Impacts of ENSO on Philippine Tropical Cyclone Activity

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ABSTRACT

This study investigates the El Niño–Southern Oscillation (ENSO) contribution to Philippine tropical cyclone (TC) variability, for a range of quarterly TC metrics. Philippine TC activity is found to depend on both ENSO quarter and phase. TC counts during El Niño phases differ significantly from neutral phases in all quarters, whereas neutral and La Niña phases differ only in January–March and July–September. Differences in landfalls between neutral and El Niño phases are significant in January–March and October–December and in January–March for neutral and La Niña phases. El Niño and La Niña landfalls are significantly different in April–June and October–December. Philippine neutral and El Niño TC genesis cover broader longitude–latitude ranges with similar long tracks, originating farther east in the western North Pacific. In El Niño phases, the mean eastward displacement of genesis locations and more recurving TCs reduce Philippine TC frequencies. Proximity of La Niña TC genesis to the Philippines and straight-moving tracks in April–June and October–December increase TC frequencies and landfalls. Neutral and El Niño accumulated cyclone energy (ACE) values are above average, except in April–June of El Niño phases. Above-average quarterly ACE in neutral years is due to increased TC frequencies, days, and intensities, whereas above-average El Niño ACE in July–September is due to increased TC days and intensities. Below-average La Niña ACE results from fewer TCs and shorter life cycles. Longer TC durations produce slightly above-average TC days in July–September El Niño phases. Fewer TCs than neutral years, as well as shorter TC durations, imply less TC days in La Niña phases. However, above-average TC days occur in October–December as a result of higher TC frequencies.

1. Introduction

The loss of life and damage to property caused by tropical cyclones (TCs) in the Philippine region are well known (e.g., www.ndrrmc.gov.ph). The Philippines is situated in the western North Pacific (WNP), the most active TC basin in the world. The country is affected by about 18 TCs every year, mostly of typhoon intensity, constituting ~70% of all WNP TCs (Corporal-Lodangco 2014). The strong winds and torrential rain from TCs produce flooding, storm surges, and landslides.

El Niño–Southern Oscillation (ENSO) is a tropical atmosphere–ocean interaction that modifies the thermodynamic and dynamic states that influence the weather and climate system (Bjerknes 1969). Kim et al. (2008) consider it to be the most important planetary-scale phenomenon affecting interannual variations in TC activity in the WNP. The relationship between ENSO and TC activity in the WNP has been explored extensively in previous studies (e.g., Chan 1985, 2000; Dong 1988; Lander 1993, 1994; Chen et al. 1998; Kimberlain 1999). The work of Chan (1985), Chen et al. (1998), Chia and Ropelewski (2002), and Wang and Chan (2002) focused on the cyclogenesis locations, whereas those of Chan (1985), Dong (1988), Wu and Lau (1992), Chen et al. (1998), and Camargo and Sobel (2005) examined the total number, intensity, and lifetime of TCs. The ENSO influence on TC tracks and landfalls also has been assessed (e.g., Wang and Chan 2002; Wu and Wang 2004; Wu et al. 2004; Camargo and Sobel 2005; Fudeyasu et al. 2006; Camargo et al. 2007a; Yonekura and Hall 2011; Colbert et al. 2015).

There is extensive literature addressing the influence of ENSO on WNP TC activity. However, most of these
studies do not focus specifically on Philippine TCs. Only two studies exclusively address Philippine TC activity (e.g., Kubota and Chan 2009; Lyon and Camargo 2009). The current study is a comprehensive investigation of a range of Philippine TC activity metrics [viz., statistics of TC numbers, landfalls, intensities, days, accumulated cyclone energy (ACE), cyclogenesis locations, and tracks] during the various phases of ENSO. It extends a preliminary study by Corporal-Lodangco (2014) in which a wavelet analysis revealed ENSO as the major global mode affecting Philippine TC variability. The irregularity in TC activity occurs only in certain quarters during El Niño and La Niña phases but not throughout the year. The change in the planetary-scale circulation associated with ENSO phases explains the relationship between ENSO and TC activity (Chan 2000). Consequently, the emphasis in this study is on interseasonal (quarter years) time scales, reflecting the seasonal relationship between ENSO and Philippine TCs. Previous studies reveal significant differences in landfall rates in the northern Philippines between El Niño and La Niña events, with more intense typhoons making landfall in northern Luzon in La Niña years (Saunders et al. 2000; Elsner and Liu 2003). Moreover, the number of landfalling TCs in the Philippines is significantly less than the mean in September–November of El Niño years (Elsner and Liu 2003; Wu et al. 2004).

This paper has four sections. In section 2, the datasets used and the methods employed are described. Section 3 discusses the main results, including the statistics of TC frequency, landfalls, days, and ACE as well as the variability of TC intensity, genesis, and tracks, and provides an analysis of the impacts of ENSO. In section 4 findings are discussed and conclusions drawn.

