south (Luzon and Mindanao Islands, respectively), and a sea-island mix at its center (Visayas Islands), which should have less influence on passing TCs than the former two major island groups. Recently, Wu and Choy (2015) examined 50 TCs (1980–2014) crossing Luzon Island to determine its effects on their intensities and motion. Their results showed that TCs weakened as they passed through the terrain of Luzon Island and that TCs accelerated (decelerated) as they approached (moved away). Furthermore, they found that TCs deflected to the right (left) before landfall tend to be deflected to the left (right) after landfall.

Previous studies that examined the TC activity over the Philippines mainly focused on the seasonal landfalling TCs using either a large domain (i.e., including the entire Philippines) (Kubota and Chan 2009; Takagi and Esteban 2016; Lin and Chou 2018) or those TCs affecting Luzon Island only (Chou et al. 2011; Wu and Choy 2015; Cruz and Narisma 2016; Racoma et al. 2016, 2021; Bagtasa 2019), while limited studies are available for Visayas and Mindanao Islands. Although a small number of TCs influence Mindanao Island, the associated damage of these disturbances appears to be exacerbated by the region's lack of disaster mitigation measures as demonstrated by the high damage costs of TS WASHI (2011) and TY BOPHA (2012) (henceforth, TC names will be spelled in capital letters with its corresponding year enclosed in parenthesis). Furthermore, the topographical characteristics of the major three island groups in the Philippines are different, as shown in Fig. 1. There are three mountain ranges in Luzon Island, and two broad valley regions are located in between these mountain ranges. Mindanao Island has a more complex topography, with more mountainous regions, and located closer to the equator, where the Coriolis effect is small. These geographical features include the Diwata Mountains, North–South Mountain

Ranges, Davao Oriental Mountains, and Kitanglad-Kalatungan Mountains. Visayas, on the other hand, is a sea-island mix. In this study, the main Visayas Islands consist of the following: Leyte, Samar, Cebu, Negros, Panay, Mindoro, and Masbate. Therefore, it is expected that the three island groups will have different effects on the TC tracks, intensity changes, and change in translational speeds.

Based on the above research gaps, the aim of this study is to determine the changes in intensity, translational speed, and direction of movement of TCs passing through Visayas and Mindanao Island, which has not been examined in previous studies. Most TC studies over the Philippines focused only on the TC season (i.e., June to October). However, more TCs affect Visayas and Mindanao Island during the off-TC season, which is the main point of discussion of Rodolfo et al. (2018); hence, all TCs across all months were analyzed in this study. The findings of this study can assist the government in preparing for future extreme events in the region. Moreover, understanding the specific changes in the intensity and movement of TCs over certain terrains can help determine vulnerable areas during such events and improve mitigation efforts.

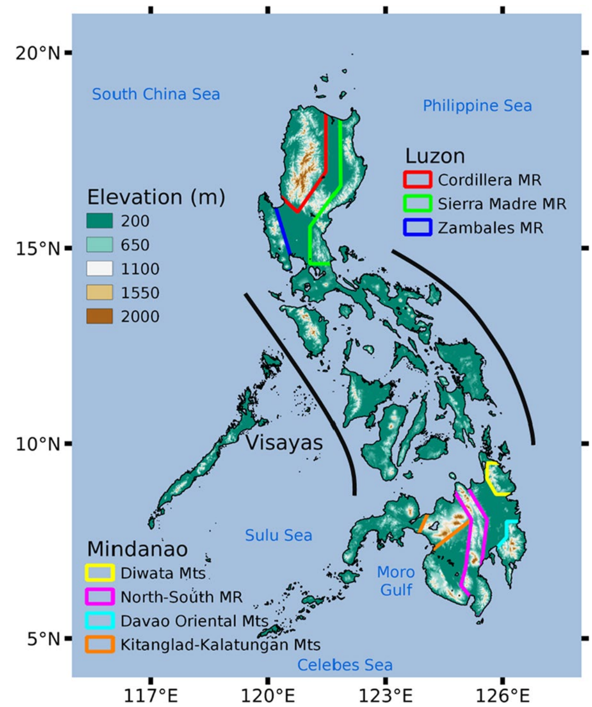

Fig. 1 Topography (m) and the three major island groups (Luzon, Visayas, and Mindanao) of the Philippines. The major mountain ranges are boxed. The thick black lines to the east and west of central Philippines are the demarcation lines used to filter the landfalling TCs over the Visayas. (SRTM, https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-shuttle-radar-topography-mission-srtm-1)

2 Data and methodology

This study focused only on the landfalling TCs over Mindanao Island (5–10° N), southern Philippines, and those that cross the smaller islands in Visayas, central Philippines (10–15° N), from 1979 to 2020. Mindanao Island in this study is defined to be the mainland Mindanao, hereinafter referred to as Mindanao, and excludes the surrounding smaller islands. Landfalling TCs passing through the Dinagat Islands, northeast of Mindanao, are excluded in the definition of landfalling TCs over Mindanao. As for the TCs landfalling over the Visayas, only those TCs crossing the demarcation lines depicted in Fig. 1 (solid thick black lines on the eastern (123° E, 15° N; 127° E, 10° N) and western coast (119° E, 14° N; 122° E, 8° N) of central Philippines), were used in the analyses. The TCs must enter and exit the respective demarcation lines to be considered landfalling TCs over Visayas. TCs that entered and dissipated while inside the demarcation area without existing are also included in the study.

Three best track positions were defined in this study following Wu and Choy (2015), which are the approaching point (AP), landing point (LP), and departing point (DP). The AP is the location before the TC makes landfall, while DP is the location after leaving the landmass of Mindanao Island. For Visayas, we define AP as the point before a TC makes landfall in any island near the eastern demarcation line depicted in Fig. 1, while DP is the point when a TC departs the last island to the west of Visayas or just before exiting the western demarcation line. All TCs that crossed Visayas have multiple LPs. For simplicity however, as long as the TCs cross Visayas, they will be considered to only have one LP.

The data set used to visualize the different topography features of the Philippine Archipelago was from the Shuttle Radar Topography Mission of the United States Geological Survey (SRTM, https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-shuttle-radar-topography-mission-srtm-1).

TCs that have made landfall in Mindanao regardless of having an LP or no LP, and continued tracking toward Visayas were excluded in the definition of landfalling TCs over Visayas, e.g., SARAH (1983), CANESSA (1991), JANGMI (2014), etc. TCs without data regarding AP and DP intensities are also excluded from the study.

The intensity, translational speed, and direction of movement of the TCs were computed based on the 6-hourly best track archive of the World Meteorological Organization from National Centers for Environmental Information's (NCDC) International Best Track Archive for Climate Stewardship (IBTrACS) (NCDC, https://

www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00834). Both translational speed and direction of movement at a particular best track position were derived relative to the future 6-hourly position. The study used the Saffir-Simpson scale when examining TC intensity, ranging from Tropical Depression (TD) at < 33 kts, Tropical Storm (TS) from 34 to 63 kts, and Categories 1 to 5 having > 63 kts or those at Typhoon (TY) category and above based on the World Meteorological Organization standards.

The translational speed of the TC was computed by finding the difference between the displacement traveled by the TC from the current TC position and its previous 6-h position and dividing the distance by six.

The deflection of the TC was adapted from the methodology of Wu and Choy (2015) wherein the bearing of the TC was determined by drawing a line from the current TC position and its previous 6-h position. Then, the change in deflection in the next 6-h movement direction relative to the previous 6-h position is defined to be the deflection. Wu and Choy (2015) also selected a 5° threshold to differentiate the transient ($\Delta < 5°$) and significant deflections ($\Delta \geq 5°$).

To test the significance of the differences in the means, we used the bootstrapping method for hypothesis testing as proposed by Efron and Tibshirani (1993). One of the advantages of this test is that it does not assume normality (nonparametric) between the samples, unlike an ordinary *t*-test. More specifically, the test is used to check if there is a significant difference of the TC's translational speed or intensity between the 6-h characteristics (e.g., AP − 24 vs AP − 18, AP − 18 vs AP − 12, … DP + 6 vs DP + 12).

The Pearson Product Moment Correlation was also used to test whether there is a significant correlation between two distinct groups. In this experiment, the TC characteristics (intensity and deflection) were separately tested to check whether a correlation exists when the TC is at AP versus at DP. The paired bootstrapping method was used at 10% significance to compare if there are any significant changes on TC intensity and translational speed in 6-hourly intervals. For example, the intensity of a TC is compared to its intensity 6 h before AP and after (i.e., at AP − 6-AP vs AP–LP).

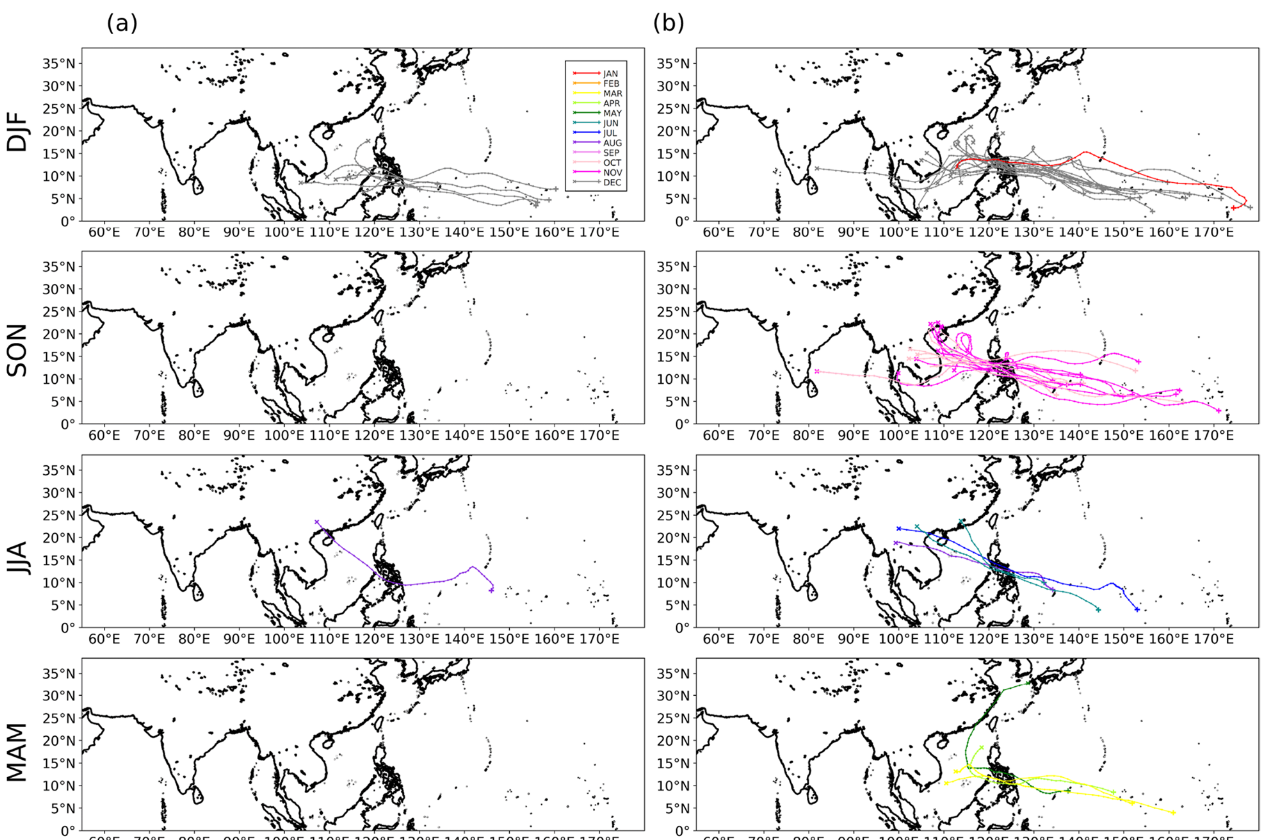

Fig. 2 Tracks of the **a** 8 TCs that crossed Mindanao and **b** 39 TCs over Visayas from 1979 to 2020. The crosses (x marks) indicate the genesis (dissipation) location

3 Results and discussion

There were 24 TCs that crossed Mindanao from 1979 to 2020. The following TCs with recurving or erratic tracks were excluded in the analysis: (i) formed/dissipated too close to Mindanao (4 cases) and (ii) incomplete data upon landfall in Mindanao since WMO does not provide the windspeed of TCs less than 30 kts. (12 cases). Ultimately, only 8 TCs crossing Mindanao, shown in Fig. 2a, were used in this study. The intensities of these TC are the following: five TSs, two Category 2 TYs (C2s), and one Category 3 TY (C3). Table 1 lists the TCs passing through Mindanao, which were tabulated by months. December was a peak month, with 6 TCs. In general, there were 3 (37.5%) TCs with intensities having at least Category 1 TY.

