Climatology of Philippine Tropical Cyclone Activity: 1945-2011

Short title: Philippine Tropical Cyclone Climatology

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ABSTRACT

The Philippine region occupies the southwestern Western North Pacific (WNP) Ocean, between 5°N-25°N and 115°E-135°E. About 70% of WNP tropical cyclones (TCs) formed in or entered the Philippine region during 1945-2011. Here, a climatology of Philippine TC metrics is developed, including mean annual frequencies, landfalls, TC days, season lengths, season earliest and latest start/end dates, genesis locations, and tracks. Two distinct TC seasons, the less active (LAS; January 1-May 31) and more active (MAS; June 1-December 31) seasons, are evident. Philippine TC annual median LAS frequency is 2 (interquartile range (IQR) is 2); median landfalling frequency is 1. The annual median MAS frequency is 15 (IQR is 4.5), and median landfalling frequency is 6. About 55% of Philippine TCs reach typhoon (TY) intensity. The interannual variability of the annual average lifetime maximum intensity (LMI) for all TCs and landfalling TCs decreased slightly during the satellite era (the years since 1980). The TC annual average latitude of LMI in the satellite era exhibits a poleward migration; however, for landfalling TCs it is equatorward.

In El Niño years, TCs frequently recurve or decay before reaching the Philippine region, producing *below normal* numbers and landfalls in LAS and MAS. In La Niña years, TC numbers and landfalls are *below normal* in January-March and July-September, but *above normal* in April-June and October-December. A quiescent (TC-free) period occurs between LAS and MAS, ranging from 2 days-5 months (median 1.2 months) for LAS/MAS transitions, and 6 days-7 months (median 2.85 months) for MAS/LAS transitions. Wavelet analysis shows El Niño Southern Oscillation (ENSO) as the dominant mode affecting Philippine TCs, consistent with other studies. The wavelet analysis also indicates possible decadal and multi-decadal modes.

The climatology developed here has social and economic relevance: allowing planning, providing early risk assessment, and mitigating impacts through timely preparation and management.

KEY WORDS: tropical cyclones, tropical cyclone metrics, Philippines, climatology, western North Pacific Ocean, El Niño Southern Oscillation

1. Introduction

The Philippine region lies in the tropical cyclone (TC) belt of the southwestern sector of the western North Pacific (WNP) Ocean, the most active of the world's TC basins (McBride, 1995). About 26 TCs form annually over the WNP (Ritchie and Holland, 1999), and the threat of TCs in the WNP possibly is increasing (Park *et al.,* 2014). Over the 67-year period 1945-2011, about 70% (18) of these WNP TCs passed near or crossed the Philippines. The Philippines is located close to where most WNP TCs reach their maximum intensity (Gray, 1968; Xue and Neumann, 1984). TCs are the Philippines' worst natural hazard, in terms of human casualties, socio-economic consequences, and also cause extensive damage to vegetation (e.g., Marler and Ferreras, 2014; 2015). Destructive winds, storm surges, landslides and extensive flooding are TC impacts affecting the Philippines. For example, in November 1991, Tropical Storm Thelma demonstrated that TCs even below typhoon intensity are devastating, causing over 5,000 deaths. Figure 1a shows tropical storm Thelma, before landfall, on November 4, 1991. Figure 1b shows Thelma's track, which produced massive flooding over mountainous central sections of the Philippines, in areas largely deforested for agriculture. In 2013, Typhoon Haiyan became the strongest and deadliest landfalling typhoon in the Philippines, with over 6,000 deaths and more than 4 million made homeless. Typhoon Haiyan is the strongest TC in recorded history to make landfall anywhere on the globe. More recently, slow-moving Typhoon Koppu (Lando) made landfall on Luzon, on October 18, 2015, bringing with it local rainfall totals exceeding a meter.

Hence, there is a clear need for a more complete understanding of Philippine TC activity, and its variability, than is currently available. The aim of this study is to develop a comprehensive climatology that extends the existing studies of Philippines TCs (e.g., Brand and Blelloch, 1973; Shoemaker, 1991; Chan, 2000; Wu *et al*., 2004; Chan and Xu, 2009; Kubota and

Chan, 2009; Lyon and Camargo, 2008; Zhang *et al.,* 2012; David *et al*., 2013; Corporal-Lodangco *et al*., 2016; Corporal-Lodangco and Leslie, 2016; Cinco *et al*., 2016). Except for the earlier and more recent work, the available studies mostly consider the Philippines in the larger context of the WNP, rather than focusing solely on individual Pacific islands and island clusters (e.g., Marler 2014, 2015), very notably those islands forming the Philippines. The present climatology is intended to provide increased social and economic planning, particularly before each more active season (MAS), defined here as June 1 to December 31. It also can assist in timely risk assessment and mitigation of TC impacts.

Chan (2000) examined WNP TC activity, to assess variations occurring prior to, during and after El Niño Southern Oscillation (ENSO) phases. His results suggest that Philippine region TC activity is above normal prior to an El Niño year, and below normal in October and November of an El Niño year. Furthermore, one year after an El Niño event, TC activity in the Philippines is below normal. Chan (2000) also found that Philippine TC activity is above normal in the year preceding a La Niña year, in September and October of La Niña years, and in the year after a La Niña event. Importantly, Chan (2000) suggested that El Niño and La Niña effects are most likely not the only factors determining WNP TC activity. The study of Corporal-Lodangco *et al.* (2016) focused on the interseasonal and interannual variability of Philippine TC activity associated with the various ENSO phases, and emphasized that for various reasons, such as geographical location, the characteristics of Philippine TCs are somewhat different from those of other WNP regions. To better understand the behavior of the Philippine TCs, a cluster analysis algorithm was applied to the genesis locations, tracks, and decay locations (Corporal-Lodangco and Leslie, 2016). These three characteristics of TC all affect the Philippine TC activity. The analysis identified the distinctive properties of each cluster. That study, especially the monthly analyses therein, revealed dominant clusters and showed clearly different behavior between the clusters.

The Philippine region is one of four areas assessed by Wu *et al.* (2004) for ENSO impacts on landfalling WNP TCs. Relative to Neutral years, in the September- November quarter during El Niño years, fewer TCs make landfall in the Philippines, unlike the September-November quarter of La Niña years when more TCs make landfall. They attributed reduced Philippine region TC landfalls in El Niño years to the *eastward shift* in mean TC genesis locations, along with a weaker subtropical ridge, whereas they associated increased landfalls in La Niña years with a *westward shift* in mean genesis position and a stronger subtropical ridge. The tendency for stronger and longer-lived TCs in El Nino years over the entire WNP also has been documented in several studies (e.g. Wang and Chan, 2002; Clark and Chu, 2002 and Camargo and Sobel, 2005). Chan and Xu (2009) divided East Asia into sub-regions to examine variations in annual numbers of landfalling WNP TCs. The Philippines was included as part of the south region. They found that landfalling TC frequencies in the south TC region have large interannual (2-8 years), interdecadal (8-16 years) and even multidecadal (16-32 years) variations, with the interannual oscillation being dominant.

Kubota and Chan (2009) defined Philippine TC landfall as having occurred when a TC passed through any part of the Philippine region. They identified that interdecadal variability in Philippine TC activity related to ENSO phases and the Pacific Decadal Oscillation (PDO), and showed that low PDO phases decrease Philippine TC frequencies during El Niño years but increase TC frequencies in La Niña years. However, the effect of high PDO phases on Philippine TCs becomes indeterminate in different ENSO phases. Kubota and Chan (2009) also noted that ENSO effects on Philippine TCs occur on both intra-annual and interannual time scales. Zhang *et al.* (2012) examined June-October landfalling TCs in East Asia, during central Pacific (CP) El Niño phases, comparing them with landfalling frequencies during eastern Pacific (EP) El Niño and La Niña phases. They found that Philippine TC landfall numbers decrease in June-October of CP and EP El Niño years, but increase during EP La Niña years.

2. Data and methods

The Philippine TC region is defined here as being located between latitudes 5°N to 25°N and longitudes 115°E to135°E, shown in Figure 2 (black inset), adapted from Corporal-Lodangco *et al*. (2016). The red line in Figure 2 defines the official domain of the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) for TC responsibility, and the Philippine region used in this study is chosen to be very similar to that of PAGASA.

2.1. Data source

There are several TC centers with data applicable to this study: the PAGASA, the Japan Meteorological Agency (JMA), and the Joint Typhoon Warning Center (JTWC). TC records from PAGASA, JMA and JTWC were analyzed and compared, to select the most appropriate TC data archive for this study. The JTWC data, known as the “best track”, includes mean sea level pressure (MSLP) that provides an important advantage over the PAGASA data, and the TC data extend back to 1945, providing the most comprehensive coverage. Chan (2008) also stated that JTWC best track dataset likely gives a better estimate of the number of intense TCs in the WNP. Moreover, from 1951 to 1980, JMA did not include the actual values of maximum sustained winds, instead only the intensity classifications were recorded. JMA based the measurement of maximum sustained winds on wind speeds at 10 meters height sampled for 10 minutes and then averaged. JMA began recording the maximum sustained winds in 1981, but only winds of at least 35 knots were included; lighter winds were set to zero knots.

All 1199 TCs that were recorded by JTWC in the Philippine domain for 1945-2011 are included in this study, and the Philippine TC metrics were calculated from the JTWC best track data (http://www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/). Best track data for TCs, at 6-hour intervals, includes: latitude-longitude position, maximum sustained surface wind speed, and minimum central pressure. TCs were counted if any parts of their tracks were within the Philippines TC domain. The TC frequency is the monthly number of TCs that developed or moved into the Philippine domain, and the mean and median provide the climatology. Genesis locations and tracks of TCs also are from JTWC.

2.2. SST and ENSO index data

The Oceanic Niño Index was obtained from the National Oceanic and Atmospheric Administration Climate Prediction Center (NOAA CPC, http://www.cpc.ncep.noaa.gov/). The Oceanic Niño Index is the 3-month running mean of extended reconstructed sea surface temperature (ERSST) Niño 3.4 (5°N-5°S; 120°-170°W) anomalies, relative to the 1981-2010 Philippines TC climatology. The World Meteorological Organization (WMO) definitions of El Niño and La Niña conditions were adopted in this study. For El Niño, a three-month running mean of departures from normal SSTs in the Niño 3.4 region is ≥ +0.5°C. Similarly, La Niña is defined as any three-month running mean of departures from normal SSTs in Niño 3.4 region of ≤ -0.5°C. A Neutral phase is defined in this study as when the departures from normal SSTs in the Niño 3.4 region fall within the range of <+0.5°C to > -0.5°C.

2.3. Data Analysis Methods

Tropical cyclone activity in a TC region typically is expressed as a set of mean TC measures of frequencies, landfalls, intensities, TC days, earliest and latest season start/end dates, season lengths, genesis locations and tracks, similar to those examined by Ramsay *et al*. (2008) and Goebbert and Leslie (2010). A distinctive aspect of this study is the partitioning of TC activity in the Philippines initially into two seasons: a less active season (LAS) and a more active season (MAS), based on the mean monthly TC counts. The LAS, runs from January 1 to May 31, has less than one TC on average per month whereas all monthly MAS TC averages are above one (Fig. 3). The MAS which is defined in this study to span the period from June 1 to December 31. Aside from different TC statistics between these two seasons, there are different thermodynamic and dynamic environmental conditions. A unique aspect is the nature of the transition periods found between the LAS and the MAS. Statistical measures, such as medians, means, interquartile range (IQR) and linear trends were used to define TC activity. Statistics were compiled for 3, 5, 7, and 12-monthly periods, corresponding to the individual quarters, LAS, MAS and the calendar year, respectively. The time series generating these statistics are the monthly TCs counts. Three-year and five-year running means smoothed year-to-year variability.