2. Data and methodology

The TC archive covers 1950–2011 and is purposely limited to TCs that either formed or moved into the Philippine domain. It is standard practice that TCs are included in the Philippine domain count only if some parts of their archived tracks were within the Philippine domain. In total, 1122 TCs were analyzed in this study, consistent with the focus on Philippine domain TCs. Track segments located outside the Philippine domain were excluded from the TC days analysis so that only the number of days a system was actually within the domain was included in the cumulative TC days. The TC intensity classification is based on the observed maximum sustained wind near the center. A tropical depression (TD) requires the maximum sustained winds to fall within the range of 9.72–17.78 m s\(^{-1}\), a tropical storm (TS) has winds in the range of 18.05–32.78 m s\(^{-1}\), and a TC is classified as a typhoon (TY) when the winds exceed 32.78 m s\(^{-1}\). The intensity classification established by the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) was adopted in this study. PAGASA is the World Meteorological Organization (WMO) designated agency for monitoring, forecasting, and archiving TCs that affect the Philippines.

a. Domain and TC data source

The study region encompasses latitudes 5°–25°N and longitudes 115°–135°E, shown in Fig. 1 as the black inset, and is referred to herein as the Philippine domain. PAGASA has its own domain, mandated by the WMO. It differs only slightly from the Philippine domain defined in this paper. The irregular box (red broken line in Fig. 1) shows the PAGASA area of responsibility for TCs. For simplicity and data processing, the domain in this study was chosen to be a conventional square latitude–longitude region, closely approximating the PAGASA area. The TC data used is obtained from the Joint Typhoon Warning Center (JTWC; www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/). Among other information, the best track data for each TC at 6-h intervals includes latitude–longitude position, maximum sustained surface wind speed, and minimum central pressure. Genesis locations, tracks, and all other TC metrics were generated from the JTWC data. Several studies used the same data source and period that covers the presatellite era (e.g., Elsner and Liu 2003; Camargo et al. 2007b; Zhao et al. 2014). Elsner and Liu (2003) examined TC data from pre- (1945–70) and post- (1971–2002) satellite eras and found no statistically significant difference.

b. Large-scale climate data

ENSO phases are derived from equatorial sea surface temperatures (SSTs), from approximately 120°W westward to near the date line (Barnston et al. 1997). Niño-3.4 (5°N–5°S, 170°–120°W) is typically the most important region for WNP TC activity (Camargo and Sobel 2005) and is one of the most common indices used to monitor ENSO. The oceanic Niño index (ONI) used in this study was obtained from the National Oceanic and Atmospheric Administration (NOAA; www.cpc.ncep.noaa.gov/) and developed by Smith and Reynolds (2003). The ONI is defined as the 3-month running mean of Extended Reconstructed SST (ERSST) anomalies in the Niño-3.4 region, based on the 30-yr period 1981–2010. Values of vorticity at 1000 mb (1 mb = 1 hPa), zonal wind at 850 mb, and divergence at 200 mb are provided by the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al. 1996; Kistler et al. 2001).
c. Methods

In this study, a range of statistical measures is used to investigate how ENSO influences TCs in the Philippine domain. Unlike most TC regions, Philippine TC activity is observed in every calendar month (January–December). Accordingly, traditional quarterly periods are needed to capture detailed changes in the TC metrics. The genesis locations, track shapes, and the total number of TCs and landfalls vary considerably when grouped by quarter years. The summer and winter monsoon winds greatly influence the motion and tracks of the Philippine TCs; other systems also affect the country, and they peak in particular months. The four quarters are the standard seasonal periods of January–March (JFM), April–June (AMJ), July–September (JAS), and October–December (OND). Investigation by quarter years provides information about how ENSO modulates the early, mid-, peak, and late seasons of TC activity, in terms of the TC metrics defined in section 3. The ONI is employed to classify each quarter. A quarter is classified as a neutral, El Niño, or La Niña phase of ENSO when the averages of the Niño-3.4 SST index (Barnston et al. 1997) are from at least $<0.5^\circ$C to $>-0.5^\circ$C, $0.5^\circ$C, and $-0.5^\circ$C, respectively. The quarterly ONI is shown in Fig. 2, color coded to signify the different ENSO phases. From Fig. 2, it can be inferred that the quarters represent the beginning, developing, and maturing stages of El Niño and La Niña events (e.g., Rasmusson and Carpenter 1982). The ONI in AMJ reflects the early, or developmental, stage of an El Niño or La Niña event. The ONI in JAS–OND is the time period when an event typically develops and strengthens, and the JFM quarter usually is when the event is at its mature stage, as the ONI continues to become more negative (positive). The ONI in AMJ of the following year signifies the decaying or dissipation stage of an ENSO phase, as this is the period when the tropical Pacific Ocean experiences a leveling out of the temperature gradient between the western and eastern regions, as it returns to a neutral phase. Table 1 shows the years of each ENSO phase and the corresponding number and average of TCs per quarter.

To represent the TC intensity on a quarterly time scale, the ACE, introduced by Bell et al. (2000), is calculated. The equation and definition of ACE is given in section 3a(6). The quarterly time series of TC count, landfall, intensities, days, and ACE were “standardized” to provide a representative set of TC metrics for each of the ENSO phases. The standardization involved subtracting the long-term mean (1981–2010) from the individual TC metrics and then dividing the difference by the standard deviation. It is expressed in the following equation:

$$z = \frac{(x - \mu)}{\sigma},$$

where $z$ is the standard score, $x$ is the individual TC metrics, $\mu$ is the long-term mean of the TC metrics, and $\sigma$ is the standard deviation of the TC metrics. The
long-term mean is the average of the TC metrics over a suitably long time period. Here, we employed the generally accepted 1981–2010 average. The number of TCs during neutral phases is greater than during El Niño and La Niña phases, which would suggest falsely that without standardization, ENSO has no impact on the Philippine TCs. The standardized TC metrics indicate by how many standard deviations an observation is above or below the mean. The standard scores for each quarter are grouped into ENSO phases and then averaged to get the mean standard score for each ENSO phase. To quantify the results as outstanding or not, especially for TC metrics during the various ENSO phases, a statistical significance test at the 95% confidence level is performed using the Wilcoxon test, which is a nonparametric statistical hypothesis test (see, e.g., Lowry 1999).

3. Results and discussion

a. Impacts on TC properties

A comprehensive analysis of TC data is carried out to examine possible trends in Philippine TC activity related to ENSO, using the following metrics.

