CrossMark

ORIGINAL PAPER

Statistics of tropical cyclone landfalls in the Philippines: unusual characteristics of 2013 Typhoon Haiyan

Hiroshi Takagi[1] · Miguel Esteban[2]

Abstract The unusual statistical characteristics of Typhoon Haiyan were investigated using the JTWC best track data from 1945 to 2013, particularly focusing on tropical cyclones making landfall in the Philippines. Haiyan generated the strongest winds among a collection of over 400 past storms, which was 16 % greater than the second strongest typhoon on record (Typhoon Zeb in 1998). The forward speed of Haiyan was nearly twice as fast as the average speed of these weather systems and could be the fastest typhoon on record. Thus, Haiyan can be characterized as both the fastest moving and strongest typhoon measured in the area. The return period for a Haiyan-class typhoon to make landfall was estimated to be 200 years. A statistical analysis also indicated that the number of tropical cyclone making landfall around Leyte Island in the Philippines—the area most severely damaged by Haiyan—has been steadily increasing over the past 7 decades. Analysis of sea surface temperature (SST) indicates that both Haiyan and Zeb occurred during seasons that were characterized by remarkably warm SSTs over the seas surrounding the Philippines.

Keywords Typhoon Haiyan (Yolanda) · Tropical cyclone landfalls · Philippines · Return period · Forward speed · Storm surge

1 Introduction

Typhoon Haiyan (or Yolanda, its local name) struck the Philippines on November 8, 2013, causing enormous damage to Leyte, Samar, and many other islands. A total of 6245 individuals were reported dead, 28,626 injured, and 1039 are still missing (NDRRMC, as of 6 March 2014). Haiyan was one of the strongest typhoons known to have ever made

✉ Hiroshi Takagi
htakagi.jp@gmail.com

1   Tokyo Institute of Technology, Tokyo, Japan

2   The University of Tokyo, Tokyo, Japan

landfall, not only in the Philippines but in the entire Western North Pacific. Its intensity was among the highest ever observed for tropical cyclones globally (Lin et al. 2014). The forward speed of the typhoon, reaching around 41 km/h at landfall, was also unusual among other events of comparable intensity during the past 6 decades in the Western North Pacific (Takagi et al. 2014, 2015).

As a result of its strong intensity, the typhoon caused a massive storm surge in many islands in the Philippines. A maximum inundation height of 7 m was observed in Tacloban City in Leyte Island, where the largest number of casualties took place (Takagi et al. 2014). Maximum hindcast significant wave heights during the storm reached up to 19 m off Eastern Samar, though they decreased to less than 5 m in Leyte Gulf near Tacloban (Bricker et al. 2014). The storm also brought about heavy precipitation that reached up to 615 mm between November 3 and 12, over the entire Philippines (Nguyen et al. 2014a). Haiyan, although very similar in size to Hurricane Katrina in 2005, had deeper convective clouds, so held more precipitable water (Galvin 2014).

The Philippines sits in what has been called the "Tornado Alley" of tropical cyclones (TCs)—the annual TC landfall numbers in the Philippines varied from 3.6 to 6.0 in the period between 1902 and 2005 (Kubota and Chan 2009), while the annual average number was considered to be 6.5 TCs per year between 1970 and 1989 (Shoemaker 1991), showing some discrepancy. The average TC's wind speed of typhoons just before making landfall in the Philippines was 66.9 knots, with a standard deviation of 34.4 knots (Shoemaker 1991). Garcia-Herrera et al. (2007) examined the chronology of TCs around the Philippines, as documented by Spanish Jesuits, and highlight how a total of 652 TC events happened during the period 1566–1900, indicating the long experience of this country with such weather events.

In the present paper, the authors examine the uniqueness of this typhoon in terms of its track and intensity, compared with records of past typhoons. Particularly, the focus will be placed on the statistics of TC landfalls in the Philippines as the weather system's intensity at this time is the most critical factor for the generation of storm surges. The statistics clearly demonstrate the extraordinary features of Haiyan, which help to explain the high mortality rates that resulted as consequence of the extremely strong gusts and subsequent storm surge. The present paper also estimates the reoccurrence landfall return period of a strong typhoon with an intensity equivalent to that Haiyan.

2 Tropical cyclone landfalls and their intensities between 1945 and 2013

Takagi et al. (2014) analyzed past typhoon tracks in the Western North Pacific (WNP) to verify how Haiyan was historically unusual, in terms of both its intensity and path. To extend this research, the present paper specifically focuses on the statistics of TC landfalls in the Philippines between 1945 and 2013 using the so-called Best Track Data, obtained from the Joint Typhoon Warning Center (JTWC). The data consist of time, central position, and the maximum sustained wind speed (hereinafter simply referred to as "wind speed") in knots every 6 h.