2.4. Quarterly periods

TC activity in the Philippines cannot be fully demonstrated using just the LAS and MAS classification, as variations occur in the yearly quarters. Accordingly, quarterly periods, January-March, April-June, July-September, and October-December, also are needed to capture detailed changes in intra-annual TC variations. The TC metrics all vary distinctively when grouped by quarter years. The summer (southwest) monsoon and winter (northeast) monsoon winds influence the motion and tracks of the Philippine TCs and other systems also affect the region, peaking in particular months. To investigate the ENSO impacts, quarter years were used for TCs entering the Philippine domain, and also for landfalling TCs. Quarterly SST indices are used to classify quarters as Neutral, El Niño or La Niña phases of ENSO. The quarterly TC time series were standardized, by subtracting 1981-2010 long-term means from individual TC counts, and dividing the difference by standard deviation (Corporal-Lodangco and Leslie, 2016), to provide representative TC counts for different ENSO phases. The numbers of TCs during Neutral phases are greater than during El Niño and La Niña phases, because the time that ENSO is in Neutral periods dominates that of the El Niño and La Niña phases. This dominance would lead to false claims, without standardization, about the impact of ENSO phases on Philippine TCs. Simply put, the standardized TC counts indicate how many standard deviations an observation is above or below the mean.

3. Results and Discussion

3.1. TC Statistics

TC activity is observed in every month in the Philippine region. For 1945-2011, the Philippine region had 1,199 TCs, with an annual long-term mean of 17.9. Tables 1 and 2 summarize TC activity in the Philippine region. The TC monthly count clearly suggests the existence of two distinct seasons, the LAS and the MAS. The LAS represents the relatively quiet phase of TC activity, with the monthly mean and median both less than one TC. In contrast, the MAS has all monthly means greater than one. February has the lowest TC frequency, and January-March is the least active TC quarter. Lander (1994) found similar TC behavior over the entire WNP basin, and related it to less frequent WNP cyclogenesis. In the LAS, the mean and median for

TC number are almost equal, with 2.16 and 2.0, respectively. Similarly, the mean and median for TC landfall are 0.96 and 1.0, correspondingly. The monthly MAS TC median ranges from 1 to 3, and the MAS accounts for ~89% of the mean annual numbers of TCs affecting the Philippines. The MAS TC mean is 15.73 and the median is 15. The mean for TC landfall is 5.55 and the median is 6.0. The peak months are July-September, with August the most active month of the year (Fig. 3). Neumann (1993) indicated that the WNP peak TC season includes summer and fall, encompassing the MAS.

The annual number of TCs ranges from a minimum of 10 in 1946 to a maximum of 28 in 1993 (Fig. 4a). Comparing the annual number of TCs with the number of TCs during the LAS and MAS, the mean annual total is dominated by TCs from the MAS. The LAS TC IQR is 2, and the landfall IQR also is 2. The MAS has a TC IQR of 4.5 and the landfall IQR is 3. These LAS and MAS findings are consistent with Gray (1985), confirming the global frequency of TC varies on an interseasonal time scale with alternating active and inactive periods. The linear trend lines for the LAS, MAS and annual TCs in Figure 4a all suggest increases in the numbers of TCs for the period 1945-2011. However, when the satellite era, defined here as beginning in 1980 and ending in 2011 because the dataset used in the study is only available until 2011, is considered separately (Fig. 4b), it was found that there is a decreasing trend in both the MAS and the annual numbers of TCs. There is no change in the trend of LAS number of TCs during the satellite era. The decreasing trend in the annual numbers of TCs is consistent with the trend in WNP TCs (Moon *et al*., 2015).

3.2.Season start/end dates and lengths

The year-to-year variation of TC activity in the Philippine region is shown in Fig. 5. The TC frequency over the region varies on an interseasonal time scale, with alternating LAS, quiescent periods, and MAS. The season start date is the day during a season when the first TC is located in the Philippine region. The season end date is defined as the day when the last TC is inside the domain. The season start date is the value at the lowest tip of the bar, and the season end date is the value at the upper tip of the bar in Fig. 5. The mean start and end dates for the LAS are March 6 and May 5, respectively, whereas for the MAS, the mean start and end dates are June 20 and December 10, respectively. The season length is from the first day there is a TC in the Philippine region to the last day there is a TC in the region. The annual season length is the total length of blue and red bars. For the entire period of 1945-2011, there is an increasing trend in the LAS length whereas a decreasing trend is seen in MAS length. Typically, the LAS last TC days are within the season period. However, there are years when LAS end dates occur in June, which is part of the MAS. After the LAS ends, it takes a mean of 1.5 months and a median of 1.2 months before the MAS commences. The gap between the LAS and MAS is as brief as 2 days and as long as ~5 months. The gap between the two seasons is referred to here as the "quiescent" period that, as far as the authors are aware, has never previously been mentioned. The quiescent periods confirm the distinct division of the year into two seasons, the LAS and the MAS. After the MAS, the quiescent period again is observed and is much longer than the quiescent period occurring after the LAS. It ranges from 6 days to just over 7 months (Table 1), with a mean and a median of ~3 months.

Figures 6-7 describe the characteristics of LAS and MAS in detail. A 5-year running mean is applied to all analyses to smooth the short-term fluctuations and highlights the long-term trend. The yearly LAS length, as shown in Figure 6a, is the length of the blue bars and varies widely from zero days, in years when no TCs affect the Philippines, to 155 days in 1953. The LAS length is much shorter than the MAS with a mean length of 52 days. The LAS median length is 38 days. The 25th and 75th percentiles of the LAS length are 3.5 and 95.5 days, respectively, and the IQR is 92 days. There are 11 LAS years with no TCs. The LAS TCs begin to form in or enter the Philippine domain as early as January 2nd and as late as May 31st. The mean LAS start date is March 4th and the median is February 28th. However, the LAS ends as early as January 11th and as late as June 6th. The mean LAS end date is May 6th and the median end date is May 20th. Interannual variability is very high in the LAS length time series. The LAS length has two maxima in 1955 and 1987 and a minimum in 1972 (Fig. 6b). The earliest LAS start date from the 5-year running mean occurs in 1986, and the latest is in 1979 (Fig. 6c). The earliest LAS end date is in 1972 and the latest is in 1997 (Fig. 6d). The trend lines for the LAS length and the 5-yr running mean of LAS length both show an increasing trend during the period 1945-2011, and the season start and end dates becoming later (Fig. 6a-d). When only the satellite era is considered for LAS lengths (Figs. 6e, f), the trend reverses because the season start dates are later as seen in the substantially sharper trend slope (Fig. 6g). The trend line for the season end dates indicates an almost flat trend (Fig. 6h).

For the MAS (Fig. 7a), the earliest start date is June 1st and the latest is July 30th, with June 20th and June 18th as the mean and median start dates, respectively. The MAS ends as early as September 10th and as late as January 5th the following year, with a mean (median) MAS end date of December 10 (December 16th). The mean MAS length is 174 days and the median is 176 days, with no TC-free years. The MAS length has a minimum of 96 days in 2002 and a maximum of 209 days in 1950. The 25th, 50th and 75th percentiles of MAS length are 161.5, 176, and 189.5 days, respectively. The IQR MAS length is 28 days. The 5-year running mean of the MAS length is shown in Fig. 7b. The longest MAS lengths are in 1950 and 1987, and the minima occur in 1955, 1971 and 2000. Similarly, the maxima in the 5-year running means of start dates (Fig. 7c) and end dates (Fig. 7d) indicate the latest start/end dates, whereas the minima indicate the earliest start/end dates. Unlike the LAS, which has an irregular annual season length, the MAS length varies less (Fig. 7a), consistent with the IQR (Table 1). Both 1945-2011 and 1980-2011 periods indicate a decreasing trend in MAS lengths (Figs. 7a,b and 7e,f). The MAS start dates in 1945-2011 period shows a flat trend (Fig. 7c). However, the trend in MAS start dates in satellite era appears to be increasing, which means the season start dates are becoming later or a later onset of the MAS (Fig. 7g). For 1945-2011 period, the trend line in the MAS end dates indicates a slight decreasing trend, which means the MAS ends a little earlier (Fig. 7d). However, in the 1980-2011 period, the trend line suggests a more rapid decrease, which means the season end dates are becoming much earlier (Fig. 7h). The slopes of the trend lines in MAS length and start/end dates are considerably sharper during the satellite era.

3.3. TC days

A TC day has at least one TC in the Philippine domain. A TC day can vary from an hour up to 24 hours. The number of LAS TC days ranges from 0 to 25 days (Fig. 8a). The LAS mean TC days is 9 and the median is 8. The 25th and 75th percentiles of LAS TC days are 2.5 and 13.5 days, respectively, with an IQR of 11 days. The number of MAS TC days far exceeds LAS TC days. The MAS TC days range from 22 to 102 (Fig. 8b). The MAS mean TC days is 55 and the median is 51. The 25th and 75th percentiles of MAS TC days are 44 and 64 days, respectively, and an IQR of 20 days. The annual TC days count is the sum of LAS and MAS TC days (Fig. 8c). The annual TC days range from 23-114, the mean TC days is 64, and the median is 61 days. The 25th and 75th percentiles of annual TC days are 50 and 76 days, with an IQR of 26 days.

3.4. Landfalling TCs

TC landfall is defined in this study as occurring when the TC circulation center reaches the Philippine coastline. The Philippine archipelago occupies just 6% of the WNP and, of 1199 TCs that occurred during the study period, many (435, or 36%) struck the Philippines and more came close to making landfall. The annual long-term mean of TC landfalls in the Philippine domain is 6.5, with a median of 7.0. Quarterly statistics for TC counts and landfalls are in Table 2. July-September has more TC activity, with 48.8% of the TC count. In July-September, the environmental elements necessary for TC genesis are more likely to be present. October-December has the largest percentage of quarterly landfalling TCs, with 53% of October-December TCs, and 45% of total TC landfalls. Although July-September has the highest mean TC occurrence in the Philippine domain, the October-December season has the greatest mean number of landfalling TCs, attributable to the weak monsoon westerlies, strong trade wind easterlies and an intense subtropical anticyclone north of the Philippines, producing more TCs with straight line tracks and thereby increasing the likelihood of TCs making landfall in the Philippines. TCs are more intense when straight-moving TCs remain at lower latitude. There are more recurving TCs in July-September, coinciding with the peak of summer (southwest) monsoon, weak trade wind easterlies, a deep monsoon trough and a subtropical anticyclone well northeast of the Philippines, causing the TC tracks to recurve and thereby reducing landfalling TCs compared with the mean number of October-December landfalls. The conditions conducive for straight-moving and recurving TCs are cited in the work of Chen *et al*. (2009).

3.5. Intensity

The TC intensity categories used in this study are based on observed maximum sustained winds near the center, at 6-hourly intervals. Here, Philippine TC activity comprises three TC categories, namely, tropical depression (TD), tropical storm (TS) and typhoon (TY). A TD has maximum sustained winds from 9.73 m s^{-1} to 17.9 m s^{-1}, a TS has sustained winds from 18.0 m s^{-1} to 32.78 m s^{-1}, and a TY has sustained winds exceeding 32.78 m s^{-1}. Figure 9a shows quarterly TC frequency for the three intensity categories. Of these, TDs are least likely in each quarter, with ~16% of the total TCs. The 345 TSs during 1945-2011, were ~29% of all TCs, and were the second most frequent TC intensity category in each quarter. About 55% of Philippines TCs are TYs with an annual average of 10, a high percentage compared with other TC basins (e.g. NOAA Hurricane Research Division 2014). July-September has the highest frequency of TYs but, in October-December, TYs are most likely to occur, with ~ 59% of October-December TCs reaching TY intensity. Figure 9b shows quarterly landfall intensities. Of 435 total TC landfalls, 103 (24%) are TDs, 132 (30%) are TSs and 201 (46%) are TYs. Most (~36%) of January-March TCs are TDs. The majority of the April-June, July-September and October-December TCs are TYs. October-December has the highest frequency of landfalling TCs and mostly of TY intensity.