For the Visayas, there were 114 TCs that crossed the central Philippines from 1979 to 2020. Note that TCs that have skirted either the Dinagat Islands or northeastern Mindanao and made landfall in Visayas were included in this part of the study. The following TCs with recurving or erratic tracks were also excluded in the analysis: (ii) initially made landfall in Mindanao and continued its track to Visayas (1 case), and (i) recurved northward and did not cross the west demarcation line (33 cases), and (ii) incomplete data upon landfall in Mindanao since WMO does not provide the windspeed of TCs at less than 30 kts. (41 cases). Ultimately, only 39 TCs crossing Visayas, shown in Fig. 2b, were used in this study. The intensities of these TCs are the following: 18 TSs, 11 C1s, six C2s, three C3s, and one C4s. Table 2 lists the TCs passing through Visayas, which were tabulated by months. November and December were peak months similar to those in Mindanao, with 10 and 15 TCs, respectively. In general, there were 21 (53%) TCs with intensities having at least Category 1 TY.

Figure 3a and b shows the locations of AP, LP, and DP of the 8 and 39 TCs that crossed Mindanao and Visayas, respectively. Similar to Wu and Choy (2015), a track may have no LP as an intermediate position within Mindanao or may have more than one LP points (mostly for TCs traversing Mindanao in a westward direction or those that traversed multiple islands in Visayas). Additionally, the best-track position 6 h before AP and 6 h after DP was denoted as AP − 6 and DP + 6, respectively, and a similar notation will be used to other positions, henceforth. Figure 4 shows some examples of TCs having, one LP, two LPs, and three LPs over Mindanao. Based on estimation (computation shown in Sect. 3.1) from the number of cases with one LPs, 6 TCs, or 75% of the total analyzed TCs over Mindanao swept the island within 4 to 15 h. On the other hand, TCs pass through Visayas within 14 to 37 h.

3.1 Characteristics of tracks

Based on Tables 1 and 2, higher TC landfall frequency occurs during November and December over Mindanao and Visayas. More TCs form and traverse the central and southern Philippines in these months following the southward migration of the monsoon trough (e.g., Wang et al. 2007).

For TCs landfalling in Mindanao, there were 6 (75%) TCs with one LP, 1 (12.5%) TCs with 2 LPs, and 1 (12.5%) TCs with 3 LPs. After the TCs made landfall in Mindanao, about 7 (87.5%) TCs curved northward, mostly passing through the Visayas, 1 (12.5%) TC traversed westward and continued toward the Sulu Sea. One TC exhibited unique track characteristics, TC JANGMI (2014) exited northeastern Mindanao in a northwesterly track and then curved southward after passing through Visayas.

Following the estimation method of Wu and Choy (2015), a TC would likely sweep through a distance of 2–4 degrees of longitude over Mindanao, depending on its actual track. The distance is computed by getting the difference of the AP and DP. The 95% confidence interval (CI) of the translation speed at AP is between 11.12 and

Table 1 List of tropical cyclones that made landfall over Mindanao Island from 1979 to 2020

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
			MAMIE (1982)					IKE (1984)[RI]				MARGE (1986)
												NELL (1993)
												WASHI (2011)
												BOPHA (2012)[RI & RW]
												JANGMI (2014)
												TEMBIN (2017)
Total	0	0	1	0	0	0	0	1	0	0	0	6

TCs are grouped per month, and the year of occurrence is enclosed in parentheses

[RI] TC underwent rapid intensification

[RW] TC underwent rapid weakening

Table 2 As in Table 1 but for the landfalling TCs over Visayas

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	ROY (1988)		NELSON (1982)	OWEN (1994)	CHANCHU (2006)	DOT (1990)	VERA (1983)	BETTY (1987)[RI]		GEORGIA (1986)	HAZEN (1981)[RI & RW]	LEE (1971)
			ROKE (2005)			NANGKA (2009)				ZACK (1995)[RI]	IDA (1986)	BEN (1979)[RI]
										MIRINAE (2009)[RI & RW]	NINA (1987)[RI]	NORRIS (1986)
										SON-TINH (2012)	SKIP (1988)[RI]	PHYLLIS (1987)[RI]
										MOLAVE (2020)[RI]	MIKE (1989)[RI]	MANNY (1993)[RI]
											KYLE (1993)	LOLA (1993)
											NEPARTAK (2003)	AXEL (1994)[RI]
											MUIFA (2004)[RI]	FAITH (1998)
											DURIAN (2004)[RI]	UTOR (2006)[RI]
											HAIYAN (2013)[RI]	WUKONG (2012)
												HAGUPIT (2014)[RI & RW]
												MELOR (2015)[RI]
												NOCK-TEN (2016)[RI]
												PHANFONE (2019)[RI]
Total	1	0	2	1	1	2	1	1	0	5	10	15

[RI] TC underwent rapid intensification

[RW] TC underwent rapid weakening

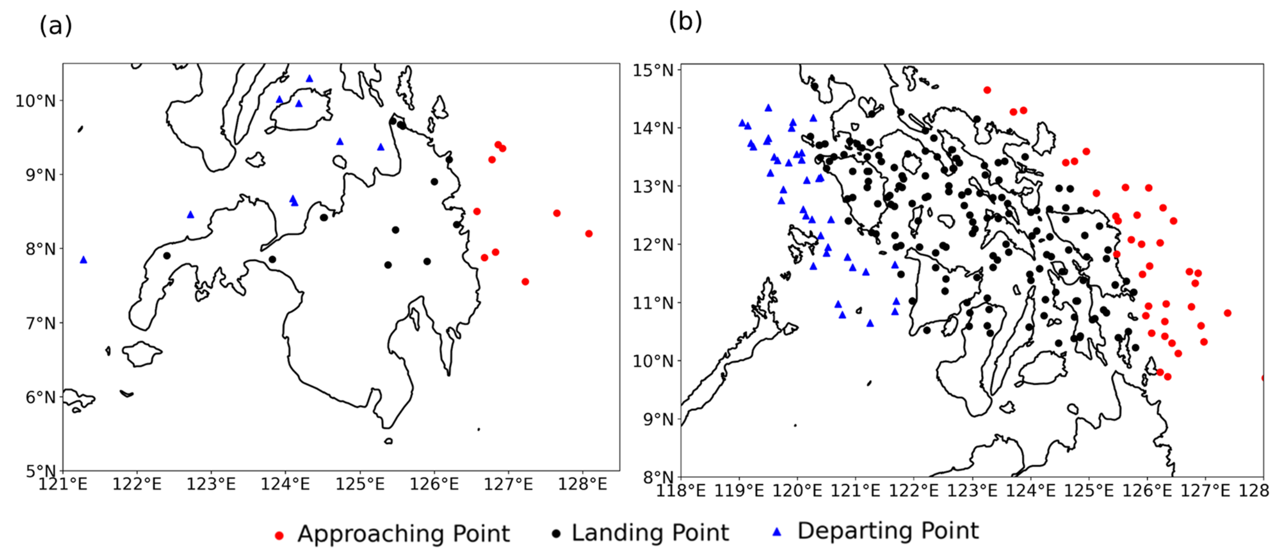

Fig. 3 Locations of approaching points (AP; red circle), departing points (DP; blue triangle), and landing points (LP; black circle) of the **a** 8 landfalling TCs over Mindanao and **b** 39 landfalling TCs over Visayas

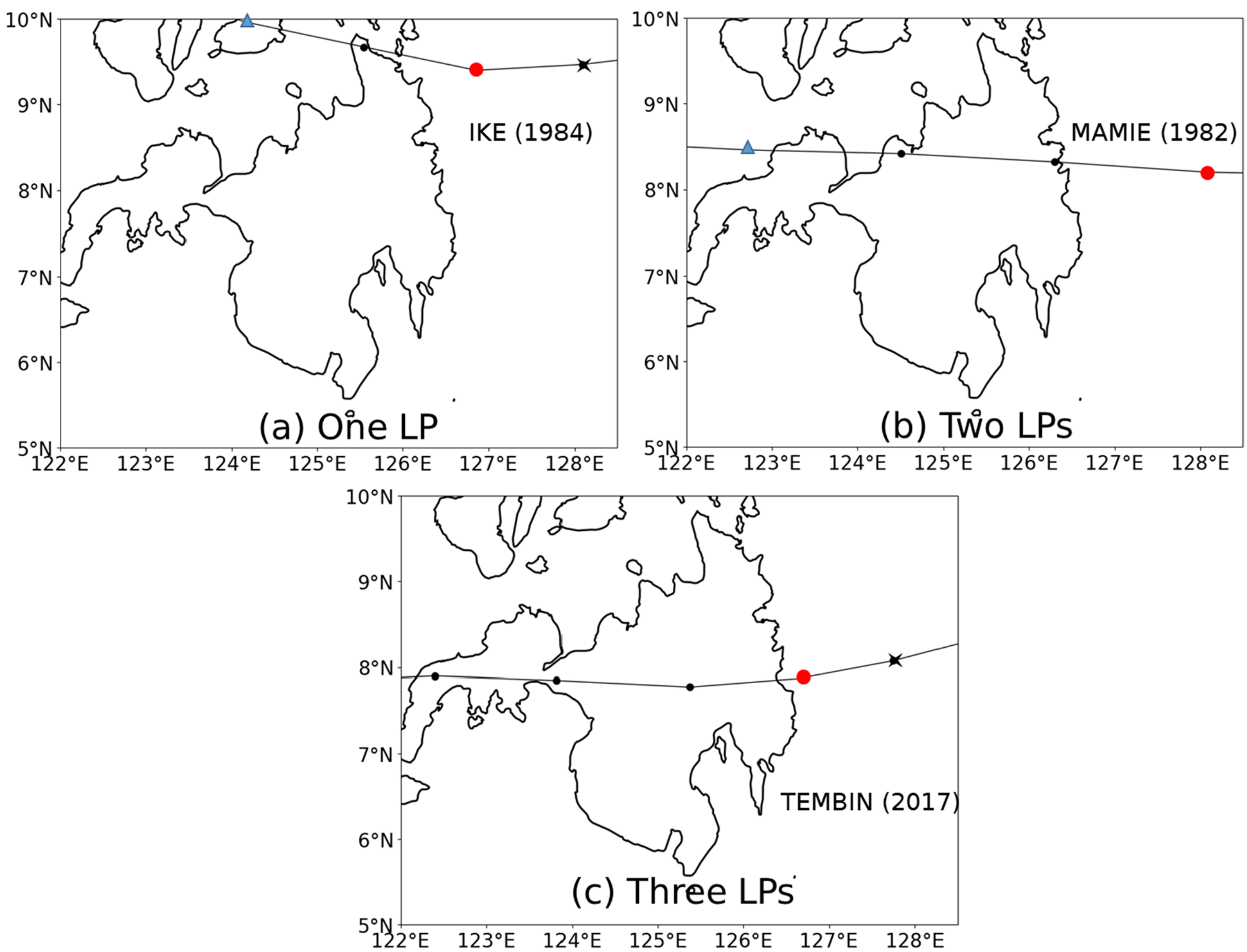

Fig. 4 Examples of cases with **a** no LP, **b** one LP, **c** two LPs, and **d** three LPs over Mindanao. Red (black) solid circle shows the AP (LP), and the blue solid triangle indicates the DP of the TCs

16.24 kt. Thus, it can be deduced that most TCs would take about 7 to 14 h. This is also manifested by the fact that there are 6 (75%) cases of TCs having one LP, which usually follow a northwesterly direction and traverse along northeastern and northern Mindanao. Note that TCs having more than one LP are the cases that traverse through Mindanao in a generally westerly bearing.