1) GENESIS POSITIONS

The Philippine domain lies in that part of the WNP where TC genesis occurs most frequently—namely, in the monsoon trough (McBride 1996; Chen et al. 2004; Lander 1994). The monsoon trough is marked by moist, southwest monsoon flows to the south and easterly trades to the north of the trough. Tropical disturbances often are found in the trough where there is a weak cyclonic rotation. As the cyclonic spin in the trough increases, the system intensifies into a TC, ranging from storms to typhoons (Sadler 1967). The impact of ENSO on the mean TC genesis location has been extensively studied for the WNP but only tangentially for the Philippine domain. A displacement to the southeast (northwest) in El Niño (La Niña) years (Chan 1985; Dong 1988; Chen et al. 1998; Dong and Holland 1994;
<table>
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<th>Year</th>
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<th>JFM El Niño TCs</th>
<th>JFM La Niña TCs</th>
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<th>JAS El Niño TCs</th>
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<td>All TCs average</td>
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**Table 1.** List of years for each ENSO phase in every quarter, with the corresponding numbers of TCs and their averages.
Lander 1994; Wang and Chan 2002; Chia and Ropelewski 2002) associated with the eastward extension of the monsoon trough and westerlies and a reduction of vertical wind shear near the date line increase genesis east of the climatological mean genesis point (Lander 1994, 1996; Clark and Chu 2002; Wang and Chan 2002). Preferred genesis regions shift systematically, responding to changes in the large-scale environments associated with both ENSO phases.

Figure 3 shows the quarterly genesis locations of Philippine TCs for each ENSO phase. January, February, and March are the quiet months and represent the least active period of TC behavior in the Philippine domain. In JFM, (Figs. 3a–c), TC formation is less frequent, being located east of the Philippines and confined to the lower latitudes. No TCs formed over the South China Sea in JFM because the SSTs were too cold. TCs that enter the domain can form farther east, almost reaching the date line in neutral and El Niño years, whereas in La Niña years, TC development is confined to the west of 165°E. The mean genesis position (shown as a black star) in neutral years (Fig. 3a) is 6.7°N, 144.1°E. Relative to neutral years, the mean genesis position in JFM of El Niño years (Fig. 3b) is displaced to the southeast at 5.6°N, 158.5°E, while in La Niña years (Fig. 3c), the genesis position is displaced to the northwest (9°N, 138.9°E). The second quarter (AMJ; Figs. 3d–f) is marked by an increase in genesis numbers over JFM, and the genesis locations extend farther north to 22°N, with only a few TCs forming in the South China Sea. The mean genesis locations of neutral, El Niño, and La Niña phases are 10.5°N, 135.8°E; 10.7°N, 136.0°E; and 11.6°N, 130.7°E, respectively. In El Niño years, the mean genesis location is slightly displaced to the east, but in La Niña years, the location is slightly displaced to the west from the climatological mean position.
Niña years, it is displaced much farther northwestward, by 5° longitude. The genesis locations in both neutral and El Niño years are found west of 165°E and only west of 150°E in La Niña years. TC formation in the Philippine domain peaks in JAS (Figs. 3g–i). The frequency and areal extent of TC genesis both are greatest during JAS. High TC activity in JAS results mainly from the frequent occurrence of favorable thermodynamic and dynamic conditions for TC development (e.g., Gray 1979). TC genesis points occupy a much broader latitudinal and longitudinal extent, and noticeably more TCs are present in the South China Sea. The spatial distributions of TC genesis in neutral and El Niño years are very similar. The mean genesis point (black star), relative to neutral years, is slightly displaced to the southeast during the El Niño years and to the northwest in La Niña years. Mean genesis locations are 14.5°N, 136°E; 13.9°N, 136.5°E; and 16.4°N, 133.1°E for neutral, El Niño, and La Niña years, respectively. TC formation in JAS during La Niña years is west of 160°E but can reach beyond 170°E in neutral and El Niño years. Figures 3j–l show genesis locations during OND, indicating fewer TC genesis occurrences than JAS and that the latitudinal extent of cyclogenesis is not as large and dense. Consistent with previous quarters, genesis locations in neutral and El Niño years extend farther east, almost reaching the date line, whereas in La Niña years the majority of TCs formed west of 165°E. Mean genesis locations in neutral and El Niño years are in 10°N, 143°E and 10.6°N, 144.2°E, respectively, indicating a slight displacement in El Niño years, whereas the mean genesis position in La Niña years is displaced northwestward to 11.3°N, 134.6°E.

As observed in all quarters, smaller numbers of TCs occur in El Niño years, in contrast with neutral and La Niña years. Table 1 shows that, on average, in neutral years more TCs exist in the Philippine domain, compared with El Niño and La Niña years, in all quarters except in OND of La Niña years. Relative to neutral years, the mean genesis position in El Niño years is displaced significantly eastward in JFM but only slightly shifted in AMJ, JAS, and OND. The northwestward retreat in genesis locations during La Niña is apparent in all quarters. Figure 4 illustrates the cumulative density of TC genesis points in 5° latitude by 5° longitude grid boxes, showing the preferred area of quarterly TC formation during ENSO phases. The greatest concentration of genesis location is found to occur in JAS of neutral phases. The genesis locations in El Niño phases have the widest horizontal spread and are located farther east compared with La Niña years where genesis locations are closer to the Philippines. TC genesis locations in neutral and El Niño years, in all quarters, cover a wider longitudinal range; they extend beyond 160°E and reach almost to the date line.