The interannual variability of the Philippine TC intensities has been examined. Figure 10 shows the annual average lifetime maximum intensity (LMI; Kossin *et al.*, 2014) of all TCs (Fig. 10a) and the annual average LMI of landfalling TCs (Fig. 10b). Both all TCs and landfalling TCs annual average LMI imply a slight decreasing trend during the satellite era. The results suggest a weakening trend in the maximum sustained winds of Philippine TCs. This observation is not consistent with most climate change predictions of an increase in the frequency of intense

TCs in a warming world scenario. However, Chan (2009) found that not all TC basins respond uniformly under climate change. Hence, further research in the future is needed to resolve such conflicting results.

3.6 Variability

Interannual and interdecadal variations in the frequency of Philippine TCs and landfalling TCs for 1945-2011 are shown in Fig. 11. Since 1945, large amplitude variations are apparent in the time series of the annual number of TCs. In Fig. 11a, the green line is the long-term mean of TCs in the Philippine domain whereas, the pink line is the 3-year running mean, and the orange line is the long-term linear trend line. The 3-yr running mean preserves short-term fluctuations, such as the interannual variability. Years with 3-year running means below the long-term mean of 17.9 are in the below mean period (BMP), and all years with above mean TCs are in the above mean period (AMP). The BMP (yellow areas) ranges from 1 to 10 years, whereas the AMP (blue areas) ranges from 1 to 15 years. Significant variations from the mean occur in the time series, including long-term cycles in 1954-1963 and 1982-1996 periods for BMP and AMP, respectively. Short-term cycles (1945-1951, 1954-1963, 1966-1970, 1973, 1976-1977, 1981, 1997-1998, 2001-2002, 2006-2007, and 2009-2011 for BMP; 1952-1953, 1964-1965, 1971-1972, 1974-1975, 1978-1980, 1982-1996, 1999-2000, 2003-2005, and 2008 for AMP) also are evident in the 3-year TC count running means. Figure 11b is similar, but for annual landfalls in the Philippine domain, and the long-term mean is 6.5 (green line). The landfall time series also shows year-to-year variability. The AMP ranges from 1 to 10 years and the BMP from 2 to 15 years. The Philippines is influenced by environmental factors identified by Chan (2005), who attributed interannual variability in WNP TC activity to changes in planetary-scale flow patterns. SST changes in the central and eastern equatorial Pacific are associated with ENSO. TC variability also is related to the quasi-biennial oscillations phases due to its modification of the vertical wind shear. Interdecadal variability in annual TC and landfalling TC counts are related to PDO but also to the location, strength and size of the North Pacific subtropical high. The trend lines for all TCs and landfalling TCs during the 1945-2011 period both indicate increasing trend. When only the satellite era is considered, the trend in the numbers of all TCs reverses (Fig. 12a) which is consistent with the trend in the frequency of WNP TCs (Moon *et al*., 2015). Figure 12b also shows decreasing trend in the number of landfalling TCs.

The interannual variability and trends of the annual average latitude of annual average LMI for all TCs and landfalling TCs during the satellite era have also been investigated. Figure 13a shows the annual average latitude of the annual average LMI for all TCs where the trend line implies a poleward migration of LMI annual average latitude, consistent with the observed poleward shift of intense storms in WNP (Kossin *et al*., 2014 and Moon *et al*., 2015). But when the interannual variability of landfalling TCs is examined, the trend reverses. There is a slight negative trend, which suggests that the annual average latitude of LMI of landfalling TCs is slightly going equatorward (Fig. 13b).

3.7. Genesis and tracks

Over 80% of TCs in the WNP form between the Equator and within 20°N (Frank and Roundy, 2006). Briegel and Frank (1997) used the studies of Gray (1968, 1979, 1985) to define the climatological conditions necessary for tropical cyclogenesis. These include sea surface temperatures above ~26.5°-27.0°C coupled with a relatively deep oceanic mixed layer, cyclonic low-level relative vorticity and planetary vorticity, weak (preferably easterly) vertical wind shear, and organized deep convection in an area of large-scale ascending motion and high midlevel humidity. In the Philippine region, these necessary conditions are satisfied all year, especially in the MAS, so TCs can form in all months.

Philippine TC genesis locations and tracks exhibit regular monthly spatial progression. Genesis locations are the latitude-longitude positions where a TC is initially recorded by JTWC, even if it is outside the defined domain at the time of genesis. Depending on time of the year, genesis locations range widely from 2.5°N to 27.5°N, as far west as 107°E, and eastward to 179.5°E. In January-March, TC genesis locations are confined from 3°N to 16°N, and from 123°E to 179.5°E (Fig. 14a), and no TCs develop in the western side of the Philippines or in the South China Sea. Both large-scale and synoptic-scale circulations influence track type (Harr and Elsberry, 1991). Most (~76%) tracks are straight moving, although some recurve (24%, Fig. 14e). Like genesis locations, TC tracks are confined to lower latitudes, making landfall at <23°N. Some TC tracks reach the South China Sea. April-June is marked by an increase (~250%) in the genesis numbers illustrated in Fig. 14b as denser genesis points. Genesis locations extend farther north to 22°N, about 6° latitude higher than January-March genesis locations but the southern boundary does not change. Their longitudinal extent is <166°E and some TCs form in the South China Sea, reaching as far west as 109°E. As the genesis locations move north, the tracks extend up to 46°N (Fig. 14f). TC formation increases rapidly in July-September (a 213% increase over April-June), the quarter with the highest frequency of TC genesis (Fig. 14c). The latitudinal and longitudinal extent of TC genesis also is greatest in July-September with the genesis locations extending farthest north, to 27°N, about 5°latitude beyond April-June, and its longitudinal extent is from 111°E to 177°E, 11°longitude farther eastward than April-June. Again, the southern limit of the genesis locations is similar. July-September TC tracks extend farther northeast, beyond 55°N (Fig. 14g). TC tracks also reach main land China.

The October-December quarter has reduced TC genesis relative to July-September (Fig. 14d). TC genesis locations in October-December reach almost to 25°N and extend from 107°E to 178°E. TCs in October-December have both recurving and straight-moving tracks and reach 53°N (Fig. 14h). Quarterly genesis locations of Philippine landfalling TCs are in Figs. 14i-14l. About 36% of Philippine region TCs make landfall, with fewer genesis points compared with Figs. 14a-14d. Landfalling TCs, depending on the quarter season, have a mean westward to west-north-westward direction, but straight moving landfalling TCs especially those in lower latitudes originating from South China Sea can move eastward (Figs. 14m-14p). Genesis locations of landfalling TCs have narrower latitudinal and longitudinal bounds, closer to the Philippines, particularly in July-September.

3.8. The role of ENSO

WNP TC activity has interannual variability (Landsea 2000), linked to ENSO (e.g., Chan 1985, Dong 1988, Lander 1993, 1994) and is attributed to the longitudinal shift of the Walker circulation (Chan 1985, Wu and Lau, 1992). This is not necessarily the case for the entire WNP. For example, in the South China Sea, Goh and Chan (2010) found no clear link between TC frequency and El Niño and La Niña phases. Gray (1968) suggested that monthly and seasonal variations in TC activity are related to large-scale deviations from climatology. The Philippines, situated in the WNP, is strongly affected by ENSO. A wavelet analysis performed in this study confirms that ENSO is the major global mode influencing Philippine TC activity (Fig. 15a). The most significant mode is the approximately 2-7 year ENSO signal, as shown in the global wavelet spectrum (Fig. 15b). There is a suggestion that ENSO is more active every 20 years, in the 1950s, 1970s, and 1990s. There are 2 other peaks in the global power spectrum, at approximately 10 and 30 years, corresponding to decadal and multidecadal periods. However, they are not significant at the 95% confidence level, likely due to the limited length of the time series. Notably, Kubota and Chan (2009) found decadal and multidecadal signals in their wavelet analysis of a much longer Philippine TC time series, from 1902-2005.

The seasonal variability of the Philippine TC activity during Neutral, El Niño and La Niña phases of ENSO is shown in Fig. 16, adopted from Corporal-Lodangco *et al*. (2016). The green, red and blue bars represent Neutral, El Niño and La Niña phases, respectively. The standardized quarterly TC counts during each ENSO phase are in Fig. 16a. Remarkably, Philippine TC activity during the Neutral phase, relative to El Niño and La Niña phases, is always above normal from January-March to October-December. Below normal TC activity occurs all year during El Niño phases. Consistent with Chan (2000), in La Niña events, April-June and October-December have above normal TC activity unlike the below normal TC activity in January-March and July-September. Philippine TC landfall numbers were examined for different ENSO phases (Fig. 16b). TC landfalls in Neutral phases are above normal in all quarters. Although below normal landfalling TCs occurs all year during El Niño phases, there is a notable marginally negative TC landfalls in July-September. The sharp drop in TC landfalls during October-December, in El Niño episodes, supports the findings of Wu *et al.* (2004). January-March and July-September have below average La Niña phase TC landfalls, contrasting with above normal landfalls in La Niña April-June and October-December quarters. High TC landfall counts in October-December also match the results of Wu *et al.* (2004). Chan (1985, 2000) and Wang and Chan (2002) emphasized large-scale climate factors, such as ENSO, in determining genesis and preferred TC tracks, due to monsoon trough displacement, and changes in vertical wind shear near the dateline (Lander 1994, 1996; Clark and Chu, 2002) on landfalling

TCs. They also suggest that ENSO impacts on WNP TCs depend on the strength of ENSO phases. For example, suppression of landfalls is greater in strong El Niño years.

4. Conclusions

A detailed climatology was generated of the Philippine TC region, which has the highest annual median number of TCs (17) of any TC sub-basin on the globe. Two distinct Philippine TC seasons, the LAS (January 1- May 31) and MAS (June 1-December 31) are readily identified. The LAS and MAS seasons differ notably in a number of key TC metrics, such as TC frequency and landfall counts, season length, TC days, TC genesis locations, and tracks. Large amplitude variations are present in annual TC numbers, with the LAS being relatively inactive, and February is the least active month of the entire calendar year. In the Philippine domain, January-March has the lowest quarterly TC frequency, and TCs in February and March generally also are weaker. More TCs affect the Philippine region during the MAS because the environmental conditions favor TC development. July-September is the most active quarter and August is the most active month in the Philippine domain; both are periods when TC activity in the entire WNP is greatest. Observed LAS, MAS, and the quiescent periods separating the LAS and MAS, result from interseasonal large-scale circulation variability driving changes in TC activity.

Through the year, TC genesis locations and tracks move northward, reaching their highest latitudes during July-September, then regress in October-December. Straight-moving TCs are confined to lower latitudes, whereas recurving TCs occupy relatively higher latitudes and follow a northeast direction after recurving. The most common track is straight-line, and is observed year-round. Over 60% of TCs have long, straight track originating farther east from the Philippine region. Thus they have longer duration times over warm tropical SSTs and, because of climatologically low vertical wind shear, are more likely to become TYs than TCs that recurve northeastward.

This study showed that ENSO is the dominant global mode influencing Philippine TC activity, confirmed by a wavelet analysis. Philippine TC activity is above normal in Neutral phases. The impact of El Niño events on Philippine TCs is to reduce the number of TCs year-round, whereas La Niña events support above normal TC activity in April-June and October-December, and below normal activity in January-March and July-September. The difference in TC genesis locations during El Niño and La Niña phases affects the numbers of TCs entering the Philippine domain. The eastward displacement of cyclogenesis during El Niño phases typically causes TCs to recurve or dissipate before entering the Philippines, with fewer TCs entering the region. The frequency of TC landfalls in the Philippine domain also varies with ENSO phases. Above normal TC landfalls occur in Neutral phases. In El Niño years, TC landfalls are below normal, although only marginally in July-September. The January-March and July-September quarters of La Niña phases have below normal TC landfalls but above normal in April-June and October-December. The above normal numbers of TCs and landfalling TCs in April-June and October-December is attributed to the significant westward shift in mean genesis position of the Philippine TCs during La Niña phases (Corporal-Lodangco *et al.*, 2016), and the presence of a strong subtropical ridge generating a steering flow toward the west northwest. Other dynamics in WNP are responsible for the variability of Philippine region TC activity. For example, TCs preferentially occur in convective phases of the Madden-Julian Oscillation (e.g., Liebmann *et al.,* 1994).