For landfalling TCs in Visayas, we treated all the LPs as one such that their intensity and translational speed are averaged into one LP. There were 1 TCs that dissipated while traversing through Visayas which is NORRIS (1986). A TC would likely sweep through a distance of 4–7 degrees of longitude over Visayas, depending on its actual track. The distance is computed by getting the difference of the AP and DP. The 95% CI of the translation speed at AP is between 11.09 and 13.79 kts. Hence, it can be deduced that most TCs would take about 17 to 30 h. After the TC had made landfall in Visayas, 7 (18%) TCs curved northward, while 31 (79%) TCs continued to traverse in a westward direction. One TC exhibited unique track characteristics, MUIFA (2004) looped in a south-southwesterly direction before making landfall in the Bicol Region.

We also checked if there were contrasting features if seasonal instead of the annual analyses were conducted. Landfalling TCs during June to October (JJASO) and November to March (NDJFM) seasons were examined separately. In terms of frequency, there were about 1 (7) TCs that made landfall during JJASO (NDJFM) for landfalling TCs in Mindanao, while there were about 9 (28) that made landfall during JJASO (NDJFM) in Visayas. The tracks of TCs during JJASO are all northwestward and cross the northeastern portion of Mindanao, as shown in Additional file 1: Figure S1, while those during NDJFM follow a westerly to northwesterly track. For Visayas (Additional file 1: Figure S2), the TCs during the JJASO recurve northward toward the northern Indochina Peninsula, while TCs during the NDJFM recurve southward toward the southern Indochina Peninsula. No significant pattern regarding intensity and frequency of both seasons was observed for both Visayas and Mindanao. In terms of cases of rapid intensification and rapid weakening (RI and RW), only one TC underwent RI during JJASO (i.e., IKE (1984)). For NDJFM, only one TC has undergone RI and RW (i.e., BOPHA (2012)). For TCs in Visayas, 17 (4) RI cases were observed, while 2 (1) RW cases were noted for NDJFM (JJASO). It can be noted no significant difference in the intensities of the intensity drop of TCs between AP and DP for Mindanao TCs, while there is a significant difference using bootstrap t test ($p = 0.01199$) of intensity drop for Visayas TCs, such that TCs during the NDJFM have a greater intensity drop than JJASO.

3.2 Changes in intensity

Figure 5a shows the intensity change from AP − 24 to DP + 12 for the 8 landfalling TCs in Mindanao. The results show that, on average, TCs tend to intensify steadily before landfall and weaken sharply at landfall. More specifically, the average intensity at AP (DP) is about 63.38 kts (53.13 kts). Then, the TC weakens steadily as it exits Mindanao. A sharp decrease in intensity can also be seen from AP to LP, which could be partly attributed to the rapid decrease in wind speed due to friction (e.g., Powell et al. 1991; Wu and Choy 2015; Li et al. 2014, 2015), changes in the latent heat supply (Bender et al. 1987), and moisture supply over land (Wong and Chan 2006; Li et al. 2014, 2015). The intensity after DP slightly decreases before leveling off at DP + 12. During this period, the TC may cross the Zamboanga Peninsula or some islands to the north of Mindanao. However, some TCs may re-intensify after DP + 12, particularly those crossing the South China Sea-West Philippine Sea, such as TC, TEMBIN (2017).

For the 39 TCs landfalling in Visayas, Fig. 5b shows the intensity change from AP − 24 to DP + 12. Similar to the patterns observed in Mindanao, TCs tend to intensify steadily before landfall and weaken sharply at landfall. More specifically, the average intensity at AP (DP) is about 67.95 kts (54.36 kts). A sharp decrease in intensity can also be seen from AP to LP. The intensity decreases before leveling off at DP and slightly increases from DP + 6 to DP + 12 since the TCs may cross the South China Sea-West Philippine Sea. Additionally TCs may re-intensify after DP + 12 such that 4 TCs intensified up to TD/TS, 6 TCs up to C1, 6 TCs up to C2, 5 TCs up to C3, and 4 TCs up to C4. For both areas of study, the results are consistent with the findings of Brand and Blelloch (1973), Bender et al. (1987), and Wu and Choy (2015) where re-intensification usually starts about 12 h after landfall.

Figure 6a shows that stronger TCs, in general, tend to have larger decreases in intensity, while the intensity of weaker TCs appears to be less affected by Mindanao's topography. More specifically, there exists a significant positive linear relationship for the TC's intensity drop before and after landfall ($p = 0.0041$; significant at 10%; $r = 0.88$; Fig. 6e). There were 2 (25%) TCs that maintained their intensities, particularly those at TS categories, while 5 (63%) TCs decreased in intensities. About 1 (13%) TCs also show a slight strengthening by about 5 kts after traversing through Mindanao (Fig. 6a, b). For landfalling Visayas TCs, Fig. 6c shows that stronger TCs, in general, tend to have larger decreases in intensity, while the intensity of weaker TCs appear to be less affected by Visayas's topography (Fig. 6c, d). More specifically, there exists a significant positive linear relationship for the

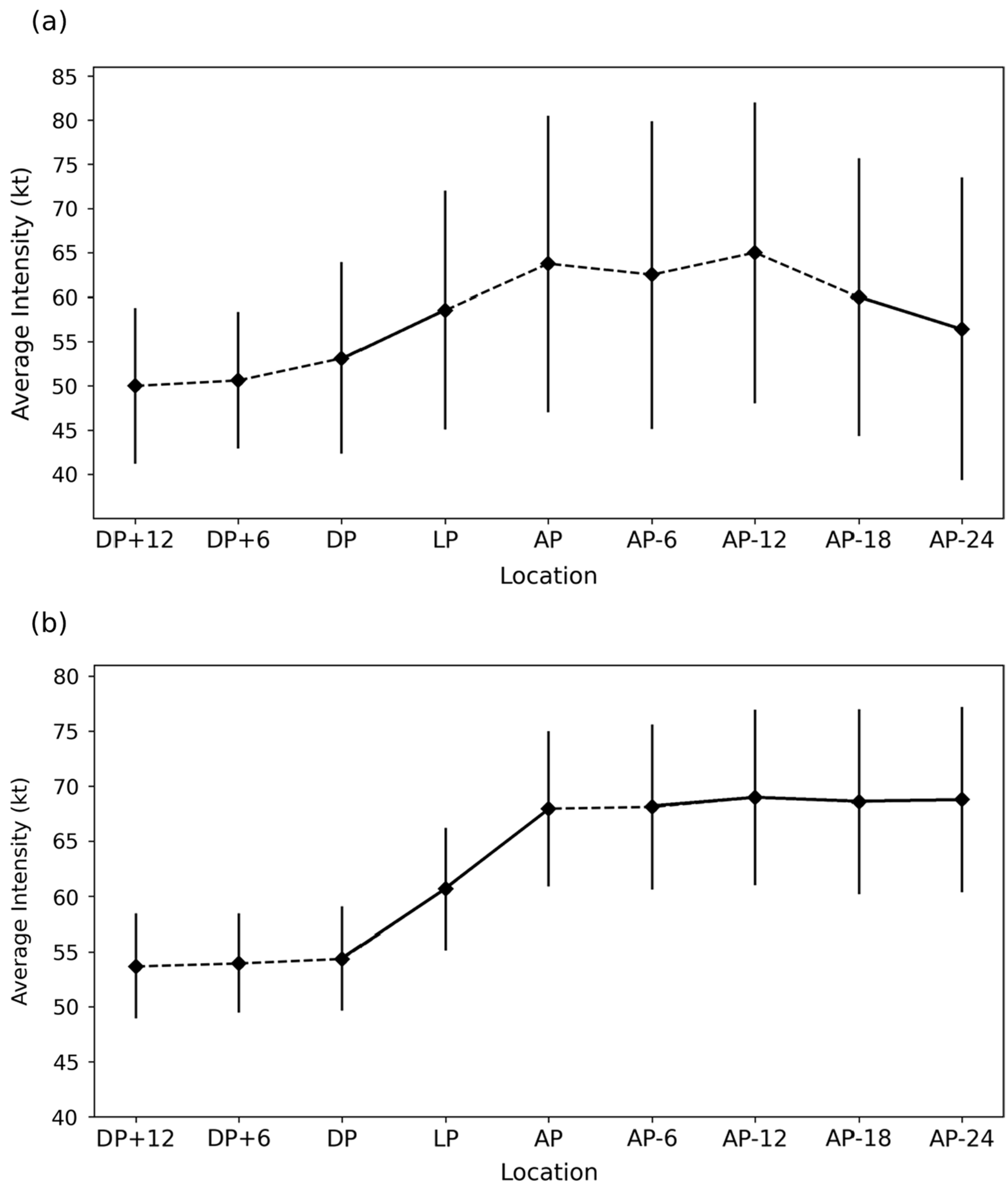

Fig. 5 Temporal variation of the average maximum sustained wind speed of the TCs from AP − 24 to D + 12 over **a** Mindanao and **b** Visayas. Solid line (dashed line) represents the difference between the intensity at two positions is (not) significant at 10% based on bootstrapped *t* test. Error bars represent 95% CI

TC's intensity drop before and after landfall ($p < 0.00001$; significant at 10%; $r = 0.71$; Fig. 6f). For both Visayas and Mindanao, the results were consistent with the findings of Brand and Blelloch (1973), who observed a similar effect of the Philippines on landfalling TCs. However, TCs passing through Visayas exhibit lesser cases of strengthening such that 6 (15%) TCs increased in intensity, while there were 4 (10%) TCs that maintained intensity, particularly those with strength at TS category, while 29 (74%) decreased for TS and TY categories.

Landfalling Visayas TCs are more prone to intensification due to the sea-island mix from the archipelagic geography (Brand and Blelloch 1973). According to Wu and Choy (2015) and Powell and Houston (1996), the increased turbulence induced by larger roughness over land may have more impact on weaker TCs. It is also important to note that no TCs with at least TY intensities