2) Tracks

Figure 5 displays all TC tracks by quarter, as well as their division by category, for neutral, El Niño, and La Niña phases. Like genesis points, the quarterly TC tracks during neutral and El Niño years again are found to be similar. Straight tracks are the major trajectory type in JFM in all the ENSO phases. TC tracks in JAS are the densest compared with other quarters. The confinement of the majority of genesis locations west of 160°E in La Niña years leads to shorter, straight-moving tracks, but the recurving tracks can extend farther northeast and reach higher latitudes in JAS and OND. The Philippines is usually affected by numerous low-latitude, westward-moving TCs in JFM and OND for all ENSO phases. The broader region of TC genesis locations in neutral and El Niño years, almost reaching the date line in all quarters, has produced more recurving TCs, whereas in La Niña years, the genesis locations closer to the Philippines produced TCs with short straight-moving tracks that made landfall. The cumulative track density in the 5° latitude by 5° longitude boxes illustrates the regions of higher concentration of TC passages and also indicates the prevailing track type during a specific ENSO phase in every quarter (Fig. 6). In JFM and OND of all ENSO phases, especially the neutral phase, there are more TC passages in the lower latitudes compared with the AMJ and JAS, where a greater density of TC passages is found in higher latitudes, and the tracks can reach as far as 55°N. In all ENSO phases, and in every quarter, a higher density of TC passages is found east of the Philippines. In JAS, when the summer monsoon is affecting the Philippines, the highest density of TC passages is found north of 15°N in all ENSO phases, whereas in other quarters, especially in OND and JFM, when northeast winds associated with the winter monsoon influence the Philippines, a higher density of TC passages can be found in much lower latitudes, from 10°N latitude. The absence of TC passages east of 160°E in La Niña years compared with El Niño and neutral years is noticeable in Figs. 6c, 6f, 6i, and 6l, consistent with previous studies by Saunders et al. (2000) and Elsner and Liu (2003). Here, it is seen that the identified changes in tracks are consistent with the change in mean genesis location.

3) Frequency

The quarterly variability of Philippine TC activity during ENSO phases initially was examined by Corporal-Lodangco (2014) and is greatly expanded upon in this study. The green, blue, and red bars in Fig. 7 represent the
neutral, El Niño, and La Niña years, respectively. The Philippine region has no TC-free months, and the calendar year is partitioned into JFM, AMJ, JAS, and OND quarters. The mean of the standardized quarterly TC count during neutral, El Niño, and La Niña years is presented in Fig. 7a. TC activity during the neutral years, relative to El Niño and La Niña years, is above average in all quarters. Below-average TC activity is observed all year round during El Niño years. In La Niña phases, AMJ and OND have above-average TC activity, but below-average TC activity is found in JFM and JAS. There is a distinct statistically significant difference at the 95% confidence level in TC count, in all quarters, between neutral and El Niño phases. The difference in TC count is significant only in OND.

Differences in landfall patterns in various regions of Asia, due to ENSO, have been discussed in some studies (e.g., Saunders et al. 2000; Elsner and Liu 2003; Wu et al. 2004). The number of TCs making landfall in the Philippines varies significantly in ENSO years. Corporal-Lodangco (2014) made an initial study of the influence of ENSO on Philippine landfalling TCs (Fig. 7b). The definition of TC landfall used in this study is when the center of circulation of the TC reaches the Philippine coastline. The 6-hourly latitude and longitude of the TC are used as the center of circulation. TC landfalls in neutral years are above average in all quarters especially in JFM and JAS. In El Niño and La Niña phases, the difference in TC count is significant only in OND.

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Fig. 4. TC genesis cumulative density per $5^\circ \times 5^\circ$ grid box during the (a),(d),(g),(j) neutral; (b),(e),(h),(k) El Niño; and (c),(f),(i),(l) La Niña phases in every quarter year.
have below-average TC landfall counts. The difference in the number of TC landfalls during neutral and El Niño years is significant in JFM and OND. The decrease in TC landfalls during the last quarter of an El Niño episode is consistent with the findings of Wu et al. (2004). The below-average numbers of TCs and landfalls observed in El Niño phases suggest that El Niño phases tend to be followed by an overall reduction in TC frequency and are related to the longitudinal shift of the Walker circulation (Chan 1985; Dong 1988; Wu and Lau 1992; Chan 2000). The displacement of TC genesis locations to the southeast during an El Niño phase causes a significant decrease in TCs entering the Philippine domain; some TCs dissipate before reaching the domain. The recurving tracks of most WNP TCs in El Niño years also contribute to the reduced number of TCs entering the Philippine domain and making landfall. The JFM and JAS quarters of a La Niña event exhibit below-average TC landfalls in the Philippine region, in contrast to the considerably above-average numbers of landfalls for both AMJ and OND. The majority of TCs in AMJ formed closer to the Philippines, west of 150°E (Fig. 3), consequently leading to more TCs and landfalls during the quarter. The tracks of most TCs in OND in La Niña years are straight moving, with a general westward motion; hence, a greater number of TCs entered the Philippine domain and make landfall in OND. Higher TC landfall counts in OND in the Philippine region are in agreement with the result of Wu et al. (2004). Gray (1968) suggests that the seasonal variations in TC activity are related to the seasonal large-scale circulation deviations from their climatology. La Niña TC landfalls are significantly different compared with neutral TC landfalls in JFM. El Niño and

FIG. 5. TC tracks during (a),(d),(g),(j) neutral; (b),(e),(h),(k) El Niño; and (c),(f),(i),(l) La Niña phases in every quarter year.
La Niña TC landfalls are significantly different in AMJ and OND.