The authors developed a FORTRAN code which can detect the approximate landfall point at which a TC track intersects a coastline from Global Self-consistent, Hierarchical, High-resolution Shoreline Database (GSHHS) provided by University of Hawaii and NOAA. TC intensities at the time of landfall can be also estimated by interpolating Best Track Data points from shortly before and after landfalls. As TCs generally reach

their peak in intensity prior to landfall (Shoemaker 1991; Scheitlin and Elsner 2009), this interpolation process is expected to improve the estimation of the intensity at this point.

Figure 1a shows TC landfall points along the Eastern coasts of four major islands (Luzon, Samar, Leyte, and Mindanao) in the Philippines. There were a total of 406 landfalls between 1945 and 2013, an average of 5.9 times per year. The wind speed distribution at landfall is shown in Fig. 1b. From this figure, it is obvious that the wind speeds of Haiyan at the time of landfall (165.8 knots) were the strongest recorded in the Philippines, 16 % stronger than the second strongest event on record (142.7 knots in 1998 during Typhoon Zeb, known in the Philippines as Iliang).

The landfall frequency is shown in Fig. 1c, from which it is possible to attempt to observe both short and decadal trends at different latitudes. The figure presents trends for every 2-degree latitude interval from (a) 18°N to (f) 6°N. It appears that the annual frequency varies significantly from year to year, which clearly demonstrates the irregular nature of TCs. The average landfall frequency for each latitude zone is (a) 1.57 times (standard deviation is 1.24), (b) 1.30 times (1.14), (c) 0.87 times (1.08), (d) 1.03 times (1.03), (e) 0.57 times (0.79), and (f) 0.14 times (0.39), respectively.

The overall trends between 1945 and 2013 were estimated by a linear regression analysis. A test to detect any linear trends was carried out using the statistical method ANOVA (Analysis of Variance), which can determine whether each line shows a significant increasing or decreasing trend. According to the results obtained, it was found that only the latitude range (d) 10°N–12°N, which encompasses Leyte Island, shows a significant increase in TC landfall. In this area, typhoon frequencies appear to have increased
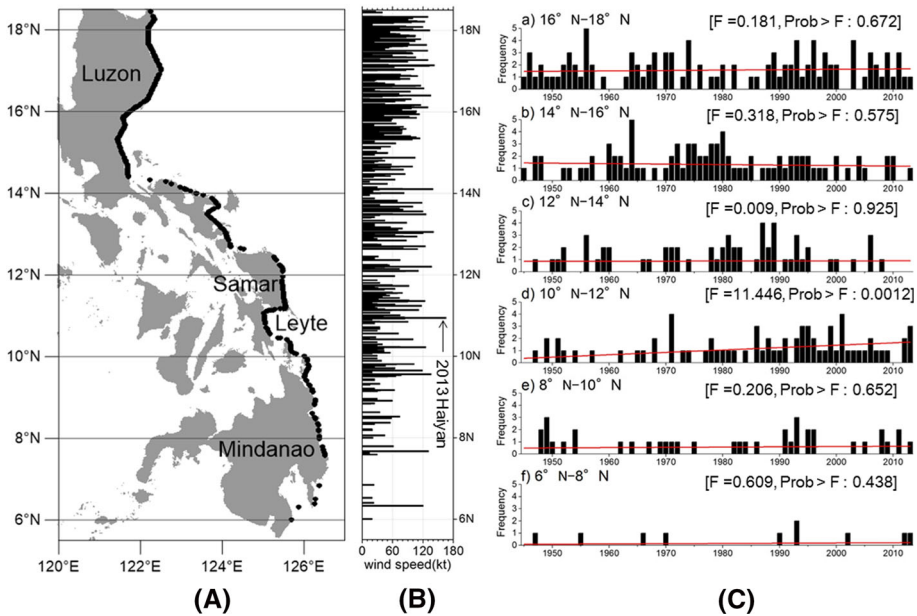
Fig. 1 **a** TC landfall points along the Eastern coasts of four major islands in the Philippines. **b** Wind speeds (1-min maximum sustained wind speeds) at landfalls, and **c** the frequency of TC landfalls between 1945 and 2013 for each two-degree latitude zones

by around +0.02 times per year (at the 95 % confidence level), while other lines do not show any particular upward or downward trends.

3 TC forward speeds at the time of landfall

A TC's forward speed is a significant parameter which has been overlooked in previous studies (Rego and Li 2009). It is important to note how a moving pressure with a storm can generate long waves that propagate ahead of the storm and cause an initial setup along the coast. This occurs when the forward speed of the storm is close to the celerity of a shallow water wave for the depth over which the storm is traveling (Sorensen 1997).

Figure 2 indicates the relationship between wind speeds and forward speeds for the strongest 67 TCs among the 406 TCs which made landfall in the Philippines between 1945 and 2013. The forward speed of each event was calculated using the geographical positions of the weather system immediately before and after landfall. From the figure, it is clear that these two parameters do not particularly show any positive or negative correlation to each other (correlation coefficient $R = -0.017$).

