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Enhanced Pacific Ocean Sea Surface Temperature and Its Relation to Typhoon Haiyan

ABSTRACT

Typhoon Haiyan, which devastated the Visayan Islands in the Philippines on November 8, 2013 was recorded as the strongest typhoon ever-observed using satellite data. Typhoons in the region usually originate from the mid-Pacific region that includes the Warm Pool, which is regarded as the warmest ocean surface region globally. Two study areas were considered: one in the Warm Pool Region and the other in the West Pacific Region near the Philippines. Among the most important factors that affect the strength of a typhoon are sea surface temperature (SST) and water vapor. It is remarkable that in November 2013 the average SST in the Warm Pool Region was the highest observed during the 1981 to 2014 period while that of the West Pacific Region was among the highest as well. Moreover, the increasing trend in SST was around 0.20ºC per decade in the warm pool region and even higher at 0.23ºC per decade in the West Pacific region. The yearly minimum SST has also been increasing suggesting that the temperature of the ocean mixed layer is also increasing. Further analysis indicated that water vapor, clouds, winds and sea level pressure for the same period did not reveal strong signals associated with the 2013 event. The SST is shown to be well-correlated with wind strength of historically strong typhoons in the country and the observed trends in SST suggest that extremely destructive typhoons like Haiyan are likely to occur in the future.

Key words: *Typhoon Haiyan, SST, Warm Pool*

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INTRODUCTION

Unusually strong and highly destructive typhoons have occurred worldwide during the last few decades. Among these are Hurricane Katrina that devastated New Orleans in 2005 and Hurricane Sandy that wreaked havoc to many cities in the eastern US, including New York City, in 2011 (*Halverson and Rabenhorst 2013*). Many powerful typhoons have reached the Philippines in recent years but there was none stronger than that of Typhoon Haiyan (known locally as Typhoon Yolanda), which caused vast destruction in many towns in the Visayan Region including Tacloban, Leyte, Philippines on November 8, 2013. The wind velocity for Typhoon Haiyan is the record high worldwide as recorded by satellites reaching a maximum of 313 km h^{-1} (*JTWC 2013*) which exceeded the previous record of 305 km h^{-1} held by Hurricane Camille that struck Mississippi in the US in 1969. The Dvorak index, which is normally used by meteorologist to quantify the strength of a typhoon was 8.1 for Haiyan compared to a previous record high of 8.0 (*Dvorak 1975*).

Anthropogenic global warming is now regarded as unequivocal (*IPCC 2007; IPCC 2013*) and incontrovertible (*APS 2007*). It is expected to cause an increase in sea surface temperature and an acceleration of hydrological cycles. It has been postulated that increases of sea surface temperature would lead to increases in hurricane frequency and intensity (*Trenberth 2005*). However, confirmation of such a relationship is still a challenge especially since modeling studies by different investigators show a general lack of consistency in the projections. The projection that warming would cause an increase in hurricane frequency is especially controversial but there appears to be a consensus that increases in ocean surface temperature will cause an increase in hurricane intensity and destructiveness (*Emanuel 2005; Knutson et al. 2010*). Nevertheless, there is room to be cautious because of considerable interannual and interdecadal variations in tropical cyclone activities that may affect the accuracy of these projections (*Zhao et al. 2014*).

The purpose of this study is to gain insights into the unusual strength of Typhoon Haiyan through analyses of environmental factors affecting a cyclone before and during the period using primarily observational data from space. Typhoon Haiyan was the most destructive on record in the Philippines and conservative estimates indicate that it caused more than $2B in damages to the province of Leyte and surrounding areas (*NDRRMC 2014*). A good understanding of the origin of the typhoon and the key triggers for such a strong event is thus of paramount importance. A question of interest is if an enhanced SST that may be related to global warming has an important role in the occurrences of strong tropical cyclones in the Western Pacific.

METHODOLOGY

Most of tropical typhoons that hit the Philippines originate from the Central Pacific Ocean around a general area near the equator and 160º E. This general area is also the location of the Pacific Warm Pool, which is among the warmest ocean area in the globe. Sea surface temperature (SST) data and associated parameters in the region were compiled and analyzed. In particular, the possible role of SST in the occurrence of the extremely powerful Haiyan typhoon in 2013 was carefully evaluated. The strategy is to examine anomalies and trends in SST using more than 30 years of data and assess what was unusual during the period especially in 2013. Other parameters are also considered including water vapor, clouds, winds and sea level pressure as well as precipitation. Two areas were selected for this study, namely: the Warm Pool Region and the Western Pacific Region, which is the region east and adjacent to the Philippines. The average SST in the Warm Pool Region provides the means to evaluate ocean conditions when typhoons occur while the Western Pacific Region provides ability of the ocean to sustain the strength of the typhoon.