4) Intensity

There are three categories of Philippines TCs: tropical depressions, tropical storms, and typhoons. Of the 1122 TCs that affected the Philippines during 1950–2011, 190 are of TD intensity. There are 321 TSs in the Philippine domain, or about 29% of the total TCs. More than half, about 55%, of all TCs that affected the Philippines were TYs, a remarkably high percentage when compared with other TC basins (Corporal-Lodangco 2014). The characteristic distribution of the three intensity categories for various ENSO phases on quarterly time scales is presented in Fig. 8. Figure 8a shows the mean of the standardized quarterly TCs that are of TD intensity. In neutral years, TDs are above average in the first three quarters of the year and below average in OND. Below-average numbers of TDs are experienced during El Niño phases year-round, particularly in JFM and JAS, which have significantly fewer TDs. A significance test shows that there is a significant difference in the number of TDs in JFM and JAS of El Niño phases relative to neutral phases. The distribution in La Niña years exhibits more TDs in JFM, AMJ, and OND, but fewer TDs are observed in JAS. The TDs in El Niño and La Niña phases are significantly different in JFM and OND. How ENSO influences TCs of TS intensity is given in Fig. 8b. TSs in the neutral phase remained constant, to above average, in the first three quarters especially in JFM and
AMJ. Conversely, OND of neutral years have below-average numbers of TSs. A sustained decline in TSs occurs in all quarters during El Niño years. Throughout the first half of the year, La Niña years have below-average numbers of TSs, but an above-average number of TSs occurs in the remaining quarters, especially in OND. The significance test implies that TSs in AMJ are significantly different between neutral and El Niño phases. Figure 8c shows the quarterly standardized distribution of TCs of TY intensity. It is noticeably above average in the JFM and OND quarters of neutral years. El Niño phases are characterized by fewer TYs in most quarterly periods and only favor average TYs in JAS, the peak quarter of TC activity. Examination of La Niña years reveals that substantially below-average TYs are common in JFM, JAS, and OND but are slightly above average in AMJ. The difference in TYs between neutral, El Niño, and La Niña phases are significant in JFM. TYs in neutral and El Niño phases are significantly different in OND.

Quarterly statistics show differences in the frequency of landfalling TCs, based on intensity classification, during various ENSO phases (Fig. 9). In neutral years, above-average numbers of landfalling TDs occur almost year-round except in AMJ. Marginally above-average TCs of TD intensity make landfall in the Philippines during AMJ and JAS in El Niño years, whereas they are below average in JFM and OND. Less intense landfalling TCs (TD intensity) during La Niña years are above average in AMJ and OND but are below average in JFM and JAS. Landfalling TDs are significantly different in OND between neutral and El Niño phases and similarly between El Niño and La Niña phases. Neutral years have a higher percentage of landfalling TS from JFM to JAS. In contrast, during La Niña years, there are fewer landfalling TSs from JFM to JAS, but there are more landfalling TSs in OND. El Niño years have below-average TSs year-round, particularly in AMJ and JAS. The difference in landfalling TSs is significant between neutral and El Niño phases in the AMJ and JAS quarters. The influence of ENSO on landfalling TCs of TY intensity is manifested as above average for El Niño phases only in JAS but below average in JFM, AMJ, and OND. Above-average landfalling TYs are observed almost year-round except in JFM in La Niña phases. Saunders et al. (2000) and Elsner and Liu (2003) also have the same observation. In neutral years, there are above-average numbers of landfalling TYs in JFM and OND and below-average numbers during AMJ and JAS. Other studies suggest that TCs are more intense in El Niño years but are weaker in La Niña years (e.g., Pudov and Petrichenko 1998, 2001; Chia and Ropelewski 2002). However, this is not the case for Philippine TCs, which depend on ENSO quarter and phase, for a particular intensity category. There is no significant difference in the landfalling TY frequencies in all quarters during different ENSO phases.

5) TC DAYS

The numbers of days during which TCs, regardless of intensity (TD, TS, or TY), were located within the
Philippine domain were counted. Figure 10 shows the distributions of the mean standardized TC days for all ENSO phases in all quarters. There are above-average numbers of TC days in all quarters in neutral years, especially in JFM. This is attributed to higher frequency of TCs and longer lifetimes of individual TCs in neutral phases. In El Niño years, significantly below-average TC days are observed in JFM, AMJ, and OND. The difference in TC days between neutral and El Niño phases is statistically significant in those quarters. The marginally above-average TC days in JAS during El Niño phases is consistent with the findings of Pudov and Petrichenko (1998, 2001), Wang and Chan (2002), Chia and Ropelewski (2002), Chan and Liu (2004), and Camargo and Sobel (2005), all of which suggests that TCs are longer-lived in that quarter during which El Niño events develop. Despite having a below-average number of TCs in JAS during El Niño years, TCs with longer lifetimes in JAS during El Niño years contribute to the marginally above-average number of TC days. The cyclogenesis found farther east relative to neutral and La Niña phases allows TCs to maintain longer life spans while tracking westward, resulting in longer durations. In La Niña years, there are fewer TC days from JFM to JAS, whereas there are more TC days in OND. TCs during La Niña phases form closer to the Philippine archipelago, and the TC count is fewer relative to neutral phases, contributing to the below-average number of TC days from JFM to JAS. The shift toward more TC days in OND can be attributed to the higher number of TCs during that quarter (although the TCs have shorter durations), producing above-average numbers of TC days. The number of TC days in La Niña phases is significantly different from neutral phases in JFM and JAS. The difference in TC days between El Niño and La Niña years are statistically significant in OND.