In fact, the forward speed of Haiyan at the time of landfall, 41 km/h on average with a standard deviation of 7.3 km/h, is nearly twice as fast as the average speed of TCs, 22.6 km/h, and ranked top among all TCs. Therefore, Haiyan could be considered the fastest typhoon in addition to having the strongest intensity on record. If assuming wind speeds and forward speeds are independent of each other, the yearly chance that any given typhoon could become the fastest typhoon as well as strongest typhoon simultaneously can be estimated to be 1/4489, which clearly demonstrates one of unusual characteristics of Haiyan.
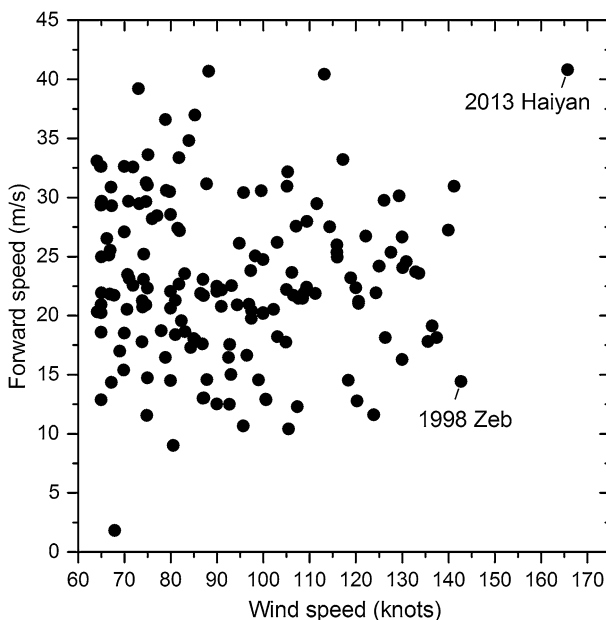
Fig. 2 Relationship between wind speeds and forward speeds for the strong 67 among 406 TCs which made landfall in the Philippines between 1945 and 2013

4 Reoccurrence interval of a Haiyan-class typhoon

High wind speeds due to typhoons pose a threat to the stability of structures and can bring significant storm surges to coastal communities. An accurate estimation of the probability of occurrence of extreme wind speeds is important to improve disaster management in a given area. Such estimates are commonly expressed in terms of the quantile value X_T, i.e., the maximum wind speed which is exceeded, on average, once every T years, the return period value (Palutikof et al. 1999). The Weibull probability density function is a good model for wind speed distributions (Hennessey 1977). A Weibull probability density function (pdf) distribution can be calculated as follows,

$$f(x) = \frac{\alpha}{\beta}\left(\frac{x}{\beta}\right)^{\alpha-1} \exp\left\{-\left(\frac{x}{\beta}\right)^{\alpha}\right\} \quad x > 0 \tag{1}$$

where α is referred to as the shape parameter and β as the scale parameter. In the present research, the maximum likelihood method was applied to estimate these parameters from the JTWC best track data between 1945 and 2013.

Figure 3 indicates the total number of annual maximum wind speeds events (a total of 69 typhoons, one for each year between 1945 and 2013, including Haiyan) that fall into each 20-knot interval along with the corresponding best-fitted Weibull distribution expressed by Eq 1. The Anderson–Darling (A–D) test (Stephens 1974) can be used to test whether a sample of data comes from a population with a specific distribution. Many researchers prefer to use the A–D test as it gives more weight to the tails than the Kolmogorov–Smirnov (K–S) test (Palutikof et al. 1999). The p value is calculated to be 0.870, and this indicates that the annual maximum wind data can indeed be modeled as a Weibull distribution with the parameters obtained.

Typically estimates of the 50-year wind speed return period require 10–20 years of observations (Palutikof et al. 1999). Therefore, the present analysis, based on 7 decades of data, would appear to be a reasonably long observation sample. However, it should be noted that a sample of extreme wind data exhibits a large variability. Therefore, the return values estimated with best-fitted distribution functions can vary considerably around the true values of population (Goda 2000).

The cumulative probability of the Weibull distribution can be calculated as follows,