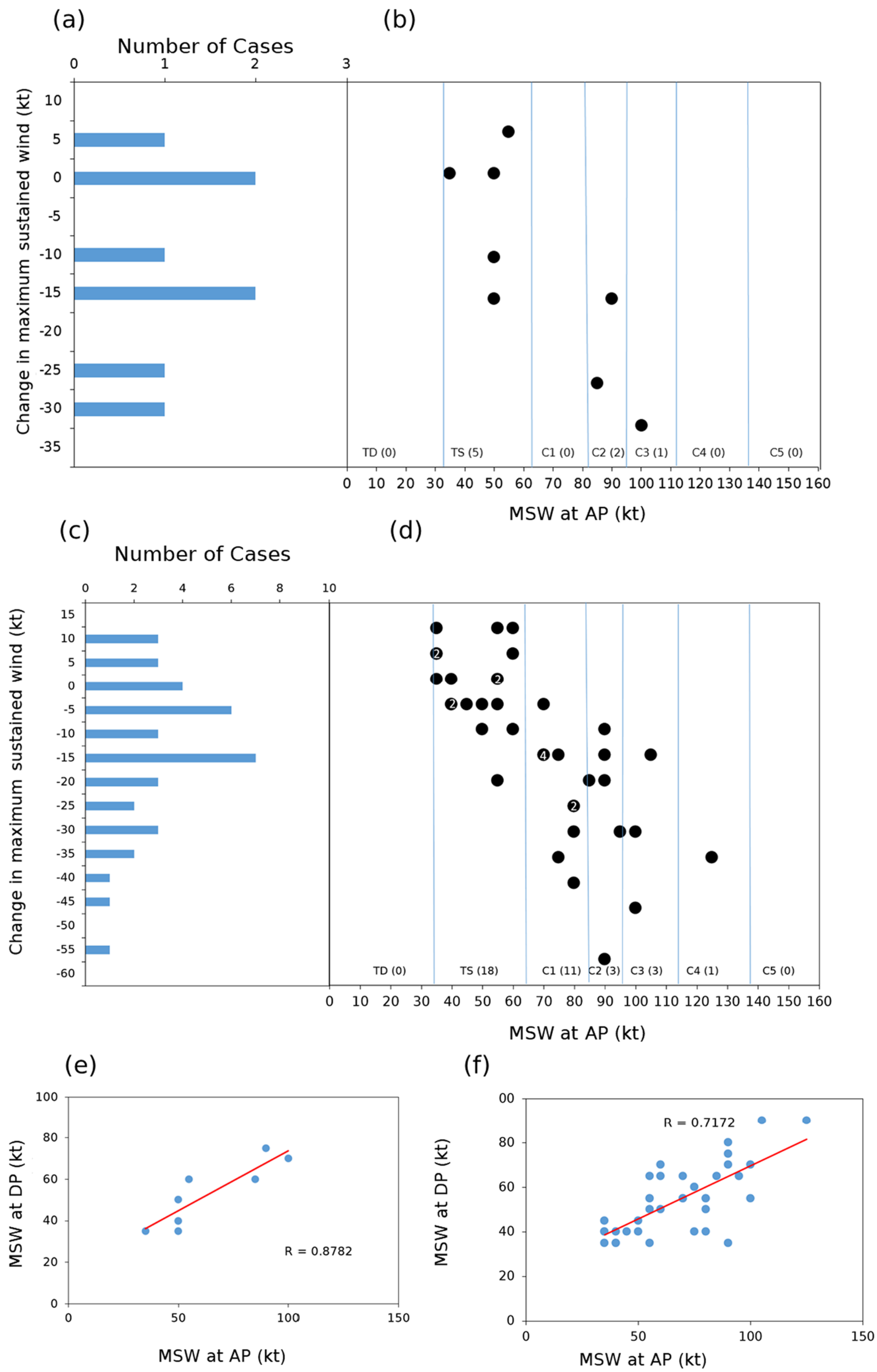

Fig. 6 **a** Frequency distribution of the intensity change over Mindanao and **b** over Visayas. **c** Scatter diagram showing the intensity change between AP and DP with respect to different TC categories over Mindanao and **d** over Visayas. The numbers inside the black circles indicate the total number of cases if it is larger than one. The numbers inside the parentheses at the bottom of the figure indicate the total number of cases for the different TC categories. Relationship of the maximum sustained winds (MSWs) at AP and DP over **e** Mindanao and **f** over Visayas.

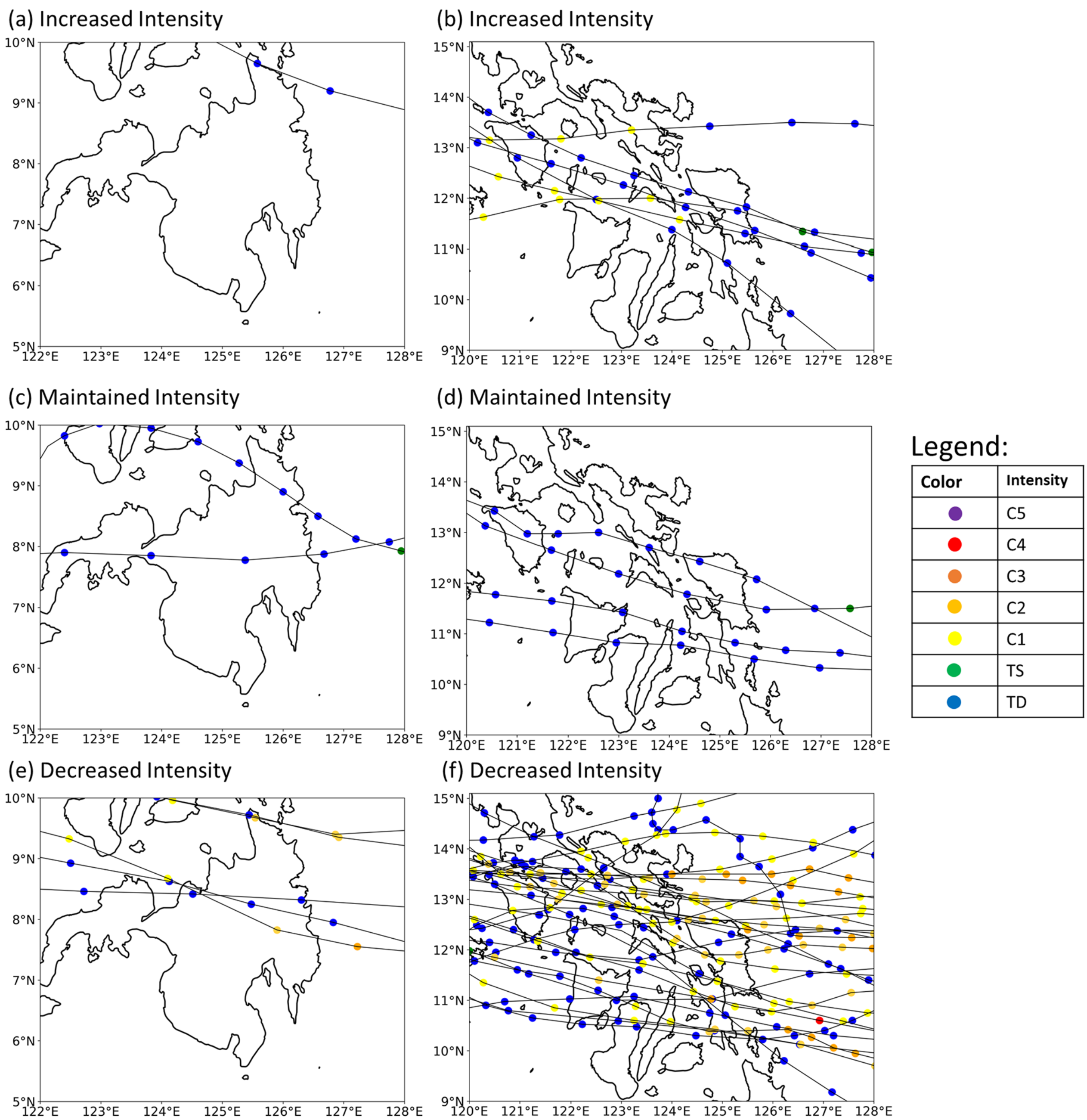

Fig. 7 Examples of cases with **a**, **b** increased intensity, **c**, **d** maintained intensity, and **e**, **f** decreased intensity based on the MSW difference between AP and DP, after crossing Mindanao (**a**, **c**, **e**) and Visayas (**b**, **d**, **f**). Points are color coded according to the Saffir–Simpson scale

experienced intensification while passing through Mindanao.

One probable cause that TCs at TS category maintained its strength while traversing is the moisture provided by the sea-island mix. More specifically, Sugino and Satomura (2010) examined the characteristics of 98 typhoons crossing the Indochina Peninsula from 1979 to 2004, particularly the lifetime after landfall. They examined two weak typhoon cases (USAGI (2001) and LOLA (1990)) whose lifetimes are longer than normal. They found that typhoon USAGI (2001) passed through a humid region over the Indochina Peninsula, while LOLA (1990) passed near the Gulf of Thailand, which they hypothesized to have resupplied the moisture for the maintenance of these two typhoons.

For TCs landfalling in Mindanao, the decrease in the MSW of TCs classified as TS is usually ≤ 15 kts, with an average decrease of 6.67 kts, whereas for TCs at TY categories is usually ≥ 15 kts, with an average decrease of 23.33 kts. More specifically, there is a significant difference between the intensities at AP and DP ($p = 0.0935$; at 10% significance). Based on Fig. 6b, there are 5 cases (63%) with a decrease in MSW listed as follows: TS (2), greater than C1 or TYs (3). The average drop in intensity for TS is about 25.0% with a 95% CI of 20–30% as estimated by bootstrapping. For TCs having at least a TY category, the average drop in intensity is about 25.4% with the 95% CI of 16.6–30.0% as estimated by bootstrapping. Overall, the drop in intensity for TCs having at least a TY category is less than 50%. This also coincides with the study of Kaplan and Demaria (1995), where the wind speed decay rate after landfall is proportional to wind speed. Only 1 TC, MARGE (1986), with a TS category has been reported to increase in intensity by 5 kts, which is about a 9.09% increase from its initial strength at AP.

For landfalling TCs in Visayas, the decrease in the MSW of TCs with intensities at TD and TS is usually ≤ 10 kts, with an average decrease of 8.13 kts, whereas for TCs at TY categories, it is usually ≥ 20 kts, with an average decrease of 24.29 kts. More specifically, there is a significant difference in the intensities between AP and DP ($p = 0.0225$; at 10% significance). Based on Fig. 7, there are 29 cases (74%) with decrease in MSW listed as follows: TS (8), $\geq$ C1 TYs (21). The average drop in intensity for TSs is about 20.5% with a 95% CI of 11.8–22.5% as estimated by bootstrapping. For TCs having at least a TY category, the average drop in intensity is about 45.5% with the 95% CI of 26.1–54.6%. Additionally, the intensity drop is consistent with the study of Kaplan and Demaria (1995) where the wind speed decay rate after landfall is proportional to wind speed. Only 6 TC, all in TS category, has been reported to increase by an average of 7.5 kts, which is about a 14.1% increase from its initial strength at AP.

Figure 7 summarizes the tracks of TCs whose intensities increased, maintained, or decreased while traversing Mindanao and Visayas. It can be noted that the TCs traversing Mindanao with increased or maintained intensities (Fig. 7a, c) are weaker TCs (i.e., TD or TS categories) and traversed through northern and northeastern Mindanao, which is a small portion of land. Chou et al. (2011) also found similar cases of TCs crossing a small portion of landmass over Luzon Island and Taiwan. The TCs that have maintained or increased their intensities after traversing Visayas are usually weaker TCs (i.e., TD or TS categories) are shown in Fig. 7b, d, except for CHANCHU (2006), which maintained intensity as a Category 1 TY. It can also be observed that TCs, which have increased in intensities, followed a northwesterly direction. For both Visayas and Mindanao, stronger TCs had greater tendency to decrease in intensity upon departure.

We also examined the TCs that exhibit rapid intensification (RI) and rapid weakening (RW) as they approach Visayas and Mindanao. DeMaria et al. (2012) defined RI and RW as a ≥ 30 kt increase and ≥ 20 kt decrease, respectively, within 24 h. Hence, following their definition, we examined cases with RI and RW for landfalling TCs in Visayas and Mindanao. This study used the TC strength between the genesis point and AP to check cases with RI/RW. For Mindanao, there were only 2 cases of RI, specifically IKE (1984) and BOPHA (2012). Note that BOPHA (2012) underwent both RI and RW throughout its lifetime. For Visayas, there were 21 (53%) cases of RI, shown in Table 2, while there were 3 cases (8%) of RW, which are HAZEN (1981), MIRINAE (2009), HAGUPIT (2014). If the RI and RW cases were to be divided between the June, July, August, September, October (JJASO) and November, December, January, February, March (NDJFM) seasons, only one TC underwent RI for each season of JJASO and NDJFM, while one case of RW in NDJFM for Mindanao. For Visayas, 17 (4) RI cases were reported during the NDJFM (JJASO), and 2 (1) RW cases in NDJFM (JJASO). Wu and Choy (2015) noted that RI and RW are caused by numerous dynamic and thermodynamic processes such as sea surface temperature and vertical wind shear. In summary, RI and RW cases are rare in the observed TCs that made landfall over Mindanao (25% and 25%, respectively) compared to TCs landfalling in Visayas, which have a higher tendency to undergo RI and RW (53% and 8%, respectively).