The SST data set that has been most often used by researchers in modeling and process studies is the Reynolds' data set (*Reynolds et al. 2002*). The data have been based originally from ship, buoy, mooring and other *in-situ* data and was previously available at a relatively coarse resolution of 2.5° latitude by 2.5° longitude. Some key problems for this data are the poor resolution and the lack of comprehensive coverage causing changes in the accuracy from one region to another. The advent of satellite remote sensing made it possible to obtain SST globally and at a much higher spatial and temporal resolution. For example, time series thermal infrared data from National Oceanic and Atmospheric Aadministration (NOAA)/Advanced Very High Resolution Radiometer (AVHRR) have been available since 1981 and since 2000 from National Aeronautics and Space Administration (NASA)/Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS). Both sensors provide SST at 1 to 5 km resolution during cloud free conditions. The SST data from AVHRR and MODIS in the polar regions have been retrieved (*Comiso 2010*). However, since the time series of this data for the Philippines is still the process of being produced, this study instead used an enhanced version of the Reynolds data set that incorporates AVHRR SST data and is generated at a vastly improved resolution of 0.25° latitude by 0.25° longitude. The data is now referred to as NOAA high resolution data provided by NOAA/OAR/ESRL/PSO and can be downloaded from the website (*NOAA/OAR/ESRL/PSO 2014*). Data from 1981 was chosen to be analyzed since it is over this time period when comprehensive data are available and the quality of the data are similarly generated.

As for the other parameters, analysis of cloud data from MODIS to evaluate the effects of clouds was done. The parameter is cloud fraction, which is the fraction of the time that a certain area has clouds within a given time. The MODIS data is used because of relatively good accuracy and it provides the most appropriate data set for this study. Also, NCEP reanalysis data (*Kalnay et al. 1996*) were used to study the impacts of wind and pressure. Satellite scatterometer data were assimilated in the reanalysis for optimum accuracy. Statistics on typhoon frequency and strength were obtained from data assembled by the Japan Meteorological Agency, the Australian Bureau of Meteorology and the U. S. Joint Typhoon Warning Center (*Digital Typhoon 2015; JTWC 2015)*.

RESULTS AND DISCUSSION

Satellite Observations of Typhoon Haiyan and Associated Precipitation

Satellite sensors play an important role in monitoring the location and strength of a typhoon. Typhoon Haiyan was observed both by geosynchronous sensors that provide continuous coverage, and polar orbiting sun-synchronous sensors that provide observations a few times a day. The magnitude and character of the cyclone was observed in the visible channel by the EOS/Aqua/MODIS sensor early morning on November 7, 2013 shortly before it hit the Visayan Island of Leyte (**Figure 1a)**. At this time, it is apparent that the storm was already affecting land although the eye of the storm was still a few hundred kilometers away. The storm as observed at the same time by the same sensor but in the thermal infrared channel is illustrated in **Figure 1b**. Two subsequent orbits of the satellite are used for these figures and the data gaps between these orbits are apparent in the images. In both images the location and size of the eye of the storm are evident and the diameter of the cyclone, as shown, is estimated to be around 800 km or more indicating the vastness of the affected area. The infrared-channel image provides additional information including the cloud top temperature and the approximate amount of precipitation that was associated with the storm. The availability of a time series of such images and data from ground-based Doppler radars enabled an accurate tracking of the storm and the quantification of the detailed characteristics of the cyclone.

A typhoon is usually accompanied by abnormal amount of precipitation that can also be monitored by satellite sensors. The amount of accumulated rain from November 2 to November 12, 2013 was inferred from the Tropical Rainfall Measuring Mission (TRMM)(**Figure 2**). It is apparent that a strong typhoon, like Haiyan, is accompanied not just by strong winds but also very strong precipitation events. The data indicate that one of the most affected regions was Leyte with the average rainfall being more than 400 mm during the period. Precipitation has been observed to usually intensify on account of the influence of a strong El Niño and the Atlantic multi-decadal oscillation (AMO) in the Atlantic Ocean (*Wang et al. 2013*). During Haiyan, there was no El Niño but there was a La Niña-like condition.