Finally, further analysis is required to explain the quiescent periods identified between the LAS and MAS and conversely. This phenomenon will be investigated as part of continued research on Philippine TCs, specifically attempting to identify the possible reasons for the existence of the quiescent period, and examining the heaviest rainfall events resulting from Philippine TCs as part of an extreme events study.

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Table 1. The metrics of the Philippine TC activity during the two distinct seasons: less active season (LAS) and more active season (MAS).

Tropical Cyclone Metrics	Less Active Season	More Active Season	Tropical Cyclone Metrics	Less Active Season	More Active Season
Season TC Mean	2.16	15.73	Season Earliest Start Date	1/2	6/1
Season TC Median	2	15	Season Latest Start Date	5/31	7/30
Season Landfall Mean	0.96	5.55	Season Mean Start Date	3/4	6/20
Season Landfall Median	1	6	Season Median Start Date	2/28	6/18
Season TC Number IQR*	2	4.5	Season Earliest End Date	1/11	9/10
Season Landfall IQR*	2	3	Season Latest End Date	6/6	1/5
Quiescent Period Mean	1.5 months	2.83 months	Season Mean End Date	5/6	12/10
Quiescent Period Median	1.2 months	2.85 months	Season Median End Date	5/20	12/16
Quiescent Period Minimum	2 days	6 days	Season Mean Length	52 days	174 days
Quiescent Period Maximum	5 months	7 months	Season Median Length	38 days	176 days
Quiescent Period IQR*	1.5 months	3 months	Season Length IQR*	92 days	28 days
Median TC Days	8 days	51 days	TC Days IQR*	11 days	20 days

Table 2. The statistics of Philippine tropical cyclones (TCs) and landfalls are presented in quarters. ALL is the sum of 4 quarters. The bottom row is the total and percentage of all tropical cyclones and landfalls for the period 1945-2011. The numbers in red are the maximum values.

Quarter	**Number of TCs**	**Percentage of TCs**	**Number of Landfalling TCs**	**Percentage of Landfalling TCs**
January-March	54	4.5%	25	46%
April-June	187	15.6%	70	37%
July-September	585	**48.8%**	143	24%
October-December	373	31.1%	197	**53%**
ALL	1199	100%	435	36%

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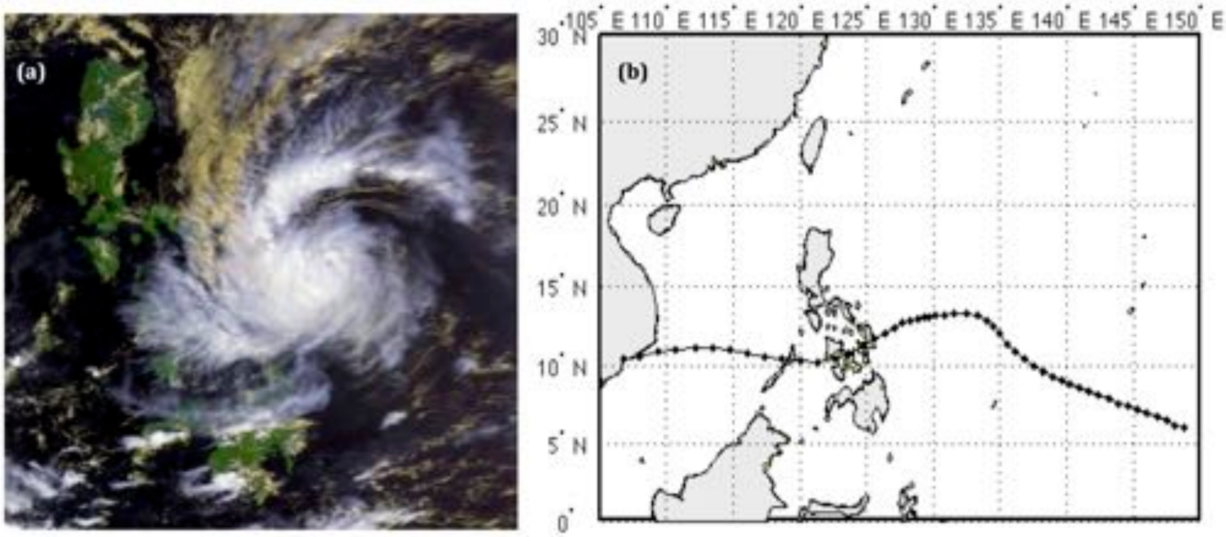

Figure 1. (a) Tropical Storm Thelma just before landfall in the Philippines on November 4, 1991. Source: http://www.noaa.gov (b) Track of Tropical Storm Thelma (6-hourly positions).

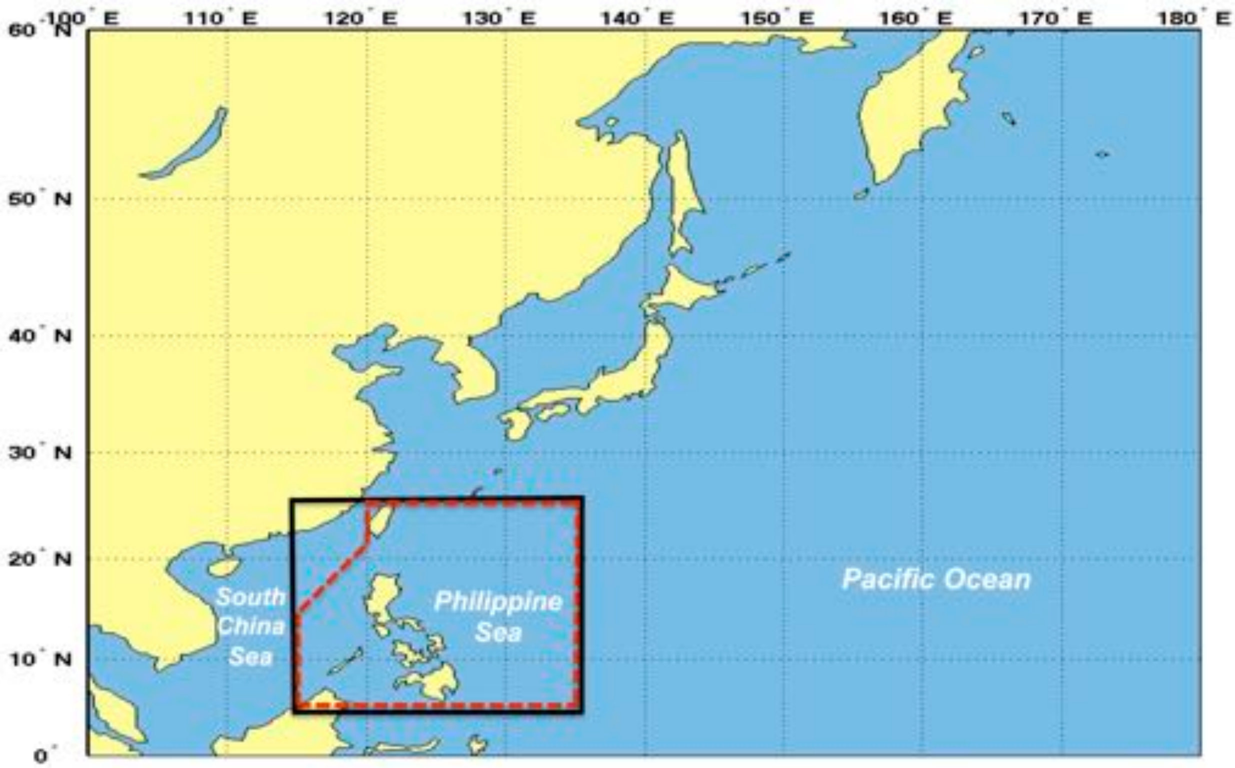

Figure 2. The study region covers latitudes 5°-25°N and longitudes 115°-135°, shown as the black inset and referred to here as the Philippine region, or domain. The irregular box (red broken line) shows the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) area of responsibility for tropical cyclones (TCs). PAGASA monitors and forecasts TCs that affect the Philippines. This figure is adopted from Corporal-Lodangco *et al*. (2016).

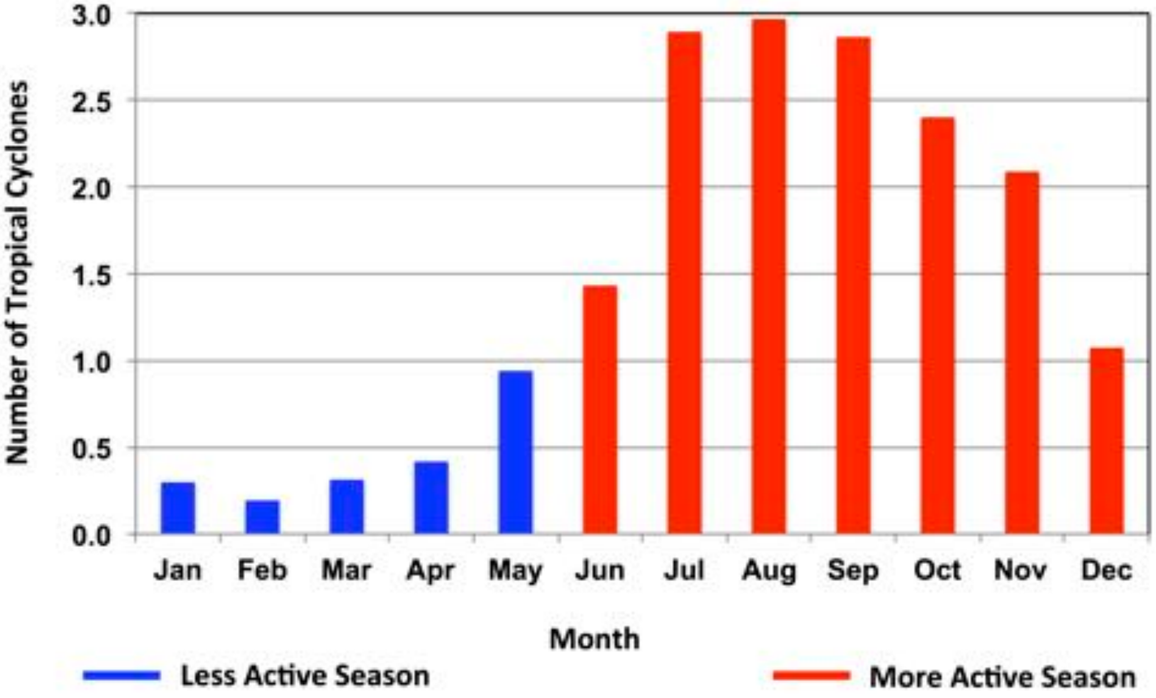

Figure 3. Mean monthly tropical cyclone (TC) counts in the Philippine region. The less active season runs from January 1 to May 31, representing the relatively quiet phase of tropical cyclone activity in the Philippine domain, during which there is a mean of less than one TC per month. The more active season is from June 1 to December 31, with all monthly means exceeding one.