3.3 Changes in translational speed

The changes in the translational speed are shown in Fig. 8. For Mindanao TCs (Fig. 8a), it is evident that the translational speed maintains prior to AP while reaching maximum at AP − 18 and decreases abruptly until LP, while for Visayas TCs (Fig. 8b), the translational speed steadily increases until it peaks at DP, then decreases at positions greater than DP. This result is different from those found by Wu and Choy (2015) where they found the peak at AP, which is 6 h prior to LP due to the interaction of the TC with topography. The gain in speed from AP − 24 to AP − 6 may be unrelated to the topography of the island as also noted by Wu and Choy (2015) for Luzon Island. Both Visayas and Mindanao also show that there is no relationship between changes in translational speed and intensity of TCs.

The difference in translational speeds at AP and DP can be better illustrated from their bootstrapped distribution, as shown in Fig. 9a, b for landfalling TCs over Mindanao and Visayas, respectively. For Mindanao, the

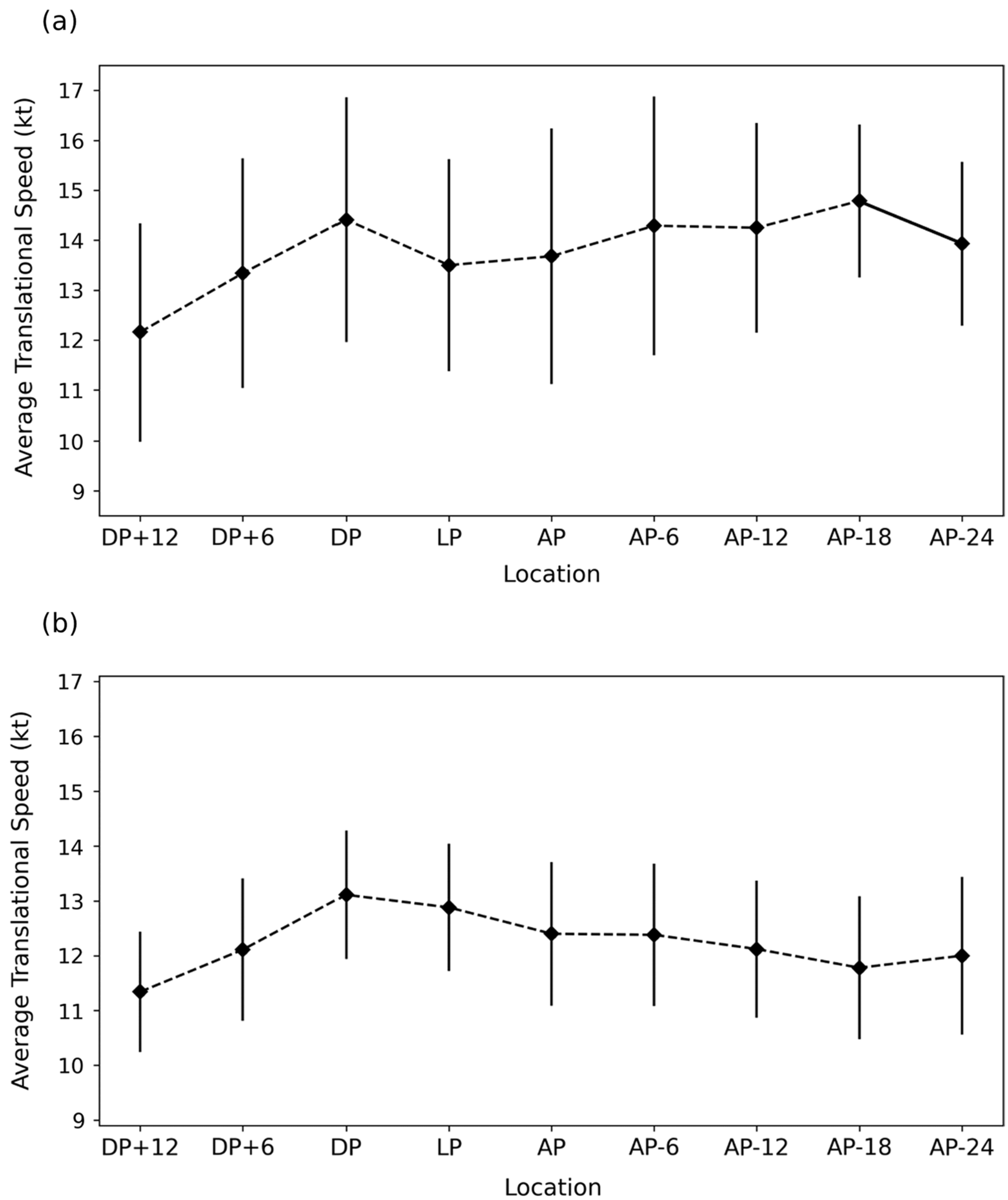

Fig. 8 As in Fig. 5 but for the average translational speed, (**a**) for Mindanao and (**b**) for Visayas

average translational speed at AP and DP is 13.68 kts and 14.41 kts, respectively. The corresponding 95% CI for AP and DP is 11.12 kts to 16.23 kts and 11.96 to 16.86 kts, respectively. For Visayas, the average speed at AP and DP is 12.40 kts and 13.11 kts, respectively. The corresponding 95% CI for AP and DP is 11.09 kts to 13.17 kts and 11.94 to 14.27 kts, respectively. Based on the significance test via bootstrapping between AP and DP, there is no significant difference in the translational speeds of TCs before and after landfall for both island groups. Both scenarios require further examination because TCs are expected to slow down after encountering land surface due to increased friction and loss of latent heat. It is possible that the TCs crossing Mindanao Island encountered a humid environment (e.g., Sugino and Satomura 2010) or that the soil was wetter than normal conditions, which may provide adequate energy to sustain TCs in a similar manner to the ocean environment (Andersen et al. 2013). Likewise, Brand and Blelloch (1973) noted that central

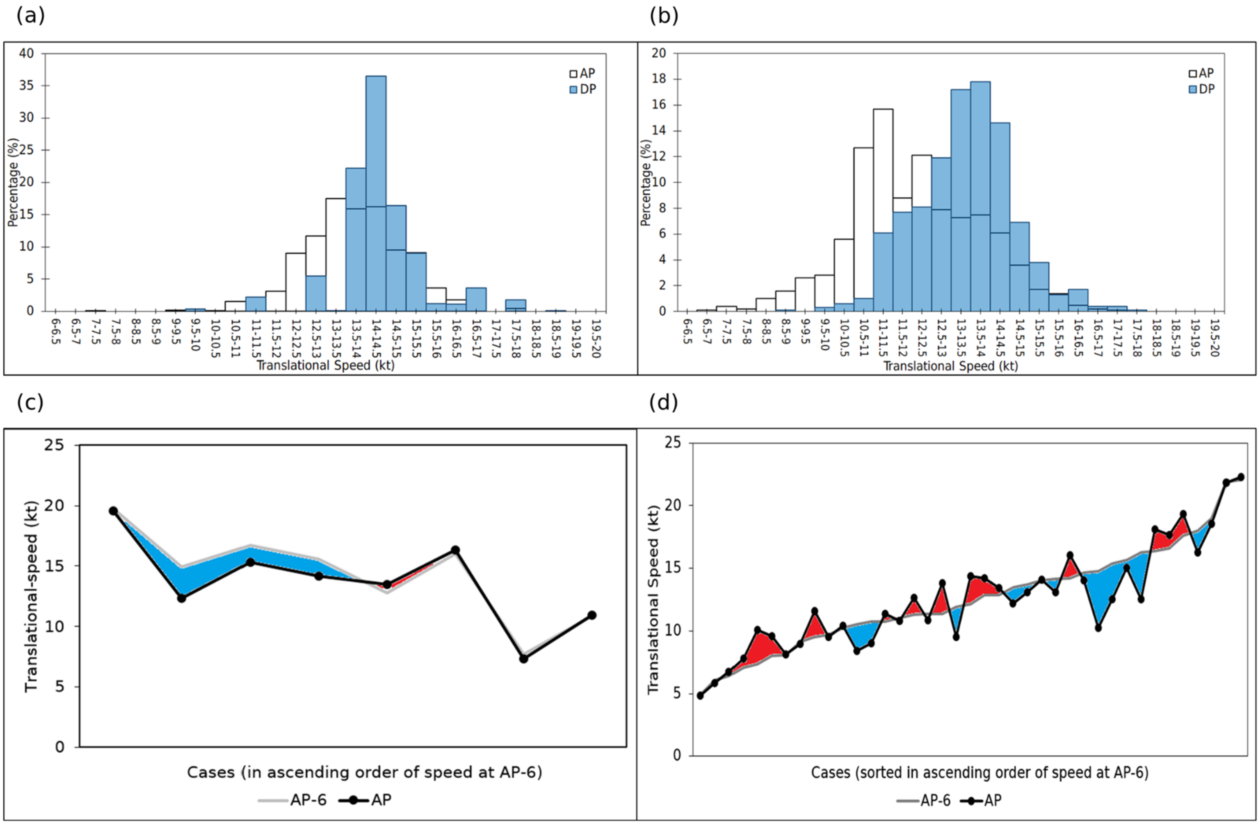

Fig. 9 Bootstrapped distribution of the translational speed at AP (blue) and DP (white) for **a** Mindanao and **b** Visayas. Comparison of the translational speeds at AP − 6 and AP for the **c** 8 TCs over Mindanao and **d** 39 TCs over Visayas, sorted in ascending order of the speeds at AP − 6. Increase (decrease) in speeds is shaded in red (blue). One TC over Mindanao, while three TCs over Visayas were excluded since they had no position at AP − 12, which is necessary for computing the translational speed at AP − 6

regions of the Philippines have less effect on the storms due to Sea-Island mix and small land surface areas.

We further examine the conditions at AP and AP − 6, as shown in Fig. 9c for Mindanao and Fig. 9d for Visayas. For TCs in Mindanao, about 3 (5) TCs accelerated (decelerated) or 38% (63%), as they approached the island. However in Visayas, about 19 (20) TCs accelerated (decelerated) or 49% (51%) as they approached the island. More specifically, the average change in translational speed from AP − 6 to AP is about − 0.61 kt and 0.028 kt for Mindanao and Visayas, respectively. Previous studies suggest that the increase in translational speed prior to landfall may be related to the interaction of TCs with the topography (Chang 1982; Bender et al. 1987) and friction-induced asymmetry in the large-scale flow, which is one of the reasons for TC drift (Wong and Chan 2006).

Additionally, the change in translational speeds of TCs after leaving both Mindanao and Visayas (comparing the TS at points DP and DP + 6) was also investigated. For Mindanao, there were 7 or 88% of the cases showing deceleration and 1 case for acceleration. For Visayas, 15 (23) or 38% (59%) cases showed acceleration (deceleration), while 1 (3%) TCs maintained their translational speeds. More specifically, the average change in translational speed from DP to DP + 6 is about − 1.06 kt and − 1.00 kt for Mindanao and Visayas, respectively.