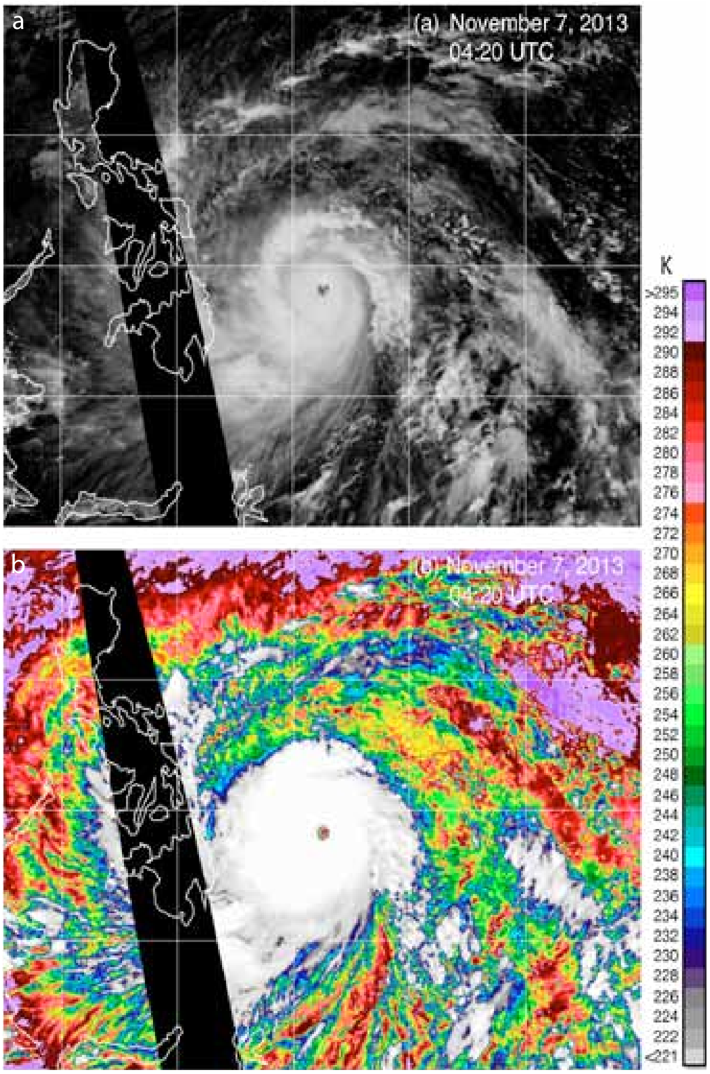

Figure 1. Spatial characteristics of the typhoon Haiyan on November 7, 2013 as observed by Aqua/MODIS (a) in the visible channel and (b) in the infrared channel. (Courtesy of NASA).

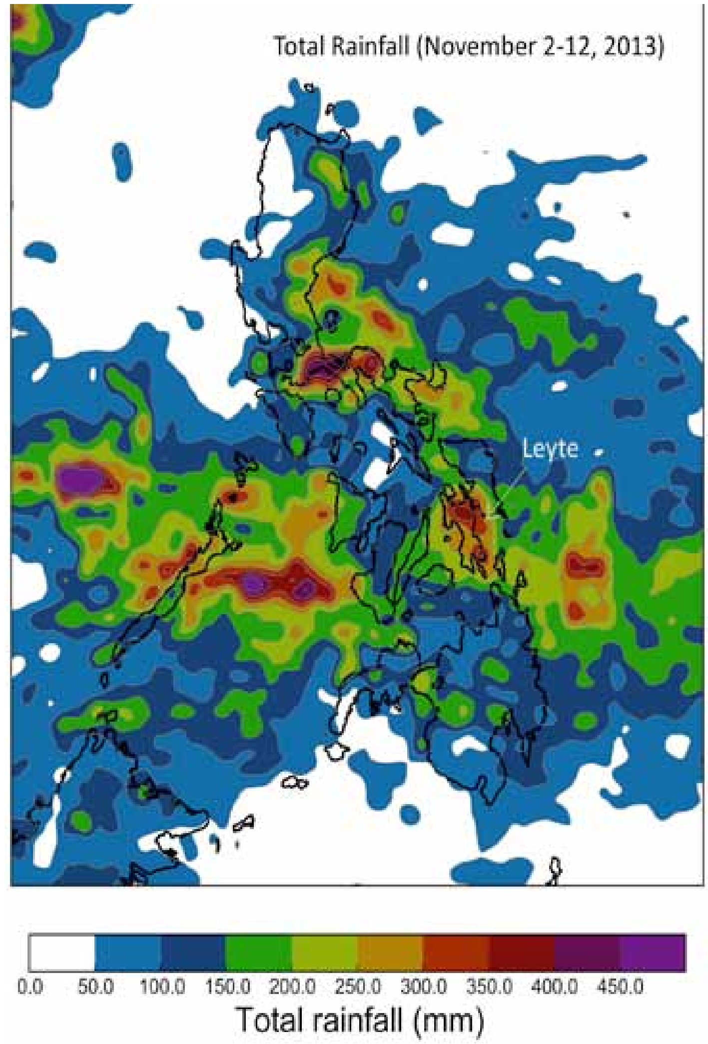

Figure 2. Accumulated total rainfall in the Philippines and vicinity as observed by the TRMM satellite for the period November 2-12, 2013. (Courtesy of NASA).

Changes and Trends in SST at the Warm Pool and Western Pacific Ocean

The spatial distribution of SST in the Western Pacific Ocean on November 5, 2013 when the cyclone was newly formed and on November 7, 2013 shortly before typhoon Haiyan hit land in the Philippines is depicted in the color coded images (**Figures 3a** and **3b)**. It is apparent that SSTs were relatively high at around 10°S to 20°N with the highest values located in an area around 162°E and 2°S that is part of the Warm Pool region. Wind vectors from NCEP reanalysis data illustrate the direction and strength of winds including those surrounding the cyclone during the two periods (**Figure 3a** and **3b**).

Figure 4a is a plot of monthly averages of SST in the Warm Pool region for the period August 1981 to April 2014. The study area, which is referred as the Warm Pool Region, is the area from 150°E to 170°E and from 10°S to 10°N. Large monthly and interannual fluctuations of SST are evident but it is apparent that the high and low values each year varies considerably from one year to another. It is remarkable that the series of monthly SSTs in the Warm Pool Region shows that the year 2013 is an unusual year. The data points for November each year, which are plotted in red, clearly shows that the average SST in November 2013 stands out as the highest monthly SST in the region since 1981.