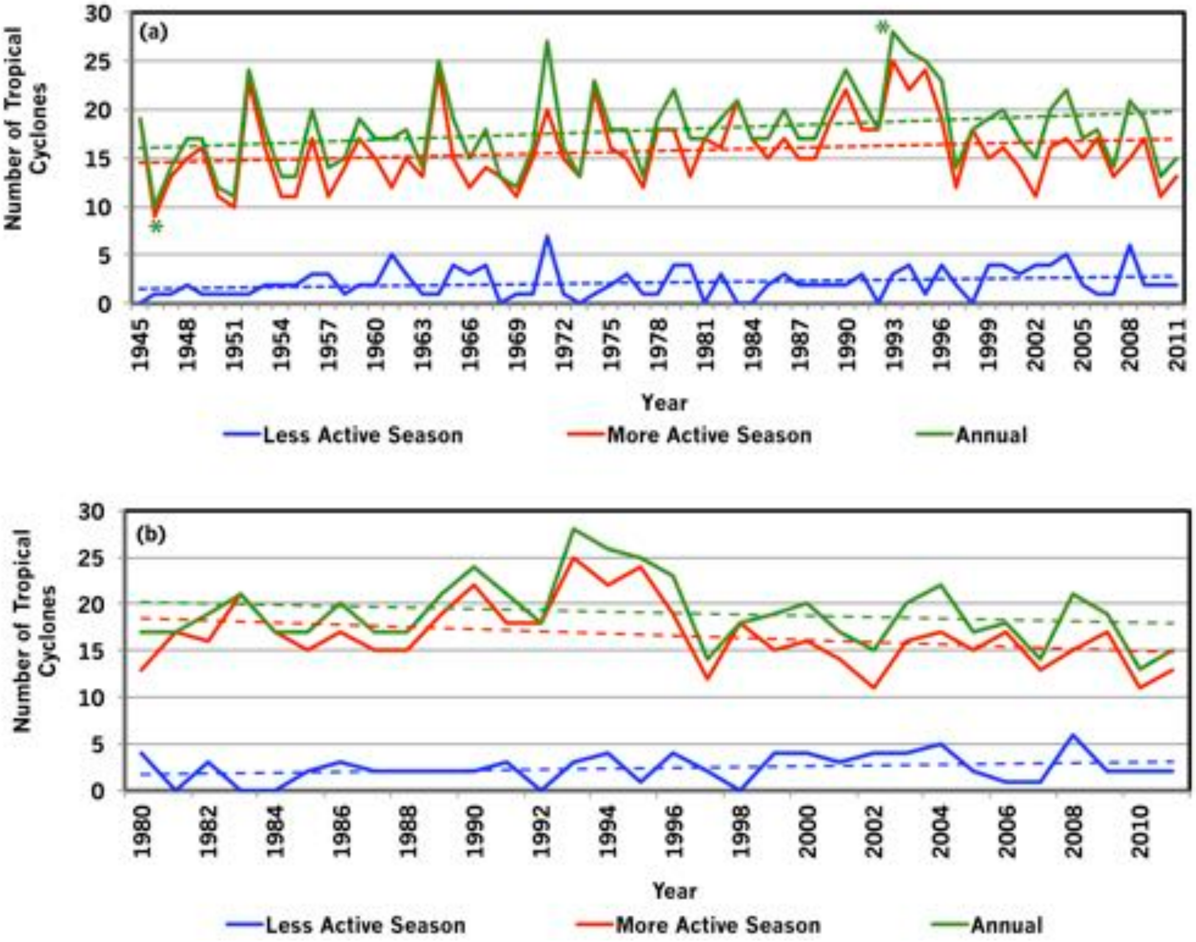

Figure 4. (a) Time series of annual number of tropical cyclones (green line) plotted against the less active season (LAS – in blue line) and the more active season (MAS - in red line) TCs during the period 1945-2011. The MAS dominates the mean annual TC numbers, accounting for about 89% of the total. The linear trend lines are shown as dashed lines. The asterisks are the minimum and maximum number of TCs during the period. (b) Same as 4a but for the satellite era, defined here as 1980-2011.

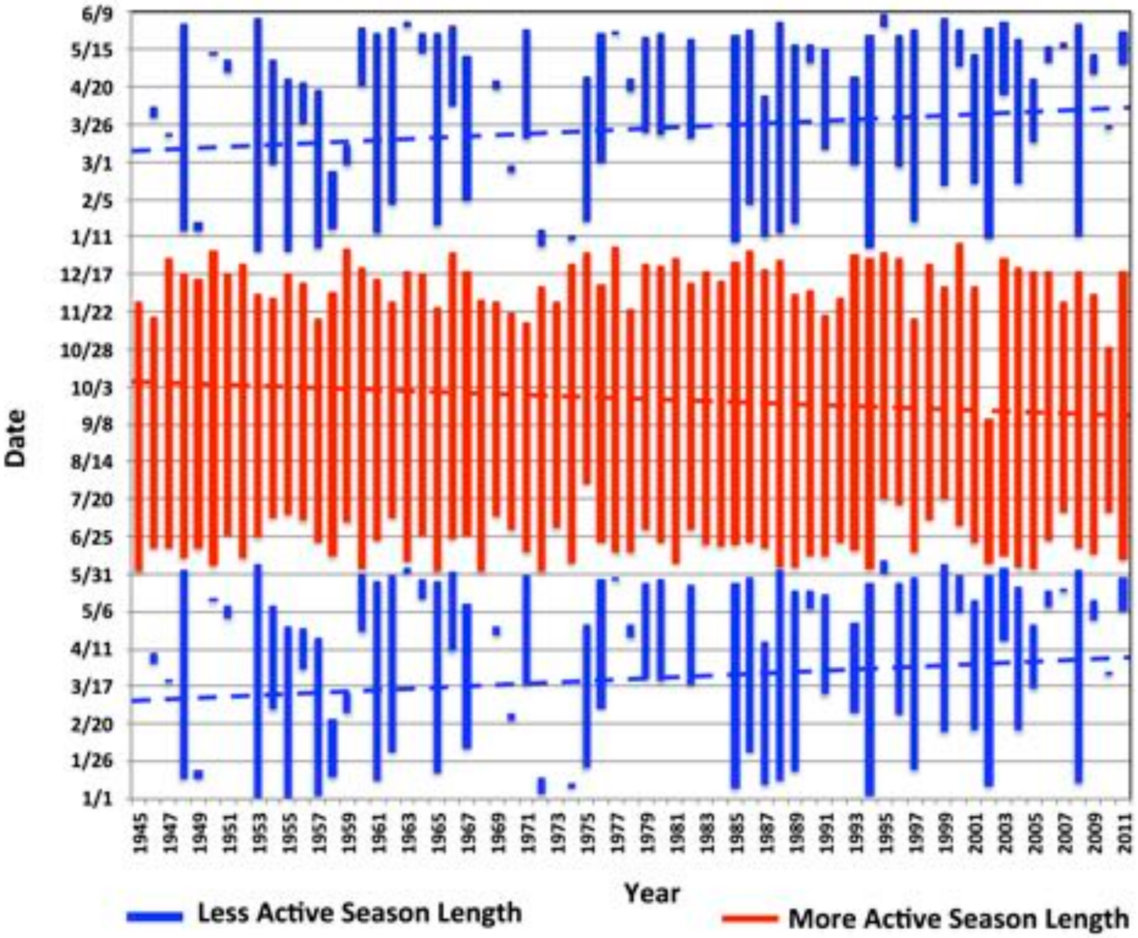

Figure 5. The year-to-year TC activity in the Philippine region showing alternating less active season (LAS), quiescent periods, and more active season (MAS). The blue and red bars denote the yearly season length of the less active season and the more active season, respectively. The season start date (lower tip of the bar) is the day when the first TC is within the Philippine domain. The end date of the season (upper tip of the bar) is defined as the day when the last TC is inside the domain. The season length is end date minus start date. Dashed lines are linear trend lines.

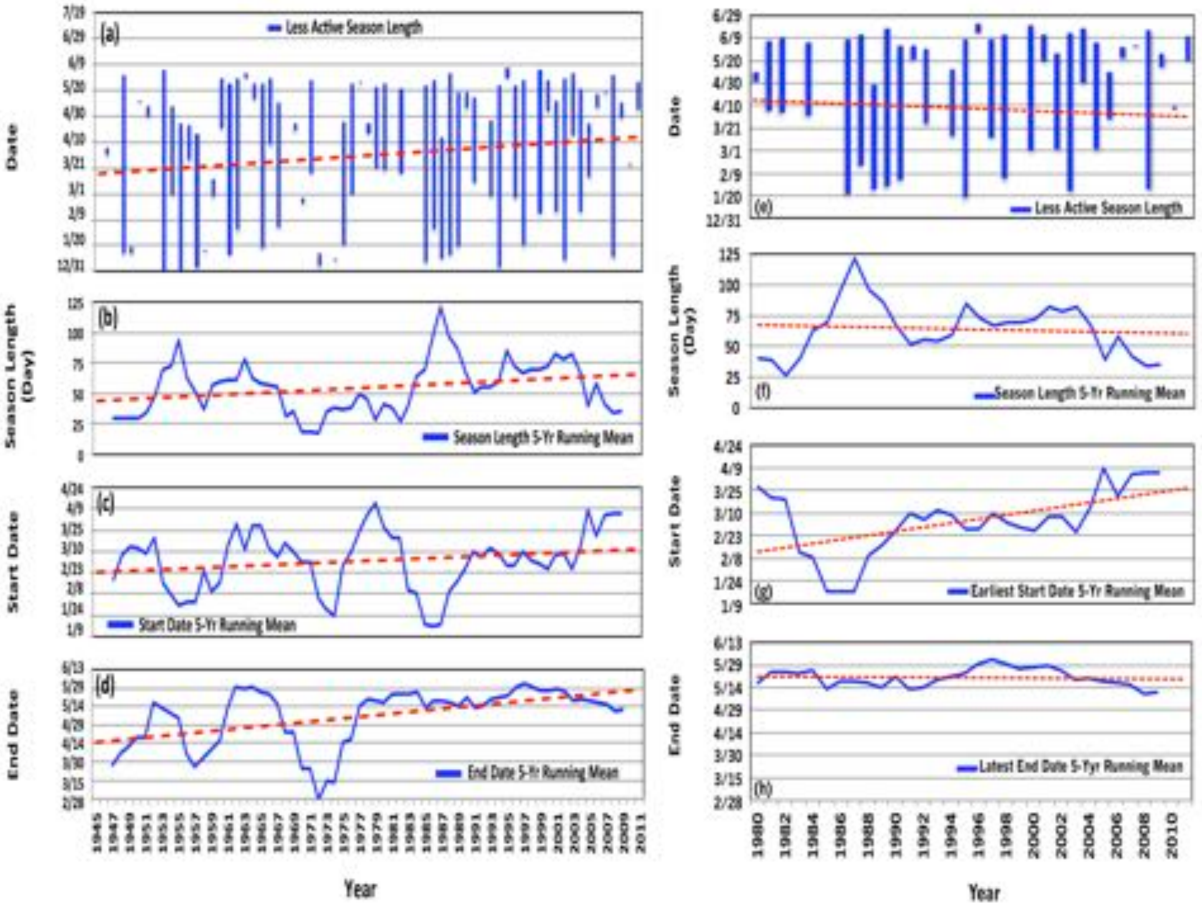

Figure 6. (a-d) The less active season (LAS) time series during the period 1945-2011. (a) The length of LAS is the length of the bar in each year, (b) the 5-year running mean of LAS length, (c) the 5-year running mean of LAS earliest start date, and (d) the 5-year running mean of LAS latest end date. Dashed lines are linear trend lines. (e-h), same as (a-d), but during the satellite era 1980-2011.