6) QUARTERLY ACE

The influence of ENSO on the quarterly ACE of TCs affecting the Philippines has been examined in this study. ACE considers the number, lifetime, and intensity of TCs occurring in a domain, over a given period of time. Here, ACE is defined as the sum of the squares of the estimated 6-hourly maximum sustained surface wind speed (kt²; 1 kt ≈ 0.51 m s⁻¹) for TCs in the Philippine domain having 35-kt intensity or greater summed over the quarter. ACE can be calculated from the following formula:

\[ \text{ACE} = 10^{-4} \sum V_{\text{max}}^2, \]

where \( V_{\text{max}} \) is the estimated maximum sustained wind speed in knots.

The annual time series of the quarterly ACE are color coded to signify the prevailing ENSO phase, and the 25th, median, and 75th percentiles (represented by dashed lines) are shown in Fig. 11. There are quarters when ACE is zero either because the TCs during those quarters have intensities below 35 kt or because no TCs have occurred during that specific quarter. This occurred 28 times in JFM. Of those, 10 are neutral, 11 are El Niño, and 7 are La Niña phases (Fig. 11a). The lowest JFM ACE on record, 0.20 (10⁴ kt²), is a La Niña year (1971), and the highest JFM ACE value, 45 (10⁴ kt²), occurred in 1958, an El Niño year. The average JFM ACE is 10 (10⁴ kt²). Out of seven El Niño years with computed
JFM ACE, there are two years with ACE values below the median and the 25th percentile, but there are five years above the median and two of these years are above the 75th percentile. There are 10 out of the 11 La Niña years with JFM ACE values below the median; 5 of them are below the 25th percentile, and only 1 La Niña year has a JFM ACE above the 75th percentile. Figure 11 illustrates the yearly AMJ ACE values in all ENSO phases. There are four years that have no ACE in AMJ, of which three are classified as neutral years and one as a La Niña year. The lowest ACE for AMJ is 0.25 (10^4 kt^2) in 1983, an El Niño year, and the highest ACE is 159 (10^4 kt^2) in 2004, a neutral year. The average ACE for AMJ is 32 (10^4 kt^2). Of 13 El Niño years, 5 have AMJ ACE above the median and all are above the 75th percentile. There are 14 La Niña years in AMJ, 7 of which have ACE values above the median, and 2 of those are above the 75th percentile. There is a substantial increase in ACE in JAS (Fig. 11c), higher than other quarters. The average ACE is 104 (10^4 kt^2) while the lowest and highest ACE values in JAS are 27 (10^4 kt^2) in 1950 and 220 (10^4 kt^2) in 1964, respectively. The average ACE for the quarter is 104 (10^4 kt^2). Of 16 El Niño years in JAS, 10 are above the median ACE and 6 of those are above the 75th percentile. There are also 16 La Niña years in JAS, but only 5 are above the ACE median and only 2 are above the 75th percentile. The average ACE in OND, which is 77 (10^4 kt^2), is lower than in JAS. The lowest ACE of the quarter is 3 (10^4 kt^2), whereas the highest ACE is 214 (10^4 kt^2). In OND (Fig. 11d), there are 20 El Niño years, and 9 of these have above-median ACE and 6 of those are above the 75th percentile. Of 22 La Niña years in OND, 9 have above-median ACE and 3 La Niña years are above the 75th percentile. The average ACE in OND, which is 77 (10^4 kt^2), is lower than in JAS. The lowest ACE of the quarter is 3 (10^4 kt^2), whereas the highest ACE is 214 (10^4 kt^2). In OND (Fig. 11d), there are 20 El Niño years, and 9 of these have above-median ACE and 6 of those are above the 75th percentile. Of 22 La Niña years in OND, 9 have above-median ACE and 3 La Niña years are above the 75th percentile.

Figure 12 shows the impact of ENSO on the Philippine domain in terms of the mean standardized quarterly ACE values. The neutral phase has above-average ACE all year but is considerably above average in JFM.
The physical mechanisms responsible for the variations in the quarterly behavior of Philippine TCs between ENSO phases are discussed in this section. Large-scale environmental conditions conducive to the development and intensification of TCs during El Niño and La Niña years differ from those of neutral years. All the re-analyses presented in this section are derived from NCEP–NCAR. The climatological settings in which Philippine TCs form appear to be noticeably different during the respective ENSO phases. The Wilcoxon significance test was carried out and confirmed that all meteorological variables in Figs. 13–16 are statistically significant at the 95% confidence level.

1) SST

The SST in the WNP differs quarterly during the various ENSO phases. The SST plays a significant role in accounting for the difference in TC number in the Philippine domain. The SST and monsoon trough position influence the seasonal distribution of TC genesis locations and frequencies (McBride 1996). The WNP is warmest in June–November when SST values of 29°–30°C are observed (Vincent and Schrage 1995). In neutral phases, warmer SSTs (warm pool) over the entire WNP and cooler SSTs in the central and eastern equatorial Pacific (CEEP) are observed. Figures 13a–d compare the quarterly SSTs during neutral phases with El Niño phases by subtracting El Niño SSTs from neutral SSTs. The positive SST difference over WNP indicates that SSTs in that region are warmer in neutral years than in El Niño years. The positive SST difference over the WNP is greatest in JFM and AMJ (Figs. 13a,b). The negative SST difference over the CEEP signifies warmer SSTs in that area in El Niño years compared with neutral years. The warm pool (Walker circulation) usually found in WNP is displaced to the east in El Niño phases (Chan 1985; Dong 1988; Wu and Lau 1992; Chan 2000), confirming the displacement of the mean genesis location in El Niño years to the east/southeast, leading to fewer TCs in the Philippine domain. The negative SST gradient over the CEEP is greatest in JFM and OND (Figs. 13a,d), consistent with the mean genesis locations being displaced considerably farther to the east during these quarters. The comparison of quarterly SSTs between neutral and La Niña years is shown in Figs. 13e–h. The La Niña SSTs are subtracted from the neutral SSTs. The negative SST gradient over the WNP suggests that, during La Niña years, SSTs over that region are warmer than in neutral years. It also implies that the warm pool is farther west (i.e., closer to the Philippines). The negative SST difference over the WNP is very pronounced in JFM, JAS, and especially OND. In OND of La Niña years, there are more TCs that developed within the Philippine domain compared with neutral and El Niño years. The region of negative SST difference found west of 160°E is consistent with the TC genesis locations in La Niña years confined just to the west of that longitude. The positive SST difference over the CEEP means that