November 2013 is the month when the typhoon Haiyan occurred. It is highly unlikely that the occurrence of Haiyan during the period was just a coincidence especially since previous studies have indicated that SST is one of the key variables that can contribute to an enhanced intensity of a typhoon (*Emanuel 2005; Knutson et al. 2010*). The plot does not show a strong seasonality (compared to that for the Western Pacific Region) because the study area straddles both the Northern and Southern Hemisphere. Due to the mismatch of the seasons in the Northern and Southern Hemispheres, the seasonal changes were smeared out because

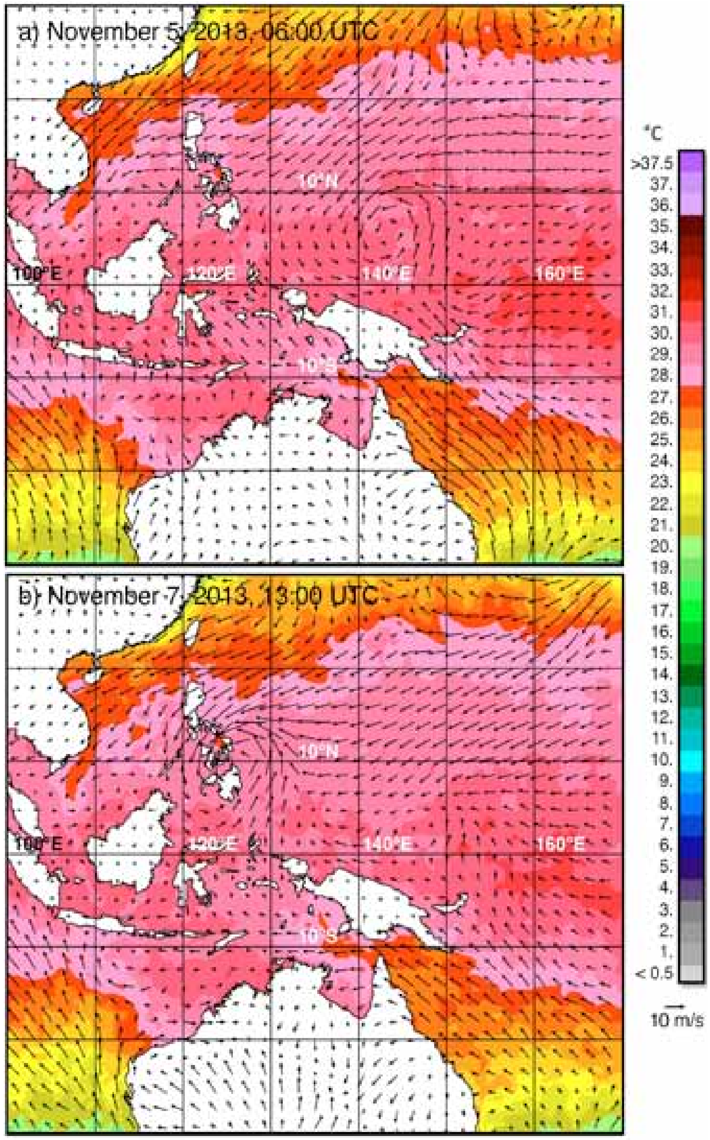

Figure 3. Color-coded map of SST as derived from the high resolution NOAA SST data (Reynolds, 2005) data and wind vectors as derived from NCEP reanalysis data for (a) October 2013 and (b) November 2013.

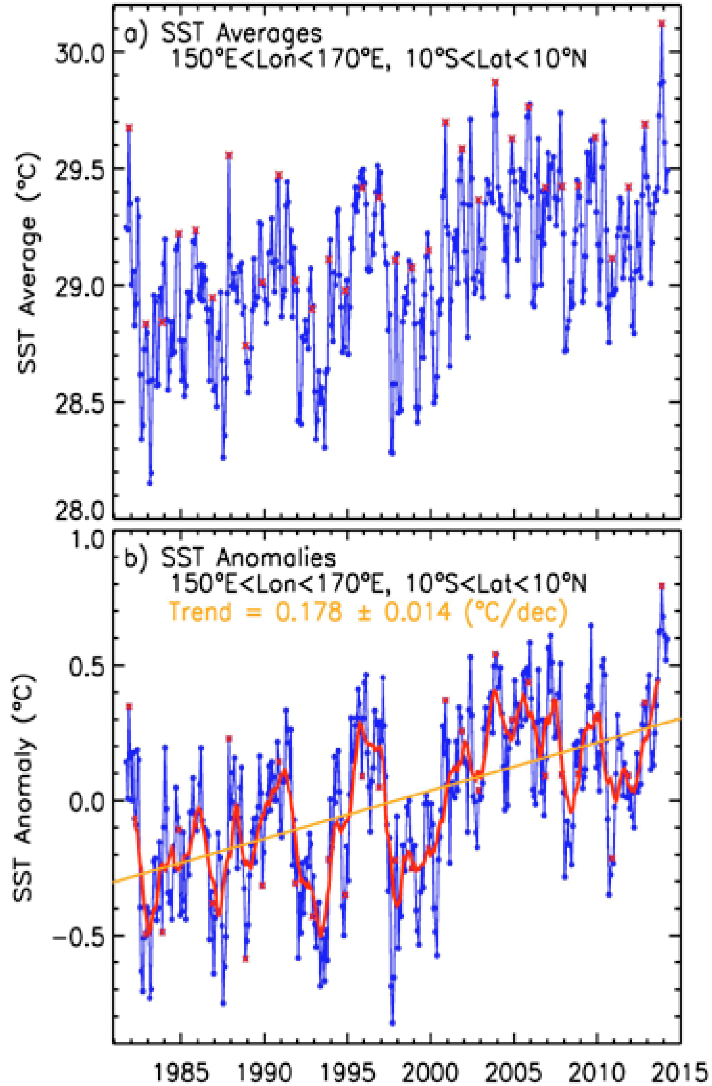

Figure 4. (a) Monthly average SSTs and (b) monthly anomalies of the SSTs in the Warm Pool Region. Red x mark represents November data for each year while the red line represents an 11-day running average.