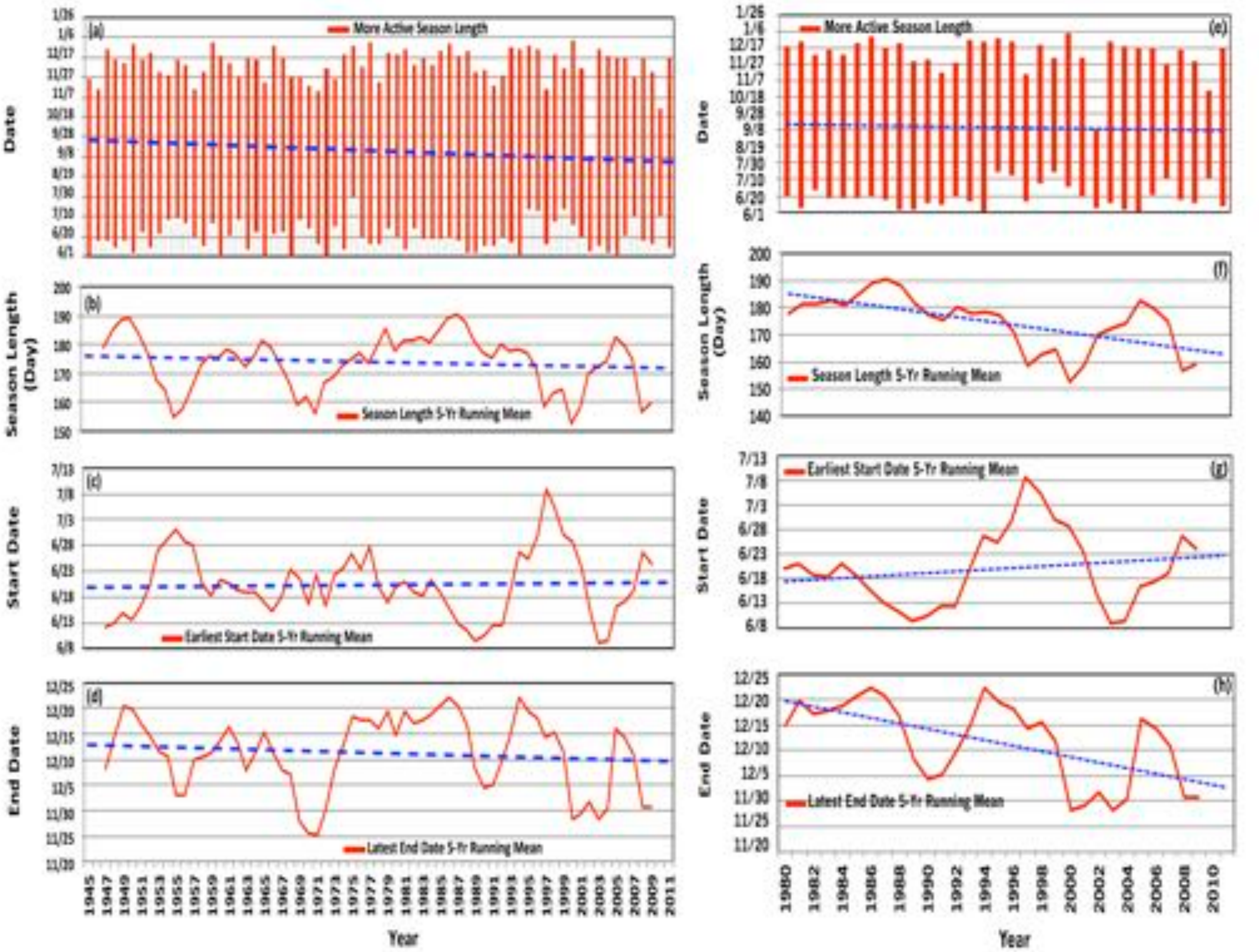

Figure 7. (a-d) The more active season (MAS) time series during the period 1945-2011. (a) The yearly MAS length as represented by the length of each bar, (b) the 5-year running mean of MAS length, (c) the 5-year running mean of MAS yearly earliest start date, and (d) the 5-year running mean of MAS yearly latest end date. The dashed line for each graph is the trend line. (e-h), same as (a-d), but during the satellite era 1980-2011.

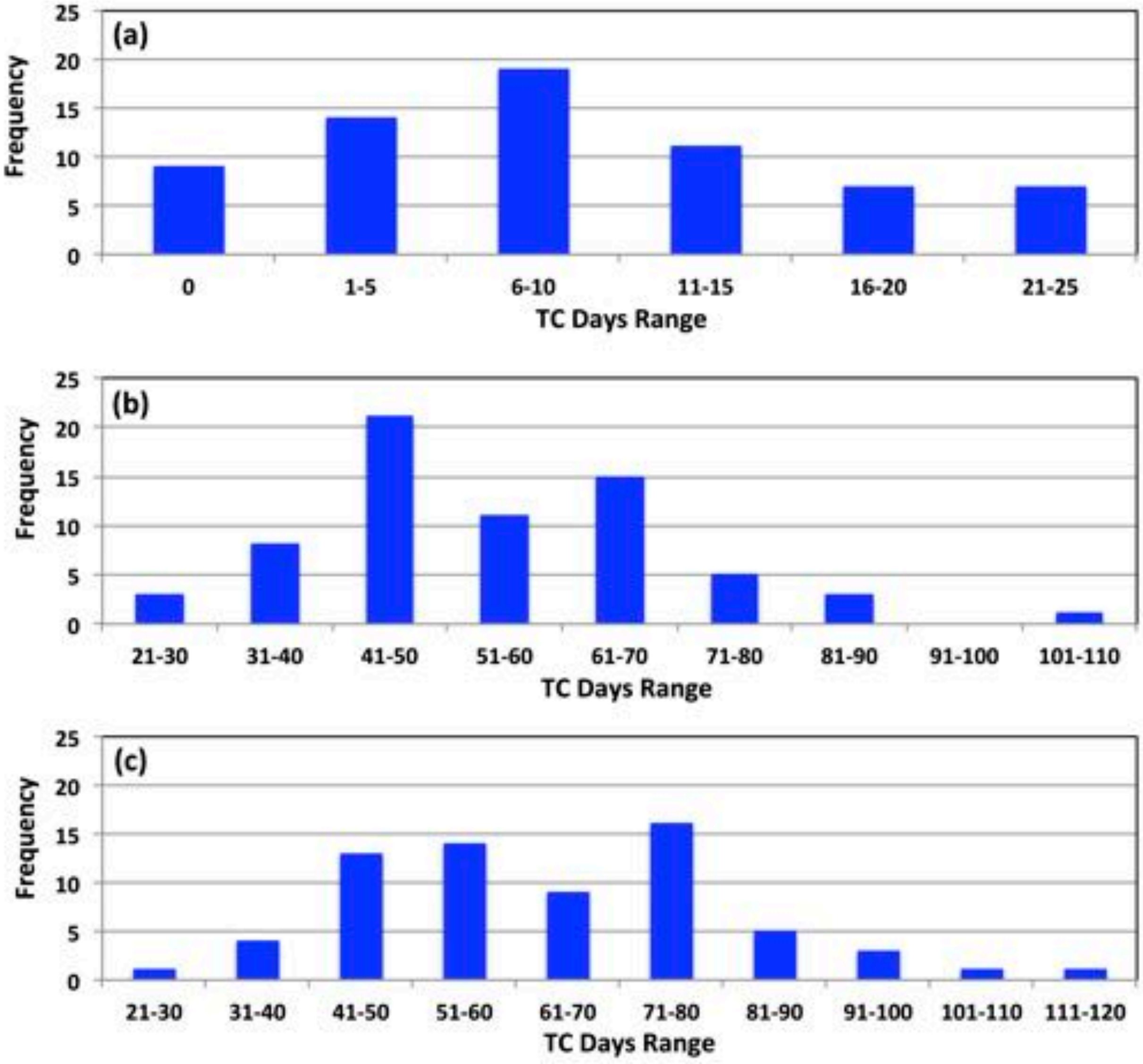

Figure 8. Frequency distribution of numbers of tropical cyclone (TC) days for (a) Less active season (LAS), (b) More active season (MAS), and (c) annual total. A TC day is defined as having at least one TC in the Philippine domain. The annual number of TC days is the sum of the TC days from both the LAS and the MAS.

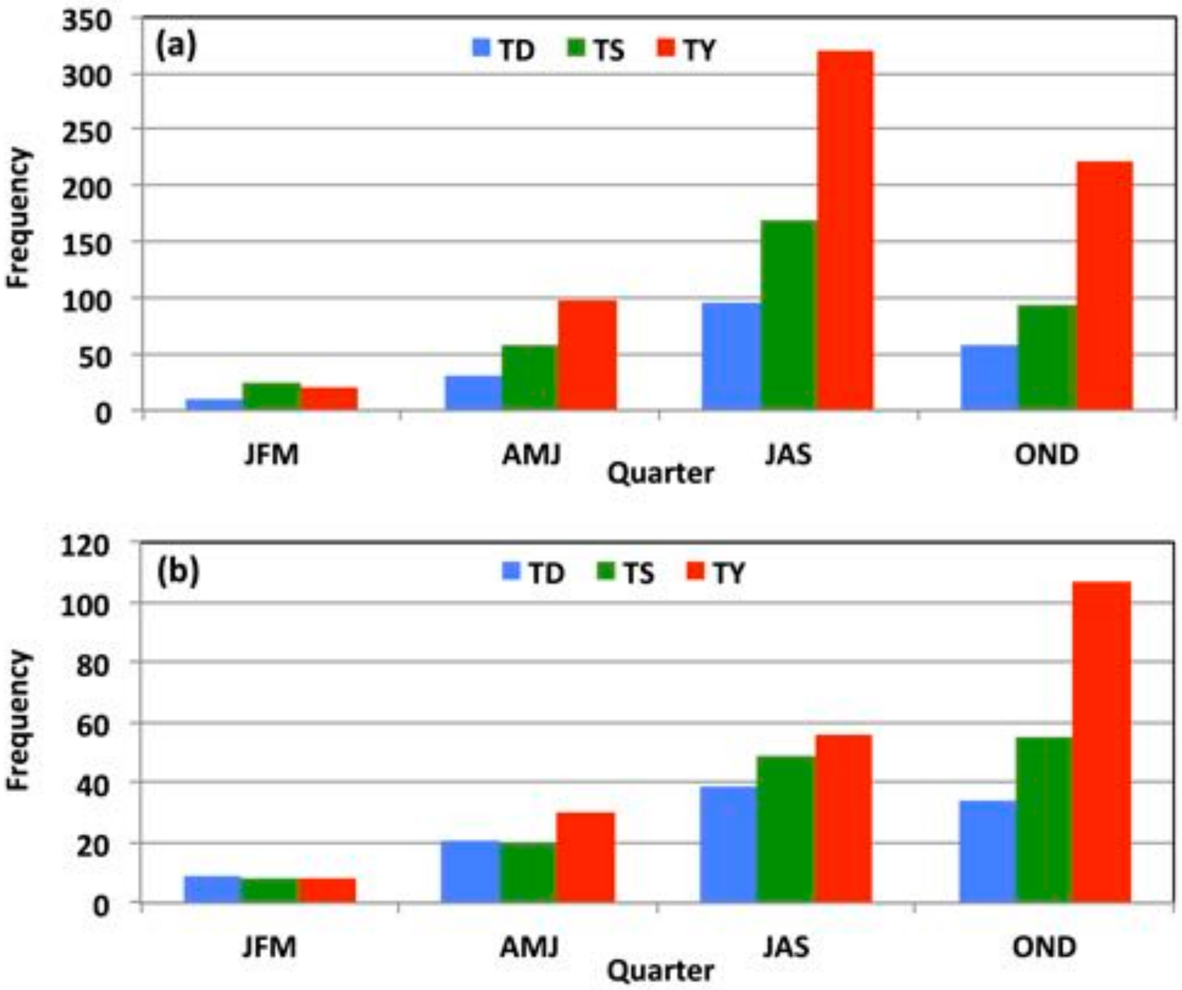

Figure 9. (a) Tropical cyclone intensity classification by quarter; tropical depression (TD), tropical storm (TS), and typhoon (TY), and (b) Same as (a), but for landfall quarterly intensity classification count.