Fig. 3 Total counts of annual maximum wind speeds between 1945 and 2013 along with the corresponding best-fitted Weibull distribution. The wind speed of Haiyan was estimated to be 165.8 knots at the time of landfall
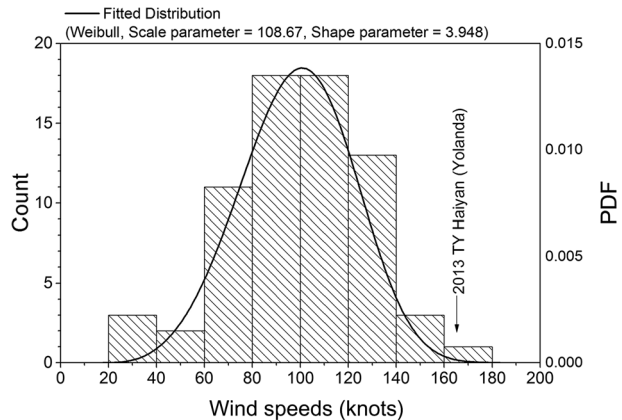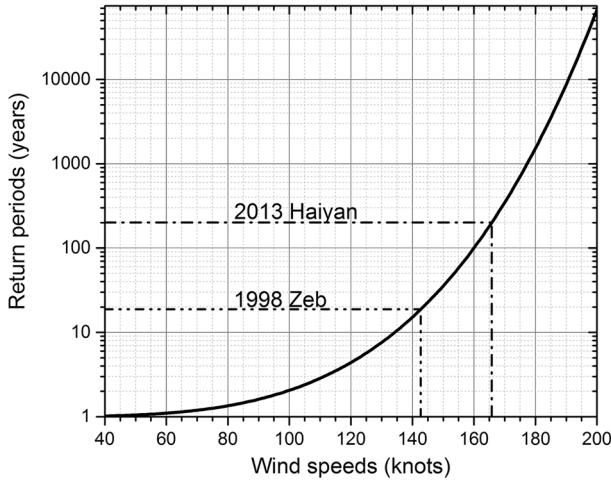
Fig. 4 Relationship between return periods and wind speeds derived from extreme value analysis using a Weibull distribution. The return period of Haiyan is estimated to be 200 years, while that of typhoon Zeb in 1998 is 19 years

$$F(x) = 1 - \exp\left\{-\left(\frac{x}{\beta}\right)^{\alpha}\right\} \quad x > 0 \qquad (2)$$

For the quantile X_T with return period T, the return period is given by $T = 1/\{1 - F(X_T)\}$. In Fig. 4, the relationship between return periods and wind speeds is drawn, as well as the two strongest typhoons ever to make made landfall the Philippines, namely 2013 Haiyan and 1998 Zeb. The return period of Haiyan was calculated to be 200 years, while that of 1998 Zeb is 19 years.

The methodologies introduced in this section are also applicable to examine the uniqueness of the other characteristics of TCs, such as the forward speed. The forward speed of Haiyan, which was as fast as 41 km/h, was estimated to have a 188-year return period, with the parameters of Eqs. (1) and (2) set to be $\alpha = 3.367$ and $\beta = 25.074$.

5 Sea surface temperature and Haiyan

It has long been recognized that sea surface temperatures (SSTs) play an important role in the intensification of TCs. However, the SST is not always a good indicator of whether an individual TC will intensify (Demaria and Kaplan 1993). The most intense storms occur over regions with the warmest SST; however, the presence of warm water is not a sufficient condition for intensification (Merrill 1987). Pun et al. (2013) suggest that the subsurface conditions in the WNP have become more favorable for typhoon intensification, though the SSTs have varied little over the last two decades.

The authors examined the trend of the SSTs over the past 7 decades around the Philippines to identify its implications on the generation of Typhoon Haiyan. The Extended Reconstructed Sea Surface Temperature (ERSST) v3b, which is a global monthly sea surface temperature analysis developed by NOAA, was used for this purpose. The monthly average SST data within the ocean basin from 6°N to 18°N and from 120°E to 140°E were
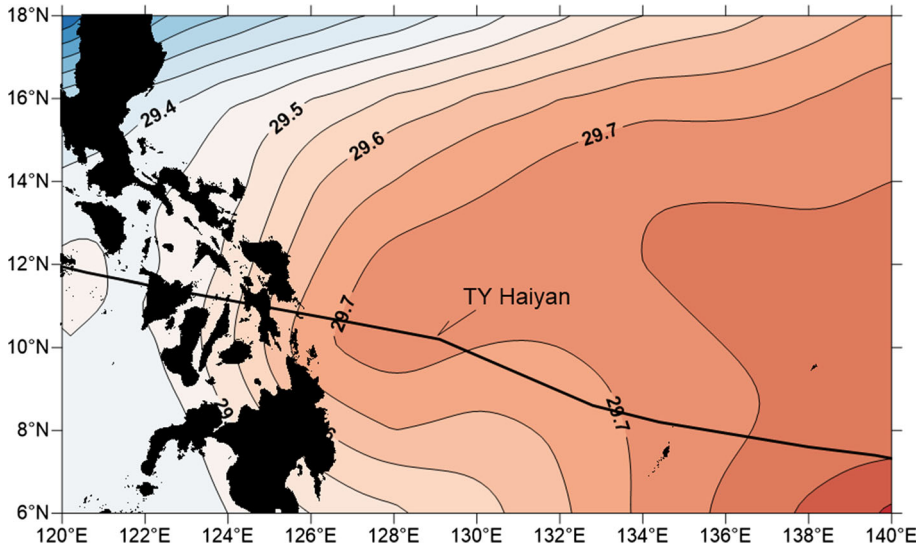
Fig. 5 SST over the ocean basin around the Philippines during the typhoon season of 2013, demonstrating that a warm pool extensively developed

extracted and processed to obtain an average temperature during the typhoon season in WNP (July–November). Figure 5 presents the SST distribution of the typhoon season of 2013 (the year in which Haiyan occurred), demonstrating how warm pool of water exceeding 29 °C developed over an extensive area of the basin, which can be considered to be an ideal situation to fuel energy to the storm. It is remarkable that the warmer surface extends westward in a tongue shape that touches Leyte Gulf, fitting very well with the actual course of Haiyan.