the peaks and dips for the two hemispheres are different.

It is also interesting that the months immediately preceding or following this record month (October or December) are also shown to be among the highest monthly SSTs during the period. This indicates that it was persistently warm in the region during the year. The peak for November 2013 is also significantly higher (at 30.1°C) compared to that of the second highest (29.8°C) in November 2003. It is apparent from the plot that there were only a few months with average monthly temperatures above 29.2 °C in 1980s and 1990s while there were many more in 2000s. The occurrence of relatively high SSTs in the recent decade may help explain why there has been many more strong typhoons reaching the Philippines in the recent decade compared withthe previous decades (*Comiso et al. 2014*).

To quantify the yearly changes, identify unusual monthly values, and be able to estimate the trends, monthly anomalies of SST for the same period (1981 to 2014) are presented in **Figure 4b**. The anomalies were derived by taking the differences of the average temperature for each month and the climatological average for the same month. In this study, a climatological monthly average is simply the average of all data during the month that are available from August 1981 to April 2014. Also shown (in red line) are 10-month running averages to identify periods of high and low anomalies and to qualitatively assess overall inter-annual changes. A linear regression analysis on the monthly anomalies yielded a trend in monthly temperature of 0.20 ± 0.01 °C per decade. This trend for the Warm Pool Region is significantly greater than the 0.15 °C per decade previously cited for tropical SSTs (*Webster 2005*). The anomalies are used for trend analysis because they provide more accurate trends than the monthly average data that have large seasonal fluctuations.

Trend analysis using yearly averages yields approximately the same result but larger statistical error. The positive trend in SST is a concern because the current values are already high and the trend suggests higher SSTs and even stronger typhoons for the future. Some precautions are needed in this regard since some studies on the correlation of SSTs (using NCEP reanalysis data) in a different area of the Pacific Ocean with typhoons in the Northwestern Pacific Ocean indicate that other factors like the occurrences of El Niño and La Niña need to be considered (*Chan and Liu 2004*).

Color coded maps of the distributions of monthly temperature anomalies for the months of October and November 2013 (**Figures 5a** and **5b**) were used to visualize the extent of warming and examine the spatial coverage and location of anomalously warm temperatures during the period. It is clear that the region of unusually high temperatures is near the equator in the Warm Pool Region and the area of high temperature region increased from October to November indicating a trend to warmer temperatures during the period.

The Western Pacific Ocean region near the Philippines also shows only a slight increase in sea surface temperature. It is interesting that the data exhibit large spatial variability with mainly negative anomalies north of 20°N. Such large variability in surface temperature has been observed previously (*England et al, 2014*), which is in part expected considering the complexity of the atmospheric circulation system in the region. The negative anomalies also compensate for the positive anomalies and explain the relatively modest increase in SST in the entire Pacific Ocean region reported in recent years (*England et al., 2014*). Such negative anomalies would compensate for the high positive anomalies observed in the tropical regions.

Figure 6a is a corresponding plot of monthly averages of SST in a selected study region of the Western Pacific Ocean that includes the Philippine Sea. The study area (which will now be referred to as the Western Pacific Region) is the region within the boundary 128°E to 143°E and 3°N to 18°N. As indicated earlier, the seasons for each year are well defined since all the data points are from the same hemisphere. Although the highest monthly average temperature in the region did not occur in 2013, the values in 2013 were among the highest during the 1981 to 2014 period. The peak temperature for each year is also different in the region and occurs in August or September instead of November. It is important to note, as discussed below, that the minimum values for each year has been increasing and are generally higher in the recent decade than in the previous ones.

The monthly SST anomalies apparently show that the highest value did not occur in 2013 but occurred earlier in 1998, instead (**Figure 6b**). The latter is likely related to the occurrence of a strong El Niño that year. However, the peak value of the running averages (in red) occurred in 2013 indicating the persistence of warming during the year. It is also remarkable that the trend in SST in the Western Pacific Region is even more positive at 0.23 ± 0.02 °C per decade than in the Warm Pool Region during the 1981 to 2014 period. The running averages (in red) also indicate that the highest values occurred in 2013.