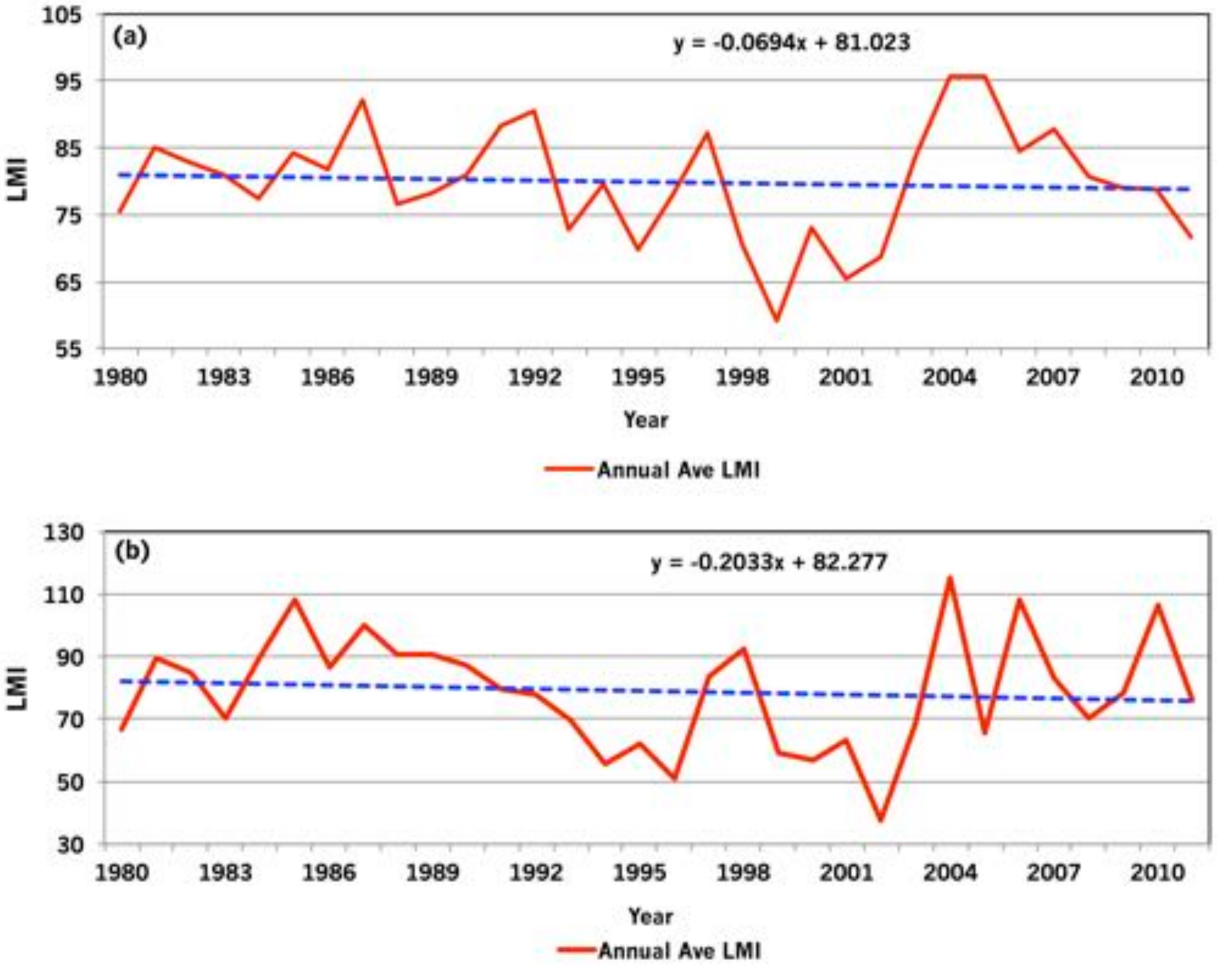

Figure 10. (a) Annual average of lifetime maximum intensities for all tropical cyclones (TCs) during the satellite era. (b) Same as (a) but for landfalling TCs.

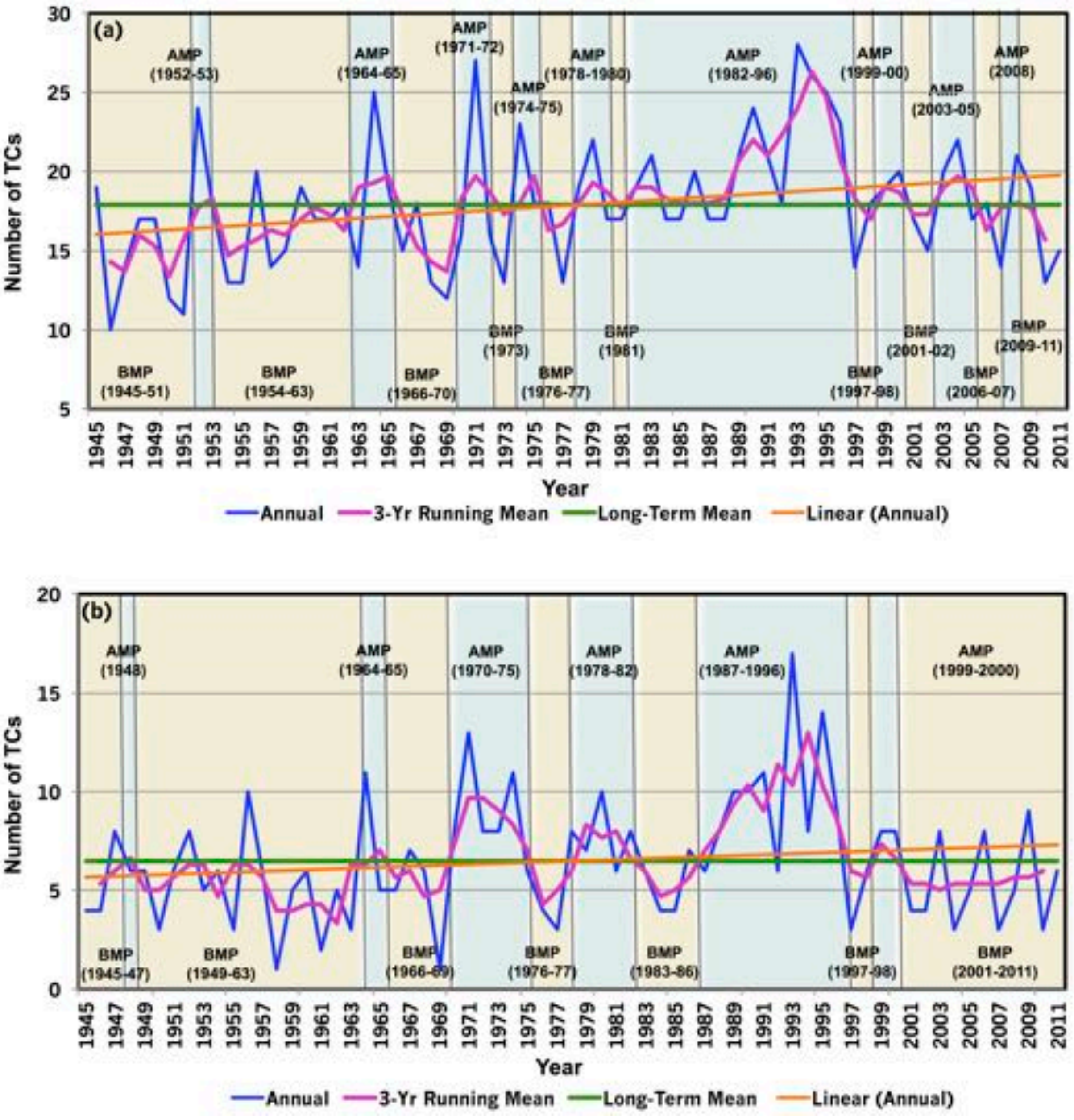

Figure 11. Philippine interannual and interdecadal variations in the frequencies of (a) all tropical cyclones (TCs) and (b) landfalling TCs, over the 1945-2011 period. Years with 3-year running means below the long-term mean of 17.9 (6.5) for all TCs (landfalls) are part of the below mean period (BMP), and all years with 3-year running means above the long-term mean are included in the above mean period (AMP). Orange line is a linear trend line.

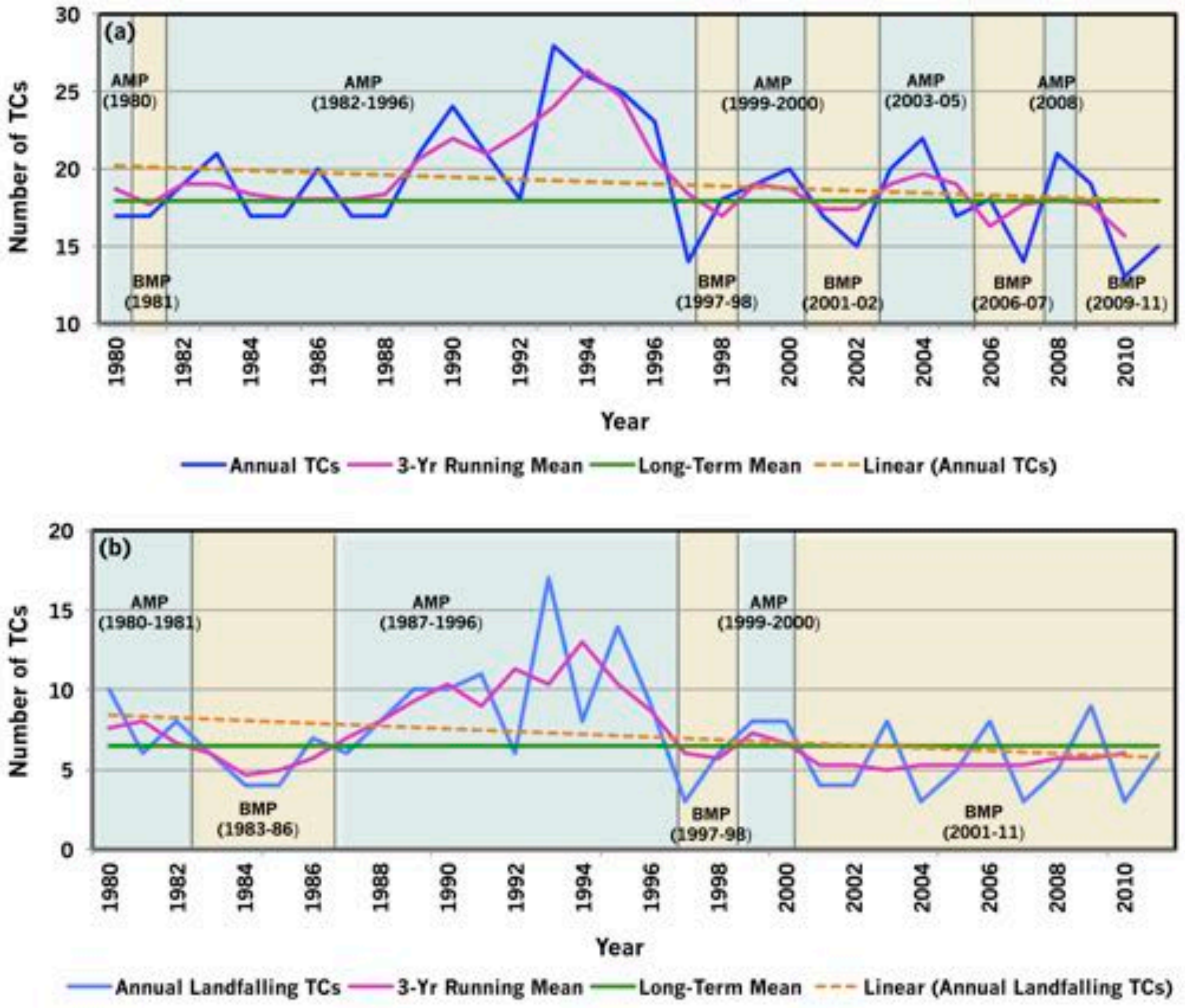

Figure 12. Interannual and interdecadal variations in the frequencies of (a) all Philippine tropical cyclones (TCs) and (b) landfalling TCs during the satellite era 1980-2011.