3.4 Changes in direction of motion

Similar to the methodology of Wu and Choy (2015), in this study, the change in the 6-h movement direction relative to the previous 6-h position is defined to be the deflection. The deflections at AP and DP are examined in this section such that only cases with one LP for Mindanao were considered, while all TCs regardless of the number of LP were analyzed in Visayas for simplicity; hence, only 6 TCs out of 8 were examined in Mindanao and all of the 39 cases were examined in Visayas as illustrated in Figs. 10 and 11. To reiterate, a 5-degree threshold similar to those used by Wu and Choy (2015) for the deflection angle was used to filter out transient wobbles ($\Delta < |5°|$) in the tracks of small amplitudes. Positive

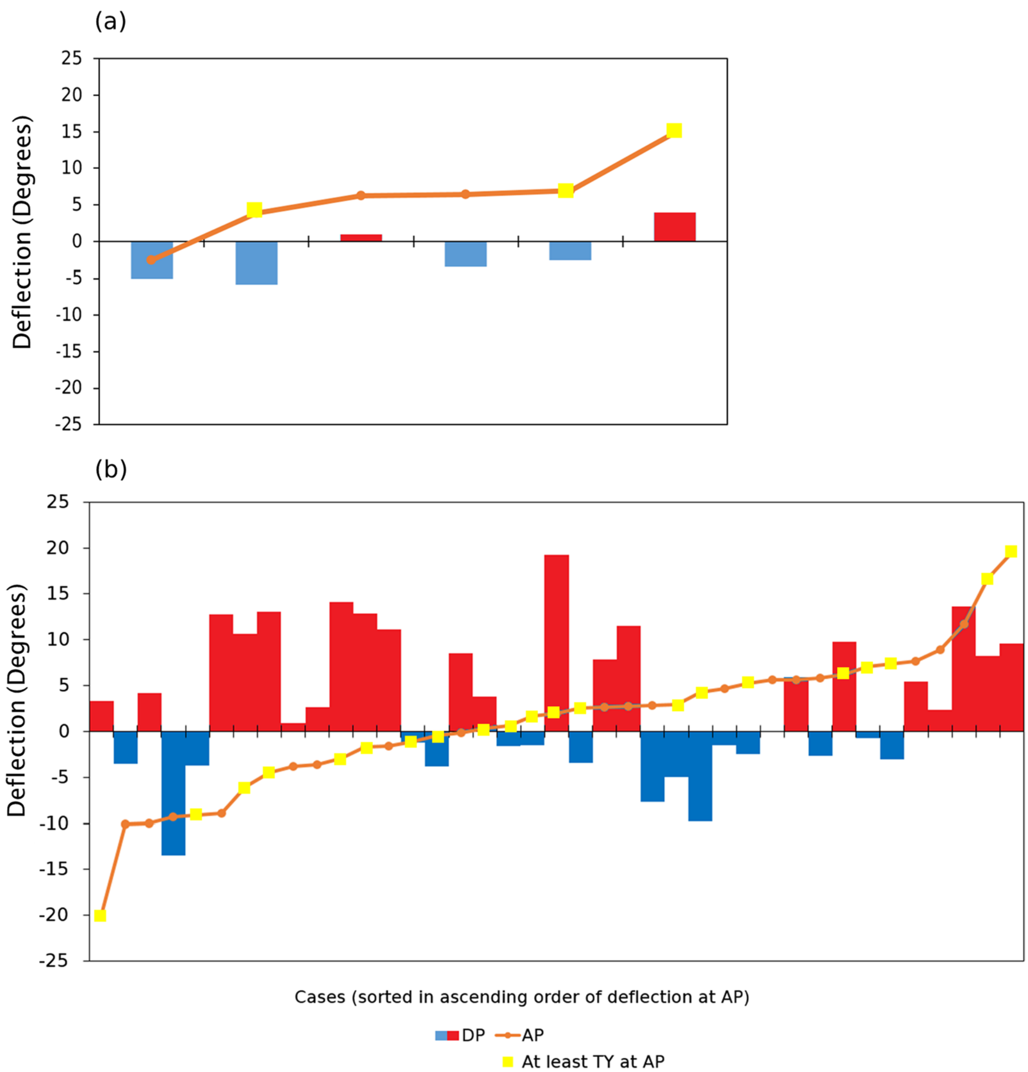

Fig. 10 Comparison of the deflections at AP and DP for those cases with one LP over **a** Mindanao and **b** Visayas. For Visayas, all TCs have multiple LPs, but for simplicity, we only treated them as one LP if they are within the demarcation line depicted in Fig. 1. Positive (negative) values, indicated by red (blue) bars represent deflections to the right (left). Yellow squares indicate TCs with at least TY intensity

(negative) values represent deflections to the right (left), i.e., clockwise (counterclockwise) deflections. The cases with deflections $\Delta \geq 5°$ are also summarized in Table 3 which can be noted that the magnitude of deflections at AP is generally larger than those at DP (Fig. 10). For Mindanao and Visayas (Fig. 10a, b), all cases at AP and DP are within $\pm 20°$.

Figure 11a categorizes the number of TCs that are deflected at AP and DP based on deflection angles over Mindanao. In the AP, about 4 TCs were deflected rightward, 3 of which have at least TY category. Additionally, there were 2 TCs having transient deflection (within $\pm 5°$), while no TCs were deflected leftward. Based on Table 3, about 66% of the TCs show deflections at AP, while only 33% show deflections at DP. There is also an apparent tendency for strong TCs ($\geq$C1) to be deflected to the right at AP (100%), and none at DP (0%). This indicates an apparent effect of topography on stronger TCs at or near landfall. Weaker TCs appear to be deflected more to the left of DP (66%) than to the right at AP (33%). TCs that had made landfall in Mindanao showed that all TCs having a TY category are deflected to the right at AP and require further numerical simulations to explain the northward (rightward or positive) deflection of TCs in Mindanao due to the different terrain features. Wu and Choy (2015) also noted that the direction change may also be attributed to the uncertainty of position and that further study

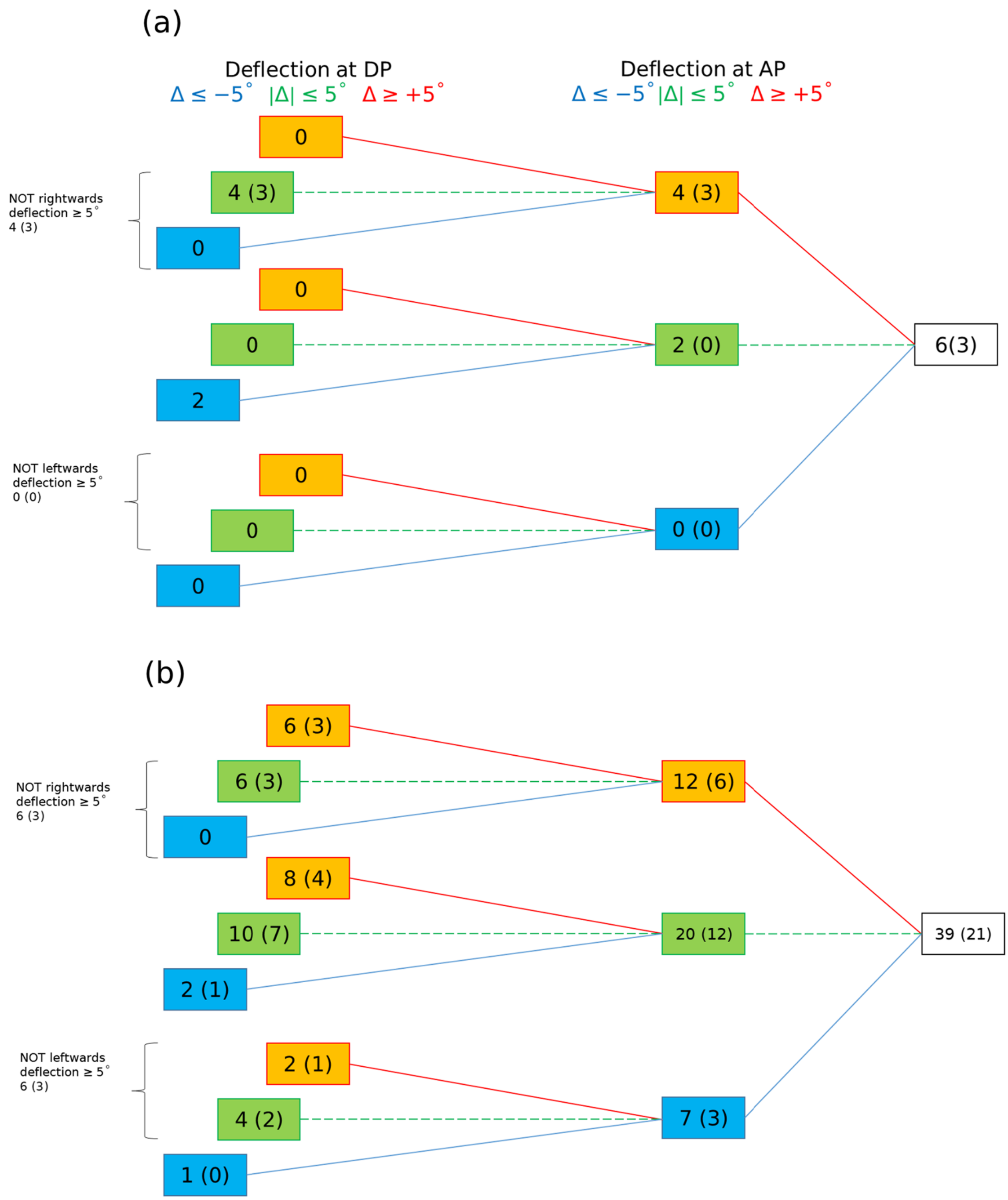

Fig. 11 Deflection at AP and DP for the **a** 6 TC cases with at least one LP point over Mindanao and **b** 39 TC cases over Visayas. Red (Blue) solid line indicates positive or rightward (negative or leftward) deflection of 5° or more, whereas the green dashed line represents a deflection less than 5°. Cases with maximum sustained wind ≥ C1 category are given inside the parenthesis

is required to determine whether there are significant or abrupt changes at AP and DP due to topography.

Based on Fig. 11b, over Visayas, 12 TCs were deflected rightward, 6 of which have at least TY category. There were 20 TCs that underwent transient deflection (within ± 5°), 12 of which have a TY category. Moreover, 7 TCs were deflected leftward, 3 of which having at least TY category. The results show that there is no significant pattern for the TC deflection at DP as the number of TC deflection is distributed across the categories and that

Table 3 Summary of the deflection (Δ) in the 6-h movement direction at AP and DP of landfalling Mindanao TCs using a threshold of ± 5°. Refer to Figs. 11 and 12 for the counting of cases. Note that Δ ≥ 5° degrees (< −5°) are regarded as positive or rightward (negative or leftward) deflection

Intensity	Cases	At AP			At DP		
		Δ > 5°	Δ < −5°	|Δ| ≥ 5°	Δ > 5°	Δ < −5°	|Δ| ≥ 5°
MINDANAO							
All TCs	6	4	0	4 (66%)	0	2	2 (33%)
> TY	3	3	0	3 (100%)	0	0	0 (0%)
TD/TS	3	1	0	1 (33%)	0	2	2 (66%)
VISAYAS							
All TCs	39	12	7	19 (49%)	16	3	19 (49%)
> TY	21	6	3	9 (43%)	8	1	9 (43%)
TD/TS	18	6	4	10 (56%)	8	2	10 (56%)

transient deflections comprise the majority of the count. Based on Table 3, about 49% of the TCs (19 cases) show deflections at AP and DP. Note that there exists an apparent tendency for weaker TCs to be either deflected to the left or right at AP and DP for TCs landfalling in Visayas, which is contradictory to the observations made in Mindanao where TCs are deflected to the right at AP and left at DP. There also exists a strong tendency for a TC to be deflected to the right at both AP and DP for both > TY and TS categories.

More specifically in the Visayas region, weaker TCs appear to be deflected at AP (56%) and DP (56%) than stronger TCs (43%). This is supported by the findings of Wang et al. (1999) and Wu and Choy (2015), where they noted that topography is more effective in deflecting weaker TCs. For Visayas TCs having a strength greater than TY category, a deflection to the right is more apparent in both the AP and DP.