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SST values in that region are warmer in neutral phases than during La Niña phases. This conforms to the broader region of TC formation that can almost reach the date line during neutral phases. We compare the SST values during El Niño phases with La Niña phases (Figs. 13i–l) by subtracting the La Niña SSTs from El Niño SSTs. Warmer SSTs are found over the WNP and are closer to the Philippines in La Niña years, as indicated by the negative SST difference over the WNP. Figures 13i–l also show warmer SST values in CEEP during El Niño years, as indicated by a positive SST difference in that area. All year, fewer TCs are associated with El Niño years compared with neutral and La Niña years and attributed to the displacement of the mean genesis locations of TC over the WNP to the southeast.

2) VORICITY

The Southeast Asian monsoon trough is a favorable region for TC genesis and is associated with large cyclonic low-level vortices (McBride 1996; Briegel and Frank 1997). The studies of Gray (1968, 1979, 1985) and Briegel and Frank (1997) showed that the monsoon trough provides an environment satisfying all the criteria necessary for tropical cyclogenesis. Flow intensification on either side of the monsoon trough increases the low-level vorticity and enhances TC genesis (Frank 1987). Changes in the atmospheric circulation associated with ENSO alter the monsoon trough location and also the location and intensity of the subtropical high, modifying TC formation locations, intensities, and tracks (Chu 2004). Lyon and Camargo (2009) identified changes in Philippine TC activity as being associated with the frequency of TCs forming at more-eastward locations in OND of El Niño years. They also found that recurving TC tracks east of the Philippines are related to the changes in vorticity and moisture fluxes in the monsoon trough. In this subsection, low-level vorticity has been investigated for various ENSO phases in terms of its influence on Philippine TC activity.

The differences in vorticity at 1000 mb between different ENSO phases are shown in Fig. 14. The quarterly
vorticity at 1000 mb during neutral years, relative to El Niño years, is stronger in the region east of the Philippines in JFM, AMJ, and OND, but is weaker over the CEEP all year (Figs. 14a–d). The negative low-level vorticity difference in the CEEP indicates that, in El Niño years, there is stronger vorticity at 1000 mb over the region. The vorticity at 1000 mb during neutral years is stronger than in La Niña years in most parts of the North Pacific Ocean (Figs. 14e–h). In JFM, a negative low-level vorticity difference is present east of the Philippines, which suggests that in La Niña years strong low-level vorticity is present over that area. The comparison of vorticity at 1000 mb in El Niño and La Niña phases is presented in Figs. 14i–l. El Niño years exhibit weaker low-level vorticity compared with La Niña years in JFM east of the Philippines, as indicated by a negative low-level vorticity difference, but stronger low-level vorticity is prevalent in WNP and CEEP in El Niño years in the remaining three quarters of the year. This is confirmed by the positive low-level vorticity difference over the equatorial North Pacific Ocean. In all ENSO phases, regions with higher values of low-level vorticity are consistent with the preferred regions of Philippine TC genesis in all quarters; this is in agreement with the areas of warmer SST.

3) ZONAL WIND

The 850-mb zonal winds are used to monitor the onset of an El Niño phase; they show how the low-level winds react to the low-level pressure and SST anomalies linked with ENSO. The low-level zonal winds are also employed to detect bursts of westerly winds over the tropical WNP that might initiate or enhance El Niño phases. Unlike Figs. 13 and 14 that show the differences in SST and vorticity, respectively, during various ENSO phases, Fig. 15 indicates the anomalies in the zonal winds associated with the development and progression of ENSO phases. Positive zonal winds imply westerlies
whereas negative zonal winds indicate easterlies. In all neutral and La Niña quarters (Figs. 15a–d,i–l), wind directions over the North Pacific are similar except that, in La Niña phases, easterly winds are stronger. Westerlies are prevalent in the neutral phase in JFM and OND, extending eastward to the central equatorial Pacific, whereas the westerlies in La Niña phases during these quarters extend eastward, reaching only the Philippines. In AMJ and JAS of neutral and La Niña phases, when the westerlies are weak, the easterlies reach the Philippines, especially in JAS. Easterly winds are strongest and concentrated over the eastern equatorial Pacific in all quarters in La Niña phases. During El Niño phases, the tropical Pacific is characterized by westerlies, replacing the usual easterlies and extending to the east of the date line, reaching the eastern Pacific in JFM. The regions of maximum tropical westerlies are found in the central equatorial Pacific in JFM and OND and west of the date line in AMJ and JAS in El Niño phases. The enhanced westerlies are in phase with the location of warmer SST during El Niño conditions. The weaker trade winds during El Niño years lead to the westerly wind bursts pushing the warm pool eastward and warming the SSTs over the CEEP, thereby displacing the mean genesis locations of the Philippine TCs.