It has been pointed out that the changes in the temperature of the ocean mixed layer is important (if not more important) to detect in connection with the strength of typhoons (*Pun et al. 2013*). In **Figures 4a** and **6a**, it is apparent that the minimum SST values for each year are

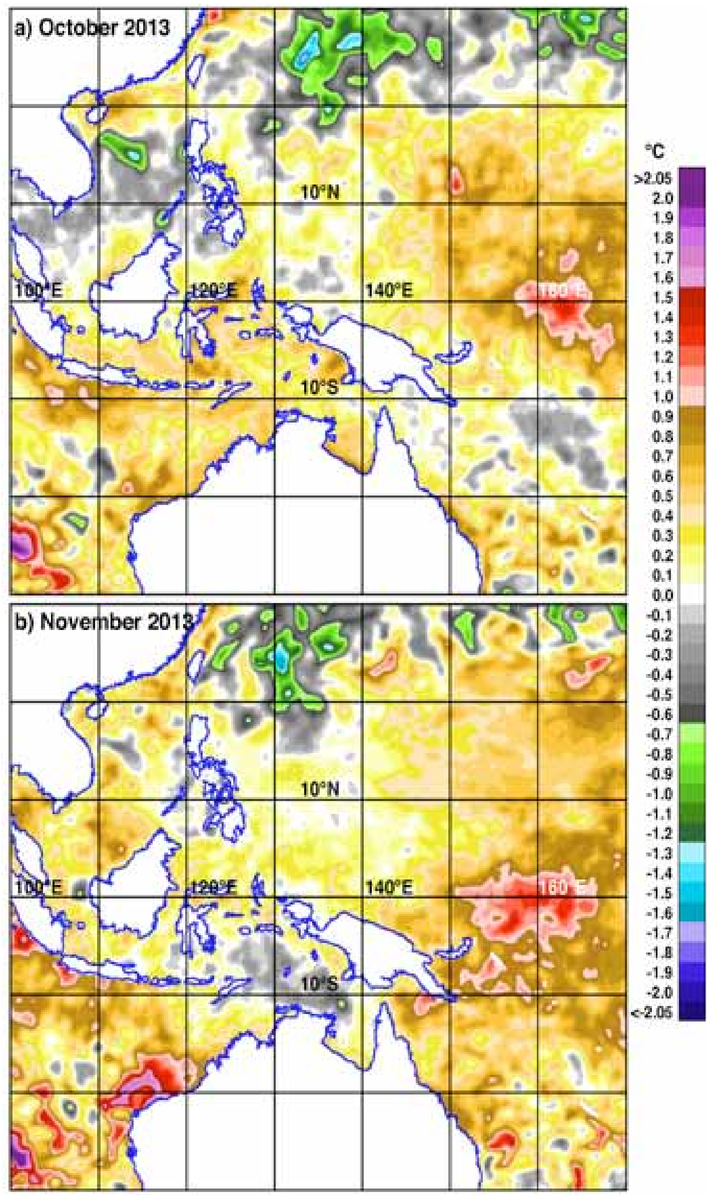

Figure 5. Color coded map of SST anomalies in the Pacific Region on (a) October 2013 and (b) November 2013.

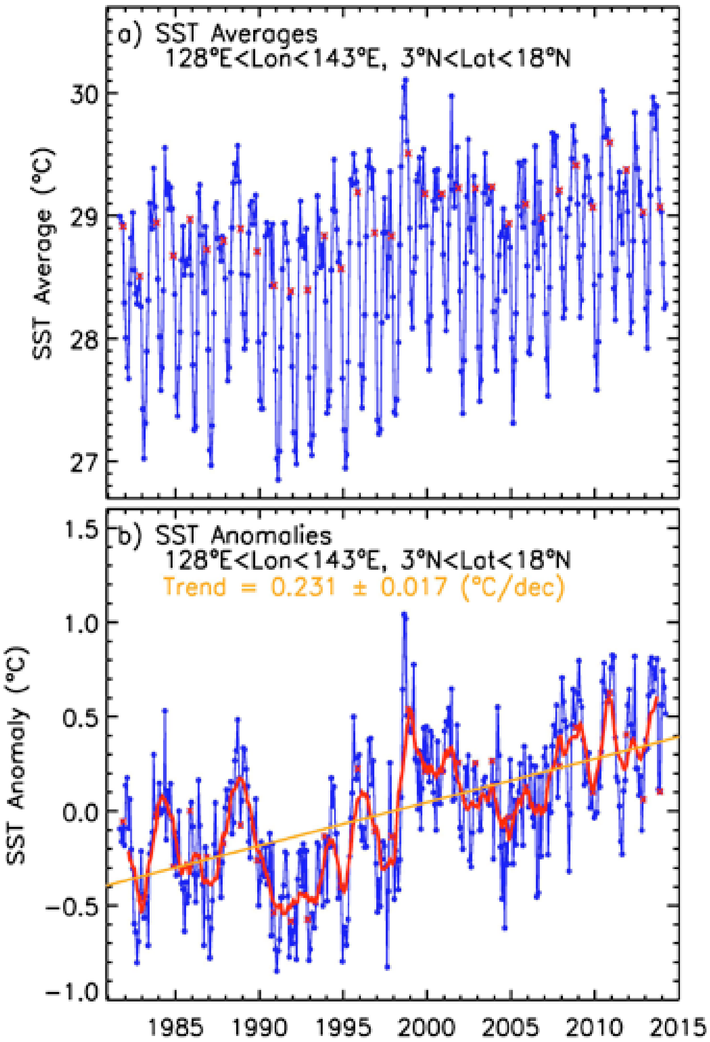

Figure 6. (a) Monthly average SSTs and (b) monthly anomalies of the SSTs in the Western Pacific Region.