Figure 6 suggests that the SSTs around the Philippines have been increasing, particularly over the past two decades. It is also interesting to note that stronger typhoons tended to occur during recent warmer temperature years, which can be corroborated by the fact that 8 out of 10 strongest typhoons which made landfall on the Philippines in the last seven decades occurred in the last three decades, which showed relatively warmer SSTs. Figure 7 demonstrates that the SST in the year 2013 was remarkably high, reaching up to 29.6 °C, which was ranked in the 97th percentile in the period between 1945 and 2013. The second most powerful typhoon, Zeb in 1998, occurred during the warmest SST period in the last 7 decades. Although high SSTs appears not to be only factor that governs TC intensities, it is clear that warmer sea surfaces provide more thermodynamic energy to the atmosphere and allow for the generation or more intense TCs such as Haiyan and Zeb.

6 Discussion

Compared to other past typhoons in the WNP, the path which Haiyan took was almost the lowest in latitude among similar intensity events, starting around 6°N, where relatively few typhoons take place (Takagi et al. 2014). However, the number of TCs which made landfall in Leyte Island (as Haiyan did) was calculated to be once a year on average, which is more frequent than in the southern island of Mindanao, which typically experiences
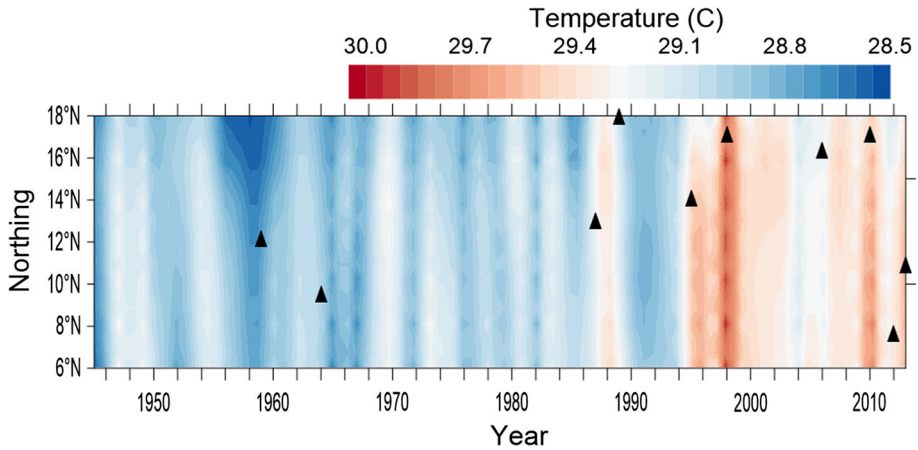
Fig. 6 Average SSTs of the typhoon season around the Philippines from 1945 to 2013. The contour was drawn by taking an average of the ERSST data within the basin from 120°E to 140°E. The triangular symbols specify the locations and years of the 10 strongest typhoons at the time of their landfalls, including Typhoon Haiyan in 2013 and Zeb in 1998
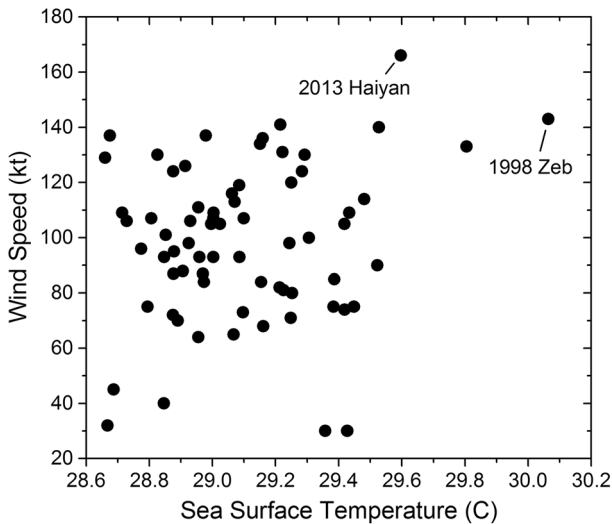
Fig. 7 Relation between wind speeds and SSTs of the typhoon season from 1945 to 2013, demonstrating that two strongest typhoons occurred during seasons of remarkably warm SSTs