4) DIVERGENCE

Upper-level divergence is associated with low-level convergence or surface low pressure area development. Surface low pressure areas require divergence aloft to continue deepening. The divergence at 200 mb between quarters in various ENSO phases is shown in Fig. 16. In Figs. 16a–d, the values of divergence at 200 mb in El Niño years are subtracted from the upper-level divergence in neutral years. The divergence aloft is stronger in neutral years over the WNP, particularly east of the Philippines, in JFM, AMJ, and OND, as indicated
by the positive gradient. Although the positive gradient does not entirely cover the WNP, the divergence aloft over that region still is stronger in neutral years relative to El Niño years, which is conducive for TC development, justifying the higher frequency of Philippine TCs in neutral phases relative to El Niño phases. The upper-level divergence over the CEEP typically is stronger in El Niño years than in neutral years, denoted by the negative upper-level divergence values. This is consistent with the warmer SST and stronger vorticity over CEEP in El Niño years, and the mean genesis locations are located farther to the east. Most parts of WNP and CEEP experience weaker divergence aloft during La Niña years when compared with neutral years (Figs. 16e–h). For El Niño and La Niña phases, comparing divergence aloft over the WNP and CEEP, the divergence in upper levels during El Niño years is stronger than in La Niña years in almost all quarters except in JFM in most of WNP and in OND over the South China Sea (Figs. 16i–l).

4. Summary and conclusions

This study assesses the impacts of ENSO on Philippine TC activity. TC genesis locations in neutral and El Niño phases in all quarters have a wider longitudinal range, extending beyond 160°E and almost reaching the date line. Neutral and El Niño phases have similar spreads and areal coverage of TC genesis positions and tracks. However, more recurving tracks occur in El Niño years than in La Niña and neutral years. This observed change in TC tracks is consistent with the change in mean genesis locations. The overall reduction in TC frequency in El Niño years is related to the eastward shift of the Walker circulation. Eastward displacement of the mean cyclogenesis location allows TCs to recurve prior to entering the Philippine domain, reducing Philippine TC frequency in El Niño years. The confinement of cyclogenesis to the southeastern WNP in El Niño years is attributable to monsoon trough displacement, which is located farther east in the Pacific Ocean. The

Fig. 16. As in Fig. 13, but for 200-mb divergence. Images provided by the NOAA/ESRL Physical Sciences Division from their website (http://www.esrl.noaa.gov/psd/).
pronounced change in Philippine TC activity during La Niña phases confines TC genesis locations to the west of 160°E, with a narrower formation region. Philippine TCs with straight-moving tracks in La Niña years are shorter in pathlength than in neutral and El Niño years. The proximity of the mean genesis locations to the Philippines and the dominance of low-latitude straight-moving tracks during La Niña phases increases TC frequency in the Philippine domain and also increases the numbers of landfalling TCs in the Philippines in AMJ and OND.

The effect of ENSO on TC intensities depends largely on the ENSO quarter and phase. La Niña phases show an association with above-average TCs of TD intensity in almost all quarters. However, the landfalling TCs in La Niña years are mostly of TY intensity observed from AMJ and extending to the last quarter. Landfalling TYs are above average only in JAS during El Niño years. This shows that, despite the findings of previous studies that La Niña phases are associated with weaker TCs and El Niño phases with stronger TCs, the irregularity in TC activity, such as in intensity, occurs only in certain quarters during El Niño and La Niña phases but not throughout the year. The below-average TC days in La Niña phases in the first three quarters are due to fewer TCs compared to neutral years and to shorter TC durations, whereas the above-average TC days in OND are attributed to the higher frequency of TCs during that quarter. The slightly above-average TC days in JAS during El Niño phases are caused by longer TC durations. The cyclogenesis found farther east in El Niño years allows TCs to persist longer while tracking westward, thus increasing the TC days. For ACE, TC frequency, days, and intensities all are taken into account. The above-average quarterly ACE in neutral years is due to larger numbers of TCs, increased TCs days of individual TCs, and increased TC intensities in JFM, JAS, and OND, whereas the above-average ACE in JAS of El Niño phases is due mainly to TC days and secondarily to TC intensities. The below-average ACE in La Niña phases is mainly attributed to fewer TCs and shorter life cycles.

The changes in physical properties of Philippine TC activity during ENSO phases are associated with the large-scale environmental variables modulating TC development and preferred areas of TC genesis. The displacement of warm SSTs to the east during El Niño phases increases TC formation farther east relative to neutral years, thereby leading to fewer TCs in the Philippine domain. However, the warm pool is farther west (closer to the Philippines) in La Niña years, especially in OND. This explains why, in La Niña phases, the mean genesis locations are usually found closer to the Philippines compared with neutral and El Niño years. Low-level vorticity is used here to indicate monsoon trough location. Variation in location and intensity of the monsoon trough impacts the genesis locations and frequencies of TCs over the WNP (Lighthill et al. 1994). The regions with higher values of low-level vorticity are consistent with preferred areas of cyclogenesis during various ENSO phases. The zonal winds near the surface react to the low-level pressure and SST anomalies associated with ENSO. The El Niño phases generally are associated with a weakening of the trade winds. The strong sub-equatorial westerlies move eastward, thereby pushing the warm SSTs over the CEEP. Enhanced easterlies are observed in all quarters during La Niña phases. In all ENSO phases, the regions of stronger divergence aloft are consistent with the regions of warmer SSTs. The TC development is associated with divergence aloft, coupled with heating of the air columns over the warmer sea surface. Although ENSO clearly affects Philippine TC activity, especially the locations of cyclogenesis during La Niña events, the variability of Philippine TC activity cannot solely be attributed to ENSO. Other climate modes [e.g., the quasi-biennial oscillation (QBO) and Pacific decadal oscillation (PDO)] also might influence Philippine TC behavior and will be the focus of future work.

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