more elevated in the recent decade than in earlier decades. The significance of such an increase is that it is indicative that the mixed layer temperature would be expected to be increasing as well. Higher temperatures for the mixed layer would cause a conditioning effect that keeps the temperature of the top layer from reaching the previously lower minimum SSTs. The SST as measured by satellite thermal infrared sensors is just the surface (skin depth) temperature but the values are affected not just by changes in the atmospheric temperature but also by the temperature of the mixed layer. The persistence of higher SST values is indicative of a conditioning that is likely associated with a relatively higher temperatures of the mixed layer in the recent decade compared to those in previous ones. Such apparent increase in mixed layer temperature is consistent with empirical studies indicating recent increases of mixed layer temperature in the Western Pacific Ocean that may be responsible for stronger typhoons in recent years (*Pun et al. 2013*).

Quantitative analysis of the minimum and maximum values of the monthly SSTs per year are presented in plots for the Warm Pool Region (**Figure 7a** and **7b)** and for the Western Pacific Region (**Figure 7c** and **7d**). What stands out in this set of plots is the record high value for SST in 2013 in the Warm Pool Region (**Figure 7b**). No other monthly value in 2013 stands out. It is apparent, however, that the yearly values show positive trends of about 0.2 ºC per decade in all cases. The trend is actually highest for the minimum SSTs in the Western Pacific Region where the trend is 0.24 ± 0.06 °C per decade. Again, this is indicative a conditioning is occurring in the mixed layer and that the average temperatures of the mixed layer in the two regions are likely increasing.

More rigorous studies need to be done for attribution but the relationship of maximum wind speed during some of the most destructive typhoons in the Philippines in recent history with sea surface temperatures at the Warm Pool and Western Pacific Regions (**Figure 8a** and **8b)**. The data used in **Figure 8** were taken from the Joint Typhoon Warning Center of the U.S. Naval Observatory (*JTWC 2015*) and the study is confined to the period 1981 to 2013. The plot shows some scatter of the data points but a relatively strong correlation (0.7) of the peak wind velocity of these typhoons with sea surface temperature in the Warm Pool Region where these typhoons usually originate. The correlation of 0.4 in the Western Pacific Region is not as high but also significant. Statistical studies also show that the frequency of typhoons with associated wind speeds of at least 150 km hr^{-1} have also been increasing with the number being 50 out of 169 (or 29.6%) for 1984 to 1993, 43 out of 141 (or 30.5%) for 1994 to 2003 and 67 out of 160 (or 41.9%) for the 2004 to 2013 periods. The data used in this analysis originated from the Japan Meteorological Agency and the Bureau of Meteorology of Australia (*Digital Typhoon 2015*). The increases in SST may indeed have an important role in causing not only unusually strong typhoons but also a larger percentage of them.

Variations and Trends in Other Environmental Parameters

The other environmental parameters that may be related to the strength of a typhoon are water vapor, sea level pressure, and cloud cover. Higher SSTs have been associated with higher water vapor concentration in the lower troposphere (*Trenberth 2005*). To gain insights into the effect of water vapor, monthly averages of water vapor in the atmosphere are derived from satellite data in the Warm Pool and Western Pacific Regions (**Figure 9a).** In both regions, the monthly averages of water vapor show large yearly variability and slightly elevated values for 2013 but not anomalously high. The trends were also estimated using monthly anomalies shown in and are slightly positive at 0.68 ± 0.23 kg m^{-2} per decade and 1.28 ± 0.19 kg m^{-2} per decade in the Warm Pool and Western Pacific Regions, respectively