Contrary to Wu and Choy's (2015) findings of a negative correlation for TCs passing through Luzon ($r = -0.65$; p value not given) between the deflection angles at AP and DP, a significant and positive correlation between AP and DP ($r = 0.8218$; $p = 0.0123$) was found in Mindanao and an insignificant and positive correlation between AP and DP ($r = 0.0091$; $p = 0.9561$) was found in Visayas cases as shown in Fig. 12, was found in this study. Note that all of the TC deflection (including the transient wobbles of < 5°) were taken into account. To demonstrate this positive linear relationship, such that deflection to the left (right) at AP corresponds to the deflection to the left (right) at DP, we illustrate 3 sample cases for Mindanao in Fig. 13a, b. Examples of TCs that were deflected leftward both at AP and DP are WASHI (2011), while examples of TCs that exhibited rightward deflections both at AP and DP are IKE (1984), NELL (1993). Additionally there were 5

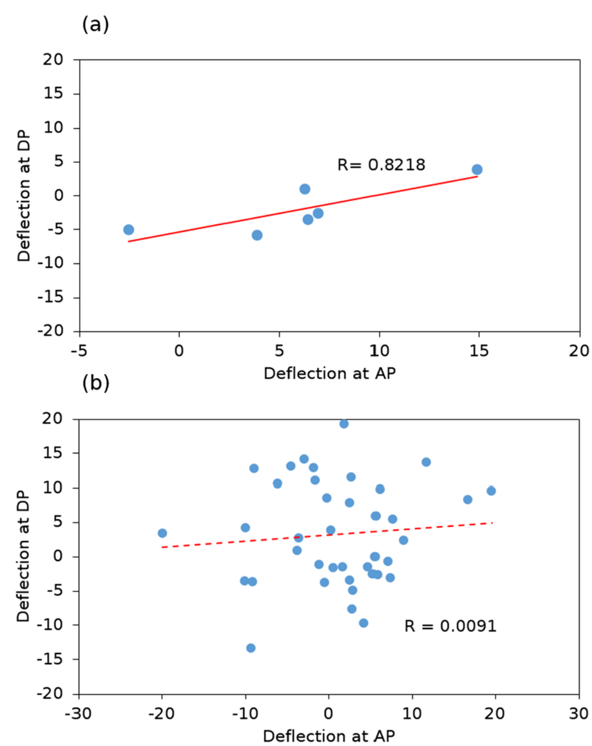

Fig. 12 Comparison of the deflections at AP and DP for the **a** 6 cases with deflections over Mindanao and **b** 39 cases with deflections over Visayas. The solid lines represent the linear trends

TCs that exhibited a different change in direction at AP and DP, which are MARGE (1986), BOPHA (2012), and JANGMI (2014). For TCs which had made landfall in Visayas, some TCs exhibited similar changes in direction as shown in Fig. 13c, d. However, there is no significant relationship between the deflection angles at AP and DP as shown earlier in Fig. 12b. This may be

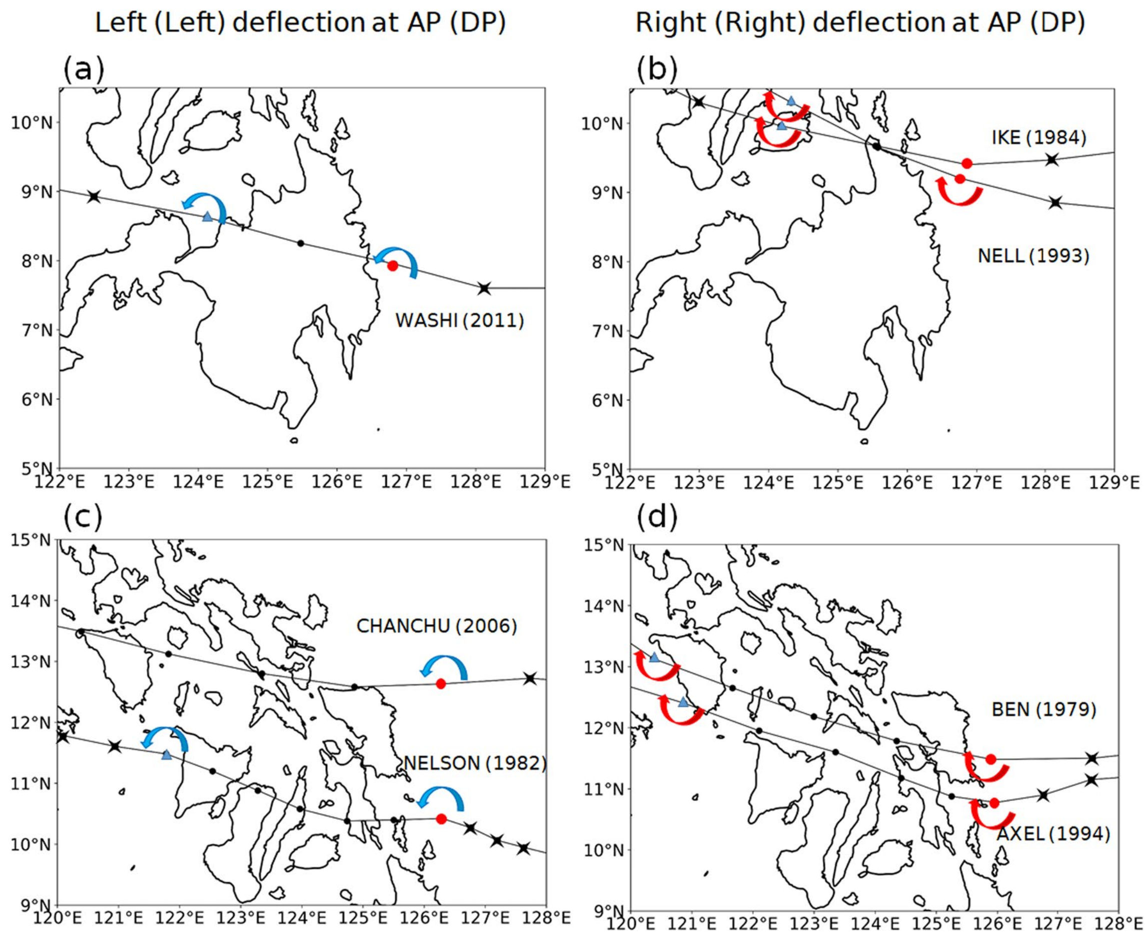

Fig. 13 Examples of cases with leftward (leftward) and rightward (rightward) deflection at AP (DP) over Mindanao (**a**, **b**) and Visayas (**c**, **d**)

attributed to the fact that the inter-island deflections were ignored in this study.

Wu and Choy (2015) noted that the conditions likely to indicate whether a TC would have a left or right deflection at AP may be determined by cross-examining the translational speed, intensity, and direction of motion from AP − 24 to AP − 6 as shown in Fig. 14a, b for Mindanao and Visayas, respectively. For TCs passing through Mindanao, TCs deflected to the right at AP tend to be more intense, the translational speed generally consistent, and the direction of motion varied across all approaching points. For TCs having a transient deflection, it can be observed that they are generally weaker compared to the TCs that were deflected positively. It is important to note that there was only one TC with a transient deflection at AP − 12 to AP − 24 since incomplete data were retrieved from the JANGMI (2014). As such, this does not provide a clear and convincing representation of Mindanao TCs that were deflected to the left. For TCs passing through Visayas, in the order of greatest to least intensity, TCs that would undergo transient deflection tend to be the most intense, followed by TCs deflected to the right, then TCs deflected to the left. In terms of translational speed, in the order of greatest to least magnitude, TCs that would be deflected to the right have the greatest speed, followed by TCs that would undergo transient deflection, then TCs deflected to the left. In terms of the direction of motion, TCs deflected to the right at AP follow a northwesterly track before landfall, while TCS that would undergo transient deflection and deflection to the left at AP follow a more westward direction. In comparison, the results of Visayas (Mindanao) TCs conform (contradict) with landfalling Luzon TCs from Wu and Choy (2015) such that TCs undergoing a transient (significant rightward) deflection at AP are the most intense compared to the other deflection classification.

3.5 Comparison of TC behavior in Luzon, Visayas, and Mindanao

Table 4 summarizes the differences in the impact of the Luzon, Visayas, and Mindanao on the intensity,

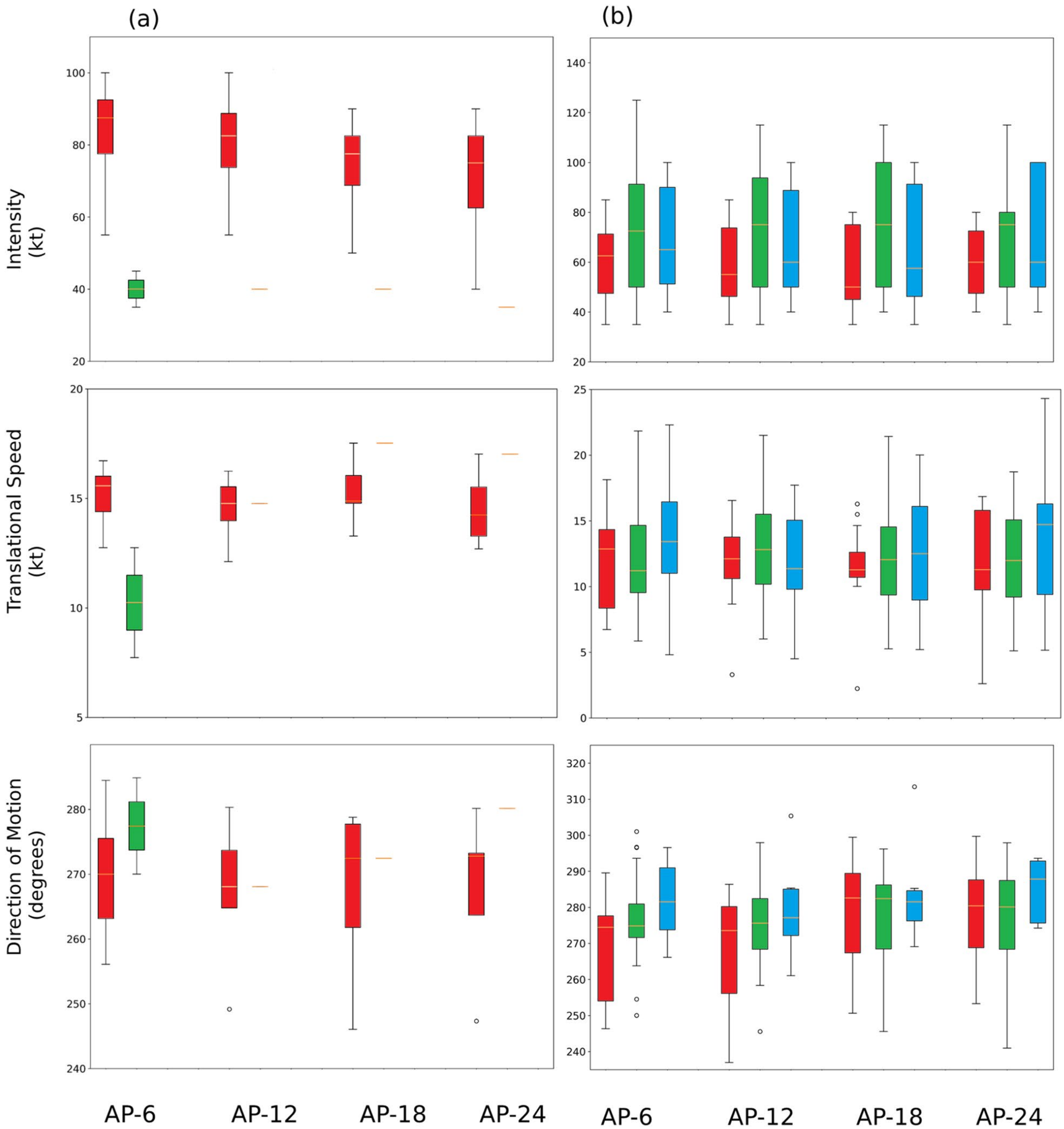

Fig. 14 Comparison of temporal variation of the average intensity (top) translation speed (middle) and direction of motion (bottom) from AP − 6 to AP − 24 for different groups in terms of the deflections at AP for **a** Mindanao and **b** Visayas. The whiskers indicate maximum and minimum values, the upper and lower limits of the box indicate 75th and 25th percentile, respectively, the solid black line indicates the median, and the circles outside the whiskers indicate outliers. Red (blue) indicates positive or rightward (negative or leftward) deflection cases. Green indicates otherwise cases which are transient deflection cases (i.e., deflection |Δ| < 5°)

translational speed, and direction of motion of landfalling TCs in each region. The results for Luzon Island shown in this table were based on Wu and Choy (2015). In contrast to those landfalling TCs over Luzon, where there is a logarithmic relationship between DP and AP, TCs crossing in Mindanao and Visayas have a linear relationship between DP and AP. This may be attributed to the distance across each islands and island