typhoons only once every 2–7 years. Interestingly, as discussed previously, Haiyan struck the coast between latitudes 10°N–12°N, where the frequency of TC has been increasing in the past decades by around +0.02 times per year. Liu et al. (2009) indicate that the position of the Inter-Tropical Convergence Zone (ITCZ) shifted southwards in latitude between 1949 and 2005. While this could have contributed to a decrease in TC numbers over the WNP (Liu et al. 2009), it could be possible that it has helped to increase numbers in a relatively lower latitude zone within the WNP, such as Leyte and Samar Islands. Because

over 85 % of all TCs form within or just on the poleward side of the ITCZ (Gray 1975), the shift of the ITCZ southwards could cause an increase in TC numbers in a lower latitude basin. However, further studies would need to be conducted to corroborate this hypothesis.

One of the most unusual characteristics of Haiyan is that it was found to be the fastest typhoon in addition to the strongest typhoon in the past 7 decades. Apart from its statistical unusualness, this is very important from the point of view of disaster management. For example, local authorities in charge of disaster prevention need to prepare for a typhoon and warn inhabitants to evacuate. However, for the case a typhoon approaching at a very fast speed the time available for preparation would be reduced, and it appears necessary for disaster risk managers to factor into their plans contingencies for fast moving typhoons.

It should be also noted that the peak storm surge occurs before landfall with slower moving storms, while it occurs after landfall for faster moving storms (Jelesnianski 1972). Haiyan approached very quickly with a forward speed of 41 km/h toward Leyte. According to rainfall intensity detected by the Doppler radar system in Cebu Island (PAGASA 2013), the typhoon's center was positioned more than 50 km west to Tacloban when the storm surge was highest in Tacloban. In fact, a movie taken during the passage of Haiyan (iCyclone 2013) shows very strong wind around 7:00 A.M., when the typhoon made landfall at Tolosa in Leyte Island (about 20 km south from Tacloban), though extensive flood did not yet occur at that time. These observations corroborate that the peak storm surge indeed took place after landfall for the case of this fast moving storm, as do numerical simulations which shows that the peak storm surge occurred around 8:00–8:30 A.M. on November 8, 2013 in Tacloban (Takagi et al. 2014).

The discrepancy between the times when the peak wind and storm surge take place is expected to cause some difficulty for late evacuees since people would hesitate to leave their houses when there is extremely strong wind and heavy rain outside. Furthermore, Rego and Li (2009) demonstrated by a numerical experiment for Hurricane Rita that increasing forward speed increases peak surge heights while decreasing the inland volume of flood. Therefore, it is possible that the storm surge was substantially more pronounced due to the fast speed of Haiyan, which exacerbated the damage to coastal communities. All these issues help to explain the high mortality due to this event, which clearly surprised local residents, despite their frequent experiences with typhoons (Esteban et al. 2015).

The return period of a typhoon with a similar intensity to that of Haiyan was estimated to be 200 years, which is far less frequent when compared to the second strongest typhoon, Zeb in 1998, with a return period of 19 years. This arguably demonstrates the rarity of Haiyan compared with other TCs in the past 7 decades. Though the probability of reoccurrence of a typhoon of similar intensity would appear small, it should be recognized that a large magnitude of variability exists. In this study, the Weibull distribution was used to estimate the return periods. However, the adoption of the other fitting curves such as generalized extreme value distribution (GEV) would result in different return periods. Jagger and Elsner (2006) estimated the 100- and 500-year wind speeds for the entire US coast to be 157 and 168 knots, respectively, assuming a generalized Pareto distribution (GPD). Despite the difference in the distributions applied, it is interesting to note that the estimated 200-year wind speed for the entire coast of the Philippines in this study seems to be comparable with those estimations in the US. Therefore, engineers or planners in change of disaster management should keep in mind such uncertainties of predicted wind speed in order not to overlook the recurrence of an extremely strong typhoon in the not too distant future.

In fact, a news story posted in The Evening World (1912) reported a typhoon on November 25, 1912, where "fifteen thousand persons were probably killed and injured in a

Fig. 8 Devastation caused by the 1897 typhoon which struck Leyte Island (Algue 1897)

typhoon that swept the Philippine Islands … The typhoon swept the Visayas Islands and is said to have practically destroyed Tacloban". Algue (1897) also presents a number of photographs that demonstrate the devastations of several coastal towns in Leyte and Samar including Tacloban (Fig. 8) due to strong winds and possibly a storm surge in October 12, 1897. The course of this typhoon seems to be quite similar with the one Haiyan took. If these typhoons had a similar intensity with that of Haiyan, it could be concluded that the return period could actually be just one century or even less.