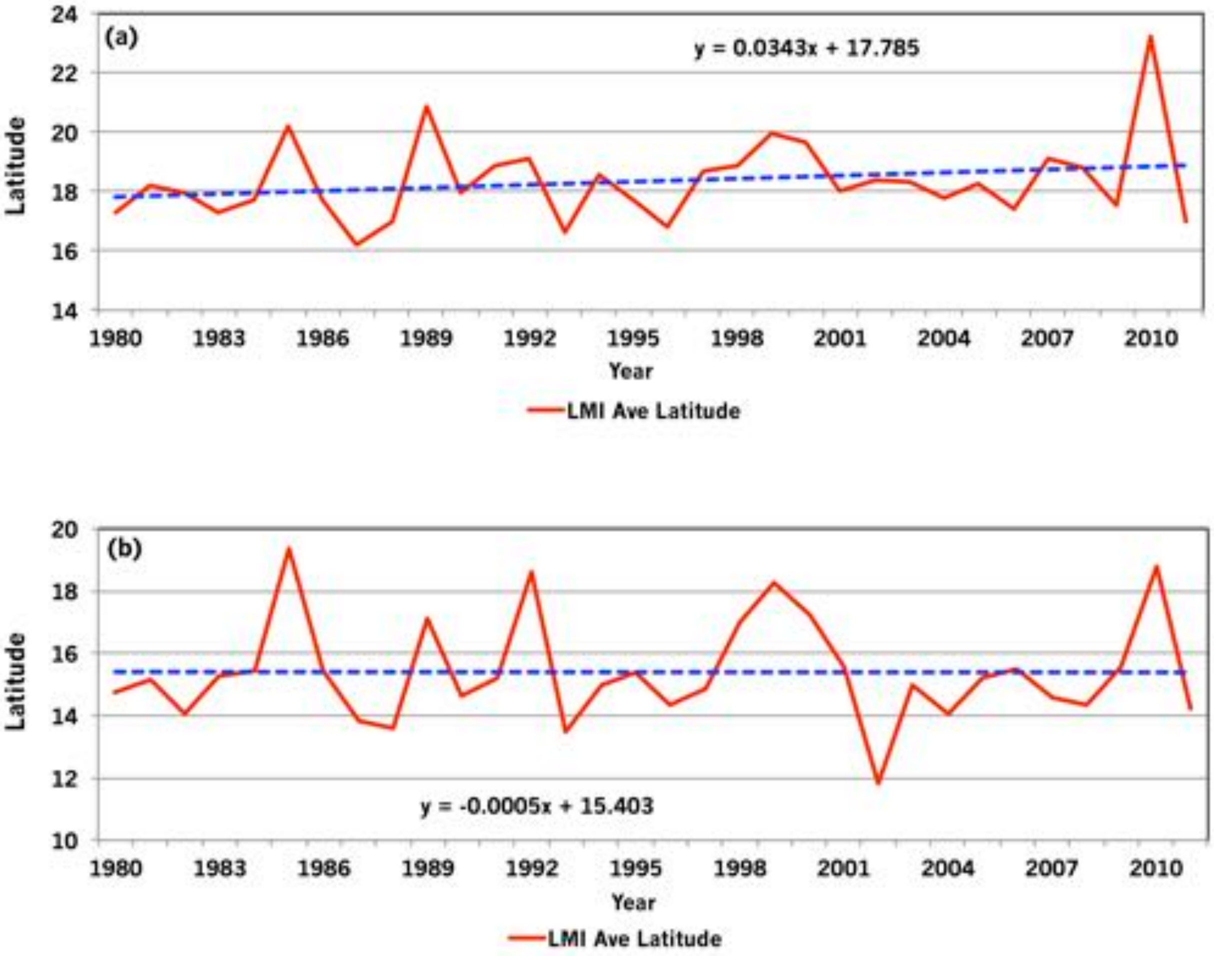

Figure 13. (a) Annual average latitude of lifetime maximum intensity (LMI) during the satellite era for all tropical cyclones (TCs). (b) Same as (a) but for landfalling TCs.

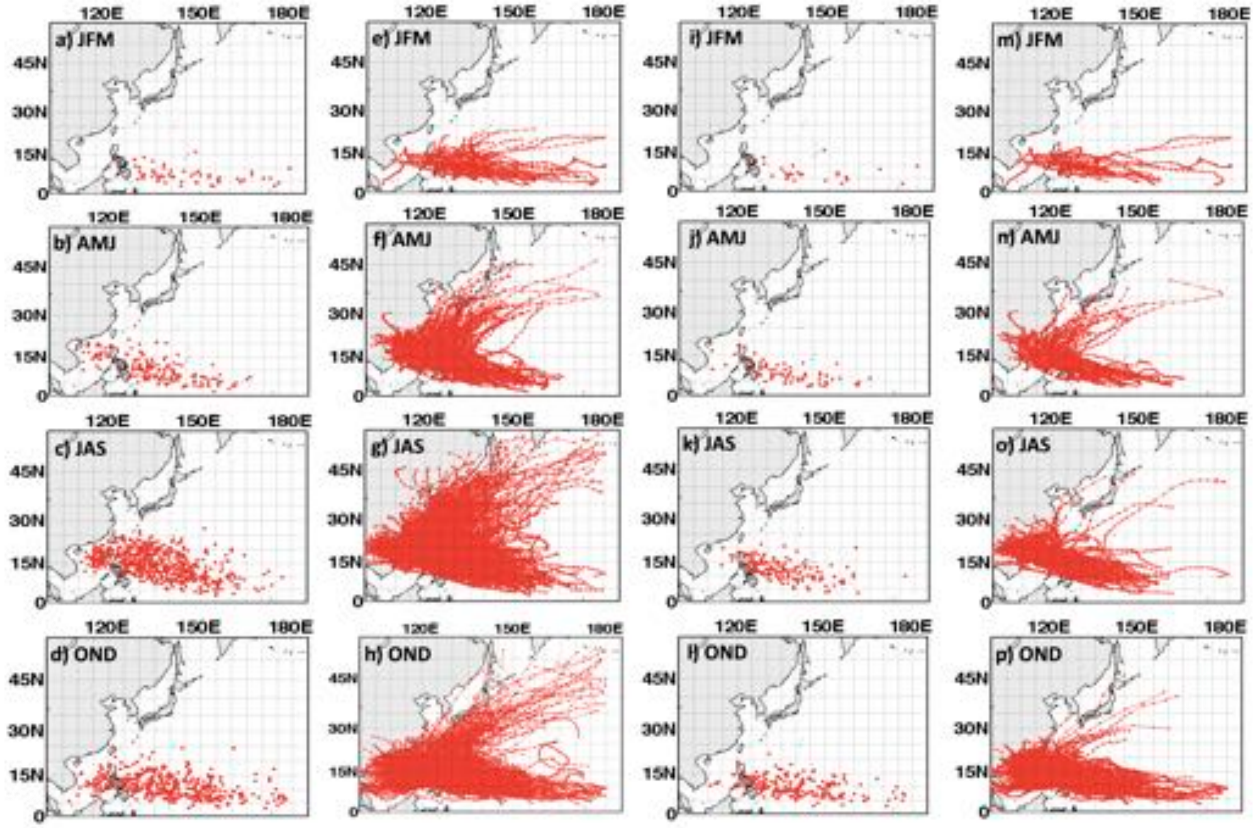

Figure 14. (a-d) Quarterly variations in genesis positions of all tropical cyclones (TCs), (e-h) quarterly tracks of all TCs, (i-l) quarterly genesis positions of landfalling TCs, and (m-p) quarterly tracks of landfalling TCs.

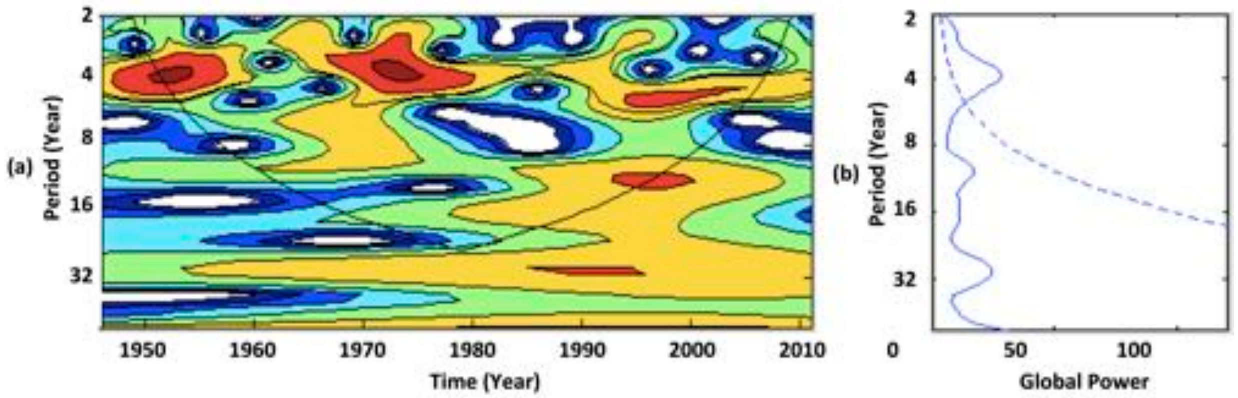

Figure 15. (a) Wavelet analysis of the Philippine tropical cyclone time series; the region above the black curve indicates the 95% level of confidence. (b) The corresponding global wavelet spectrum; the dashed blue line is the 95% level of confidence. Note the peaks in the 2-7 year, 10-12 year and 28-32 year periods.

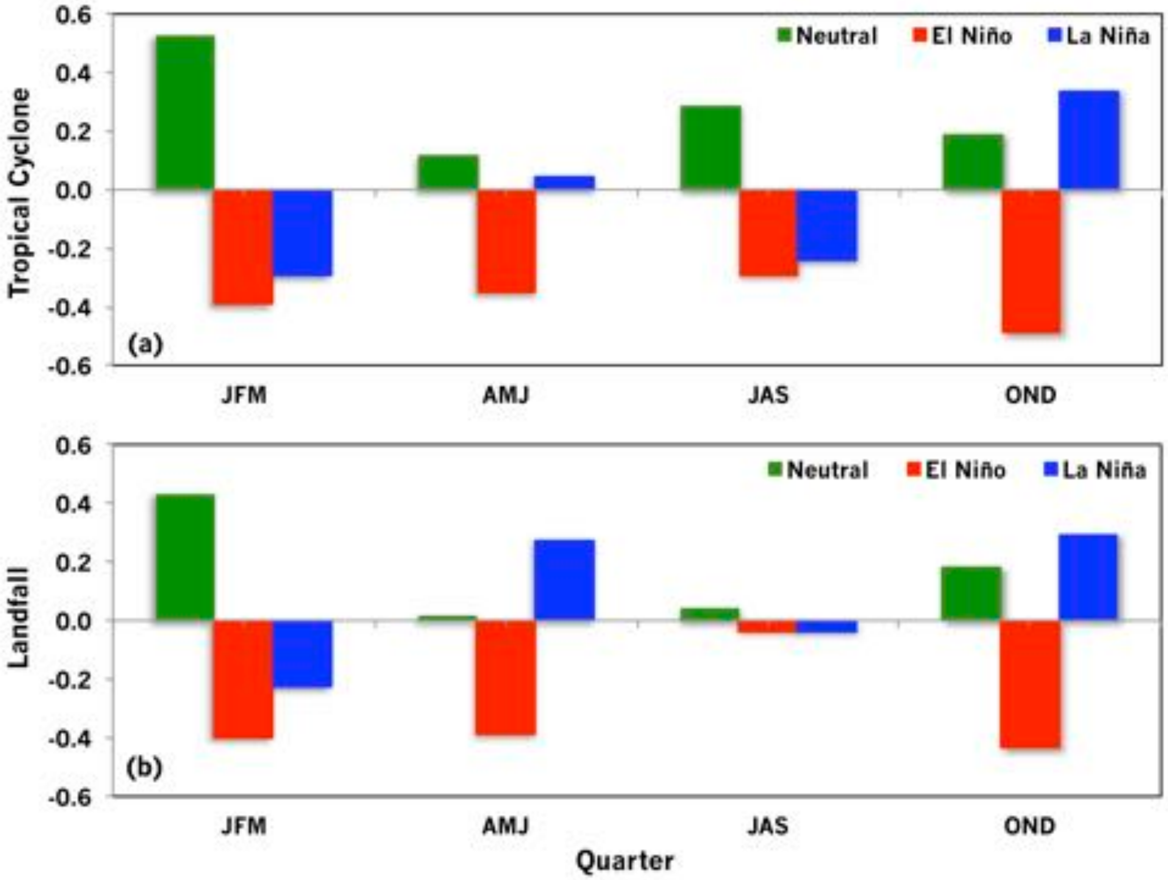

Figure 16. The quarterly tropical cyclone-El Niño Southern Oscillation relationship (a) Standardized quarterly TC mean during Neutral, El Niño and La Niña phases, (b) Same with (a) but for standardized TC landfall mean. This figure is adopted from Corporal-Lodangco *et al*. (2016).