Table 4 Regional comparison of the changes in intensities, translation speeds, and direction of motions of landfalling TCs over Luzon, Visayas, and Mindanao. The results for Luzon Island were based on Wu and Choy (2015)

	Luzon	Visayas	Mindanao
Data and methods	Landfalling Luzon TCs at > 15° N are recorded 50 TCs from 1980 to 2014 More frequent storms during JJASO than NDJFM	TC passing through the defined demarcation lines between 10 and 15°N 39 TCs from 1979 to 2020 More frequent storms during NDJFM than JJASO	Landfalling Mindanao TCs 8 TCs from 1979 to 2020 More frequent storms during NDJFM than JJASO
Intensity	Average intensity at AP is 69.2 kts Decrease in TC intensity at AP versus DP (logarithmic relationship) Estimated intensity drop for TD and TS is less than 10 kts, while for TY is greater than 10 kts 6 cases with intensity increase for Luzon TCs (TS & TD Category) 11 RI and 3 RW (24 h before AP and AP − 6) Intensity drop levels off at DP + 6	Average intensity at AP is 67.95 kts, while DP is 54.36 kts Decrease in TC intensity at AP versus DP (linear relationship) Average intensity drop for TS is 8.13 kts (− 20.5%), while for TY is 24.29 kts (− 45.5%) Average intensity increase for TS is about 7.5 6 cases with intensity increase for Visayas TCs (6 TS) 21 RI and 3 RW (from genesis to AP) Intensity drop levels off at DP	Average intensity at AP is 63.38 kts, while DP is 53.13 kts Decrease in TC Intensity at AP versus DP (linear relationship) Average intensity drop for TS is 6.67 kts (− 25.0%), while for TY is 23.33 kts (− 25.4%) Average intensity increase for TS is 5 kts 2 cases with intensity increase for Mindanao TCs (TS) 2 RI and 1 RW (from genesis to AP) Intensity drop levels off at DP + 6
Translational Speed	Average TS at AP is 12.8–14.8 kts (95% CI) TC takes about 6 to 9 h to transverse Luzon TC accelerates (decelerates) as it approaches (departs) from Luzon Island	Average TS at AP is 11.09–13.79 kts (95% CI) TC takes about 17 to 30 h to traverse Visayas TC decelerates as it approaches and departs Visayas	Average TS at AP is 11.12–16.24 kts (95% CI) TC takes about 7 to 14 h to traverse Mindanao TC decelerates as it approaches and departs Mindanao
Direction of Motion	Weaker TCs have a greater tendency to be deflected at AP compared to stronger TCs Stronger TCs have a greater tendency to be deflected at DP than AP Negative correlation at DP versus AP direction change (opposite deflection) Higher TC deflection tendency at DP than at AP	Weaker TCs have a greater tendency to be deflected both at AP and DP compared to stronger TCs No correlation at DP versus AP direction change Similar TC deflection tendency at AP and aYangt DP	Stronger TCs have a greater tendency to be deflected at AP than DP All TCs at TY are deflected to the right at AP Two TCs deflected to the left at DP Positive correlation at DP versus AP direction change (same direction deflection) Higher TC deflection tendency at AP than at DP

group (i.e., Luzon is narrower compared to Visayas and Mindanao), which is relevant to the duration of interaction between topography and the TC. Wu and Choy (2015) noted that the TC's translational speed accelerates (decelerates) as they approach (depart from) Luzon Island, which agrees with the behavior of TCs landfalling in Visayas; on the other hand, the opposite was observed for TCs passing through Mindanao, where the translational speed decreases as they approach and depart the island. Compared to Luzon and Visayas, Mindanao has a wide terrain with more complex topography, considering the presence of multiple mountains and mountain ranges, which may have caused a larger decrease in the energy budget of the TC; thus, there is a consistent deceleration of TCs as they traversed the island. More specifically, TCs take about 6–9 h to traverse Luzon, 17–30 h to traverse Visayas, and 7–14 h to traverse Mindanao. Furthermore, while there is a slight tendency for TCs to deflect leftward upon leaving Luzon Island as manifested by the significant negative correlation between DP and AP, there is a significant positive correlation found between the deflection angles of TCs before and after crossing Mindanao, such that a TC deflected to the right (left) before landfall is likely to deflect to the right (left) after crossing Mindanao, while no significant linear relationship in terms of deflections has been observed for TCs in Visayas. Unlike Luzon and Mindanao, which account for one island each, Visayas is a sea-island mix (i.e., there may have been deflections after traversing each individual island, which are not considered in this study). When examining the TC behavior from AP − 6 to AP − 24, landfalling TCs over Mindanao that were deflected to the right at AP are mostly intense TCs that have generally consistent translational speeds at all approaching points. For Visayas, TCs undergoing transient deflection tend to be more intense, but TCs that have a consistently greater translational speed are the TCs that are deflected to the right at AP. An extensive study of TCs crossing the Visayas group must be done to fully define how it affects TCs in terms of deflections.

Geography plays a critical role in TC behavior as it passes through the Philippine Archipelago (Brand and Blelloch 1973; Tang and Chan 2014; Racoma et al. 2016; Yang et al. 2022). To reiterate, the main landmasses of the Philippines, Luzon Island, Visayas Islands, and Mindanao Island are dissimilar. More specifically, three mountain ranges exist in Luzon Island, while Mindanao Island has a complex topography with mountainous regions and is located closer to the equator. Lastly, Visayas is a sea-island mix found in between Luzon and Mindanao.

4 Summary and concluding remarks

This study investigated the climatology and characteristics of landfalling TCs over central and southern Philippines from 1979 to 2020. A total of 8 TCs in Mindanao and 39 TCs in Visayas were examined in terms of the changes in tracks, intensities, and translational speeds as they interacted with the islands' topography. It was observed that TCs have a greater frequency to make landfall in Visayas and Mindanao during the NDJFM season, which are considered as the off TC season. More specifically, there were 6 TCs that made landfall in Mindanao in December, while there were 10 and 15 TCs that made landfall in Visayas in the months of November and December, respectively. Thus, this is essential information for scientists, engineers, and first responders to anticipate the increased TC occurrence during the latter part of the year.

Furthermore, results also show that TCs generally weaken as they traverse through Mindanao and Visayas. For TCs traversing through Mindanao, the decreased intensity as represented by the change in the maximum sustained winds (MSW) of the TCs with at least Typhoon (TY) intensities is about 23.33 kts on average, while TCs with intensities of TS are less affected and have an average decrease of about 6.67 kts. For TCs traversing through Visayas, the average decrease in MSW with TS intensities is about 8.13 kts. Additionally, TCs classified as TY, on average, decrease in intensity by about 24.29 kts. These decrease in intensities may be caused by friction, changes in the latent heat supply, and a change of moisture supply over land as noted in previous studies (e.g., Brand and Blelloch 1973; Wu and Choy 2015). Recall that TCs passing through Visayas take about 12 to 36 h, which may explain the greater magnitude of the intensity drop with respect to Mindanao.

Only 1 TS increased in intensity by 5 kts, which is NELL (1993), while 2 TSs maintained their intensities, which are JANGMI (2014) and TEMBIN (2017). For Visayas, 7 TSs intensified, on average, by about 7.5 kts which shows a 14.1% at AP, respectively. The maintenance or intensification of TCs after landfall can be attributed to weak low-level temperature gradients, sufficient soil moisture, and enhanced surface latent heat flux (Sugino and Satomura 2010; Andersen and Shepherd 2013; Andersen et al. 2013; Shepherd et al. 2021).

The TCs moving across Mindanao and Visayas decelerate as they approach and move away from Mindanao. As the TCs approach (move away from) land, there is a decrease (increase) in the moisture and heat from the ocean and there is an increase (decrease) in surface friction causing deceleration (acceleration) before (after) landfall. The translational speed exhibited by landfalling Visayas TCs is similar to the landfalling Luzon TCs from Wu and Choy (2015).

Comparing the results from Wu and Choy (2015) over Luzon Island, we found a similar significant intensity drop upon landfall over Visayas and Mindanao. In terms of translational speed, the results contradict between Luzon and Visayas-Mindanao wherein TCs accelerate (decelerate) as they approach (leave) Luzon Island, while TCs for both Visayas and Mindanao decelerate as they approach and depart the islands. In terms of TC deflection, weaker TCs have a greater tendency to be deflected at AP compared to stronger TCs that are landfalling in Visayas and Luzon. This contradicts with the findings in Mindanao where the stronger TCs have the greater tendency to be deflected at AP. While no correlation in terms of TC deflection has been found between DP and AP, a similar (opposite) direction of deflection has been observed in Mindanao (Luzon).

The present study was also able to show that weaker TCs in Visayas appear to be deflected more at both DP and AP compared to stronger TCs, which would indicate that topography is more effective in deflecting weaker TCs (Wang et al. 1999; Wu and Choy 2015). However, this contradicts the findings in Mindanao where stronger TCs have a greater tendency to be deflected at AP than weaker TCs. Tang and Chan (2014) attributed the rightward deflection of TCs prior to landfall over Luzon as a result of the convergence over the Philippine archipelago that weakens an anticyclonic gyre. These terrain-induced gyres were found over the mountains of Luzon, which pushes the TCs in a northeast direction.

This study only examined the characteristics of landfalling TCs over Mindanao (southern Philippines) and Visayas (central Philippines). However, a lot of issues still need to be addressed in future studies. For example, idealized numerical simulations such as those by Tang and Chan (2014) may help further elucidate how Mindanao Island or Central Visayas topography interacts with TCs crossing it. More specifically, further investigation for the existence of terrain-induced gyres may possibly explain the northeastward bias of TCs (Tang and Chan 2014). So far, only one study examined the impact of Mindanao Island's mountains on the TC-induced rainfall (i.e., Minamide and Yoshimura 2014). We expect that more insights will be gained from high-resolution numerical model simulations on topography-TC interactions. Another limitation of this study is that WMO reports the intensities of the TCs with an interval of 5 and may reduce the accuracy and that it does not provide TC intensity below 30 kts.

Abbreviations

AP	Approaching point
C1	Category 1
C2	Category 2
C3	Category 3
C4	Category 4
C5	Category 5
CI	Confidence interval
DP	Departing point
JJASO	June, July, August, September, October
WMO	World Meteorological Organization
LP	Landing point
MSW	Maximum sustained wind speed
NDJFM	November, December, January, February, and March
RI	Rapid intensification
RW	Rapid weakening
TC	Tropical cyclone
TD	Tropical depression
TS	Tropical storm
TY	Typhoon
WP	Western Pacific

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40645-023-00563-1.

Additional file 1: Figure S1. TC tracks of landfalling Mindanao TCs during JJASO and NDJFM seasons. The red crosses indicate the genesis location. **Figure S2.** TC tracks of landfalling Visayas TCs during JJASO and NDJFM seasons. The red crosses indicate the genesis location.

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Author contributions

CERP, LPST, and LMPO proposed, analyzed the data, and drafted the manuscript. JM helped in the interpretation, review, and writing of the manuscript.

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Availability of data and materials

The authors declare that they only used open access data in this paper. Specifically, the tropical cyclone data were provided by the Joint Typhoon Warning Center of the US Navy and can be accessed here: https://www.metoc.navy.mil/jtwc/jtwc.html?best-tracks.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Author details

[1]Department of Physics, Ateneo de Manila University, Loyola Heights, 1108 Quezon City, Philippines. [2]Regional Climate Systems Laboratory, Manila Observatory, Quezon City, Ateneo de Manila University Campus, Loyola Heights, 1108 Quezon City, Philippines. [3]Department of Geography, Tokyo Metropolitan University, 1-1 Minami-Osawa, Hachioji-Shi, Tokyo 192-0397, Japan. [4]Center for Coupled-Ocean-Atmosphere Research, Japan Agency for Marine Earth Science and Technology, Yokosuka, Kanagawa 237-0061, Japan.

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