The relationship between TCs and climate can be subtle. Differences in the spatial and temporal scales are large (Elsner and Jagger 2013). Furthermore, long-term changes in trends due to climate change or other unforeseeable influences could alter patterns of frequency, track, and intensity of future TCs. In terms of intensity, some increase in the mean maximum wind speed of TCs is likely (+2 to +11 % globally) due to projected twenty-first century global warming, although increases may not take place in all tropical regions (Knutson et al. 2010). However, it is interesting to note that in terms of frequency warmer surface sea temperatures in the WNP may even lead to fewer TCs, that is, as warmer surface sea temperatures do not definitely lead to an increase in TC numbers (Liu et al. 2009). The analysis by Weinkle et al. (2012) also does not indicate significant long-period global or individual basin trends in the frequency or intensity of landfalling TCs. At present, the randomness inherent in natural weather and typhoon generation conditions can be considered to be more important than climate change from the point of view of disaster risk management (Nguyen et al. 2014b).

In contrast to tropical cyclone numbers, the theory governing tropical cyclone intensities appears to have a firmer foundation (Walsh et al. 2009). In this sense, the theory of

TC maximum potential intensity (MPI) could be used to define the maximum intensity that a TC may achieve for a given atmospheric and oceanic thermal structure. The most widely recognized investigations on MPI are those of Emanuel (1988) and Holland (1997). Although considerations based on the MPI should be useful when discussing climate change and TCs around the Philippines, it is outside of the scope of the present study.

7 Conclusions

Typhoon Haiyan, which devastated Leyte, Samar, and other islands of the Philippines on November 8, 2013, could be the deadliest and most expensive natural disaster in the history of the country. The present paper investigated the unusual characteristics of Haiyan based on a statistical analysis using JTWC best track data from 1945 to 2013. Particularly, the focus was placed on the statistics of TC landfalls in the Philippines. The wind speed at the time of landfall (165.8 knots) was found to be the strongest among 406 TCs in the last seven decades, 16 % faster than the second strongest typhoon (142.7 knots during Typhoon Zeb in 1998) in this period. A significant increase in TC landfall frequency (+0.02 times per year) in recent decades was found in the latitude zone between 10°N and 12°N, which encompasses Leyte Island.

The forward speed of Haiyan at the time of landfall, 41 km/h, was nearly twice as fast as the average speed of TCs. Haiyan could be considered the fastest typhoon in addition to the strongest intensity on record. A Weibull distribution was applied to estimate that the reoccurrence interval of a typhoon with a similar intensity to that of Haiyan is 200 years, which appears to be low compared to the second strongest typhoon on record (Zeb in 1998), which had a return period of 19 years.

The relationship between SST and TC occurrence was also investigated, with the results showing that the two strongest typhoons in recent times, Haiyan and Zeb, both occurred in seasons with remarkably warm SSTs.

The findings of the present research are expected to be used as important source of information by disaster risk managers in the design of structures against high winds or storm surges and in the elaboration of evacuation plans. Such considerations are clearly very important for the improvement of the resilience of coastal communities against TCs and could be considered as a "no-regrets" adaptation strategy against climate change, as regardless of whether TCs intensify or not it is clear that countries like the Philippines are still ill-prepared against present day disasters.

References

Algue PJ (1897) EL BAGUIO DE SAMAR Y LEYTE, The Manila Observatory

Bricker JD, Takagi H, Mas E, Kure S, Adriano B, Yi C, Roeber V (2014) Spatial variation of damage due to storm surge and waves during Typhoon Haiyan in the Philippines. J Jpn Soc Civil Eng Ser B2 (Coast Eng) 70(2):231–235

Demaria M, Kaplan J (1993) Sea surface temperature and maximum intensity of Atlantic tropical cyclones. J Clim 7:1324–1334

Elsner JB, Jagger TH (2013) Hurricane climatology: a modern statistical guide using R. Oxford University Press, New York

Emanuel KA (1988) The maximum intensity of hurricanes. J Atmos Sci 45(7):1143–1155

Esteban M, Valenzuela VV, Namyi Y, Mikami T, Shibayama T, Matsumaru R, Takagi H, Thao ND, de Leon M, Oyama T, Nakamura R (2015) Typhoon Haiyan 2013 evacuation preparations and awareness. Int J Sustain Future Hum Secur 3(1):37–45

Galvin JFP (2014) Editorial: the weather of 2013. Weather 69(11):287. doi:10.1002/wea.2456

Garcia-Herrera P, Ribera RP, Hernandez E, Gimeno L (2007) Northwest Pacific typhoons documented by the Philippine Jesuits, 1566–1900. J Geophys Res 112:D06108. doi:10.1029/2006JD007370

Goda Y (2000) Random seas and design of maritime structures. World Scientific, Singapore, 443 p

Gray WM (1975) Tropical cyclone genesis. Atmospheric science paper no. 234, Colorado State University, 121 p

Hennessey JP Jr (1977) Some aspects of wind power statistics. J Appl Meteorol 16:119–128

Holland GJ (1997) The maximum potential intensity of tropical cyclones. J Atmos Sci 54:2519–2541

iCyclone (2013) Super Typhoon HAIYAN (YOLANDA): Eyewall Video. http://www.icyclone.com/. Accessed 20 Dec 2013

Jagger TH, Elsner JB (2006) Climatology models for extreme hurricane winds near the United States. J Clim 19:3220–3236

Jelesnianski CP (1972) SPLASH I landfall storms. NOAA technical memorandum NWS. TDL-46, 56 p

Knutson TR, McBride J, Chan J, Emanuel K, Holland G, Landsea C, Held I, Kossin J, Srivastava A, Sugi M (2010) Tropical cyclones and climate change. Nat Geosci 3(3):157–163

Kubota H, Chan JCL (2009) Interdecadal variability of tropical cyclone landfall in the Philippines from 1902 to 2005. Geophys Res Lett 36:L12802. doi:10.1029/2009GL038108

Lin II, Pun IF, Lien CC (2014) "Category-6" supertyphoon Haiyan in global warming hiatus: contribution from subsurface ocean warming. Res Lett, Geophys. doi:10.1002/2014GL061281

Liu C, Ma L, Liu YL, Luo Z, Lei X, Zhou X, Wang D, Xu H (2009) Linking tropical cyclone number over the western north Pacific with sea surface temperatures. In: Elsner JB, Jagger TH (eds) Hurricanes and climate change. Springer, New York, pp 205–215

Merrill RT (1987) An experiment in statistical prediction of tropical cyclone intensity change. NOAA tech memo, NWS NHC-34, 34 pp

NDRRMC (2014) Effects of Typhoon "YOLANDA" (HAIYAN), SitRep no. 107, 6 March 2014

Nguyen DT, Takagi H, Esteban M (eds) (2014) Coastal disasters and climate change in Vietnam. Engineering and Planning Perspectives. Elsevier, pp 424, ISBN-13:978-0128000076

Nguyen P, Sellars S, Thorstensen A, Tao Y, Ashouri H, Brithwaite D, Hsu K, Sorooshian S (2014b) Satellites track precipitation of super Typhoon Haiyan. Eos. doi:10.1002/2014EO160002

PAGASA (2013) Weather radar reflectivity loop of Haiyan's landfall on Leyte Island. http://en.wikipedia.org/wiki/Typhoon_Haiyan#mediaviewer/File:Radar_loop_of_Typhoon_Haiyan_(Yolanda)_making_landfall_on_Leyte_Island.gif. Retrieved 7 Nov 2013

Palutikof JP, Bradson BB, Lister DH, Adcock ST (1999) A review of methods to calculate extreme wind speeds. Meteorol Appl 6:119–132

Pun IF, Lin II, Lo MH (2013) Recent increase in high tropical cyclone heat potential area in the Western North Pacific Ocean. Geophys Res Lett 40:4680–4684

Rego JL, Li C (2009) On the importance of the forward speed of hurricanes in storm surge forecasting: a numerical study. Geophys Res Lett 36:L07609. doi:10.1029/2008GL036953

Scheitlin KN, Elsner JB (2009) A track-relative climatology of Eglin Air Force Base Hurricanes in a variable climate. In: Elsner JB, Jagger TH (eds) Hurricanes and climate change. Springer, New York, pp 217–229

Shoemaker DN (1991) Characteristics of tropical cyclones affecting the Philippine Islands, NOCC/JTWC Technical Note, 91–1, 35 p

Sorensen RM (1997) Basic coastal engineering, 2nd edn. Springer, New York. ISBN:978-1-4757-2667-1, 301 p

Stephens MA (1974) EDF statistics for goodness of fit and some comparisons. J Am Stat Ass 69:730–737

Takagi H, Esteban M, Shibayama T, Mikami T, Matsumaru R, Nguyen DT, Oyama T, Nakamura R (2014) Track analysis, simulation and field survey of the 2013 Typhoon Haiyan storm surge. J Flood Risk Manag. doi:10.1111/jfr3.12136

Takagi H, De Leon M, Esteban M, Mikami T, Nakamura R (2015) Storm surge due to 2013 Typhoon Yolanda (Haiyan) in Leyte Gulf, the Philippines. In: Esteban M, Takagi H, Shibayama T (eds) Handbook of coastal disaster mitigation for engineers and planners. Elseveir, pp 133–144

The Evening World (1912) 15,000 victims of Typhoon in the Philippines, New York. November 29, 1912

Walsh K, Karoly D, Nicholls N (2009) Detection and attribution of climate change effects on tropical cyclones. In: Elsner JB, Jagger TH (eds) Hurricanes and climate change. Springer, New York, pp 1–20

Weinkle J, Maue R, Pielke R Jr (2012) Historical global tropical cyclone landfalls. J Clim 25:4729–4735. doi:10.1175/JCLI-D-11-00719.1