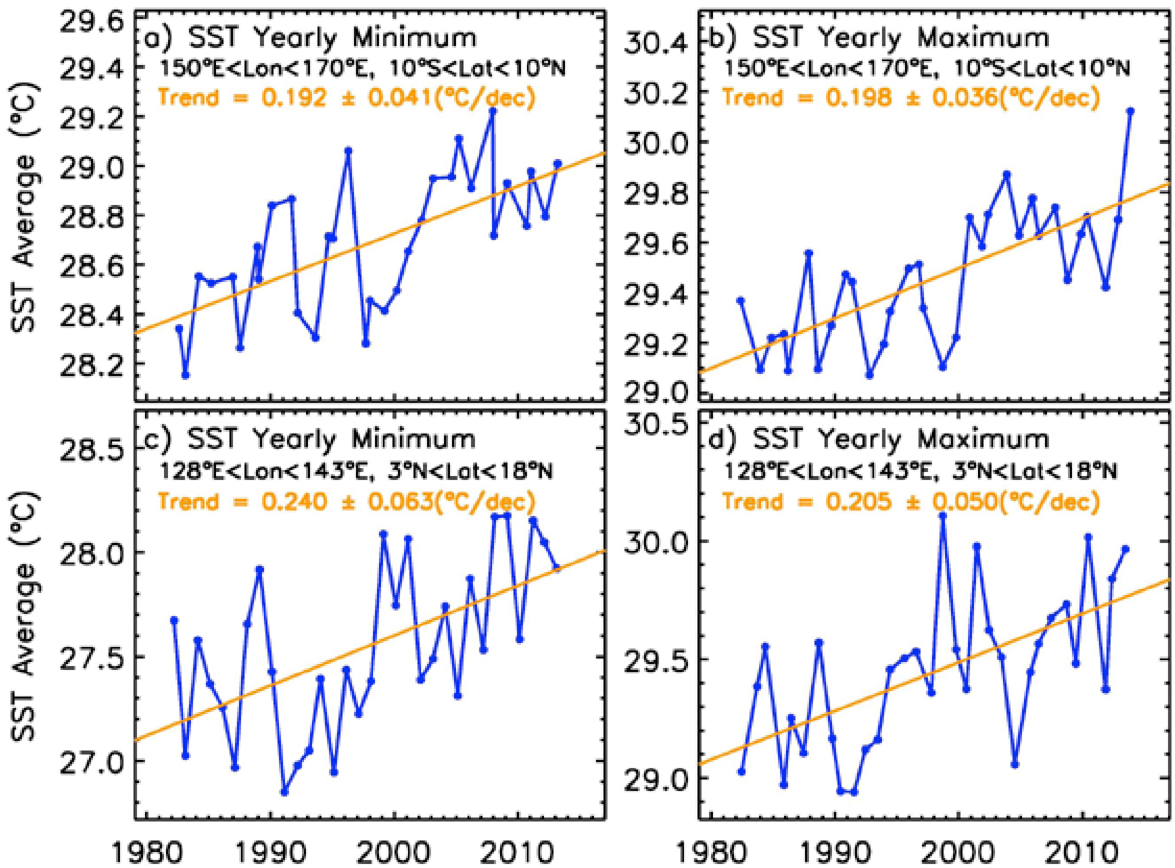

Figure 7. Minimum and maximum SSTs in Warm Pool Region (a, b) and in the Western Pacific Region (c, d).

(**Figures 9b** and **9d**). Such trends are consistent with the positive trends in SST but it appears that water vapor in the two regions are not exceptionally high in 2013.

It is apparent that the latitude band between 15°S and 15°N are relatively low pressure regions compared to surrounding areas (**Figure 10a** and **10b**). Monthly anomaly maps in October and November 2013 (**Figure 10c** and **10d**) were used to assess how typical the sea level pressures during the period. As before, the anomaly maps were estimated using the averages of August 1981 to April 2014 data as the baseline. It appears that sea level pressures were anomalously low in the Western Pacific Region in October and relatively high in November. This indicates that from one month to another, there was a significant change in sea level pressure in the region as would be expected during the occurrence of a typhoon (*Trenberth 2005*).

The climate system is heavily influenced by the persistence and distribution of clouds, as seen in the cloud cover fractions in October and November 2013 (**Figures 11a** and **11b**). It is apparent that the cloud cover in October was a lot more dense and more persistent than in November in the Warm Pool and Western Pacific Regions. This is in part because the typhoon occurred in early November and there are usually more clear skies and less clouds over an area after a big storm is over. Clouds have a cooling or warming effect

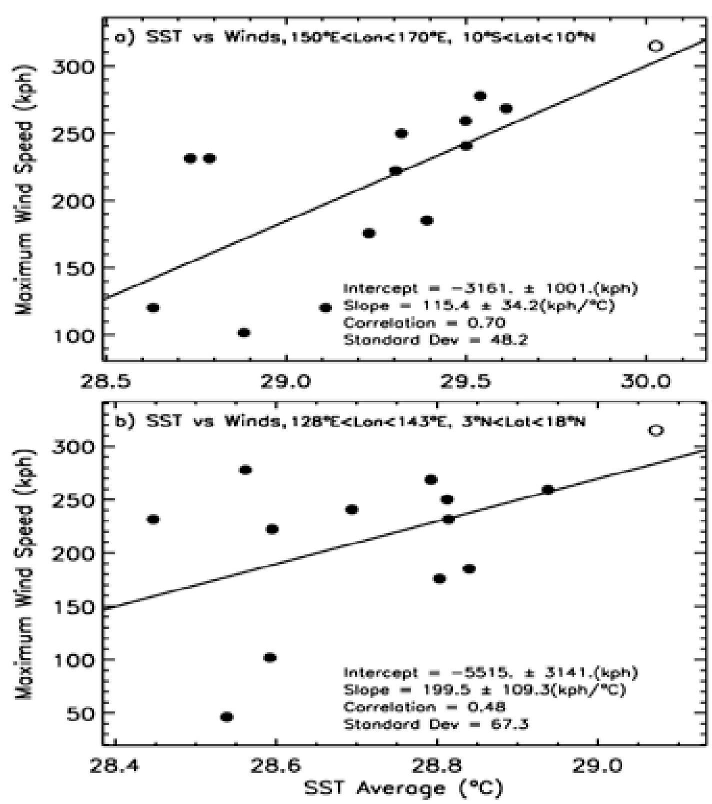

Figure 8. Scatter Plots: SST versus Winds in the (a) Warm Pool Region and (b) Western Pacific Region during the occurrence of powerful typhoons in the Philippines. The data point in open circle in the top right represents Typhoon Haiyan.

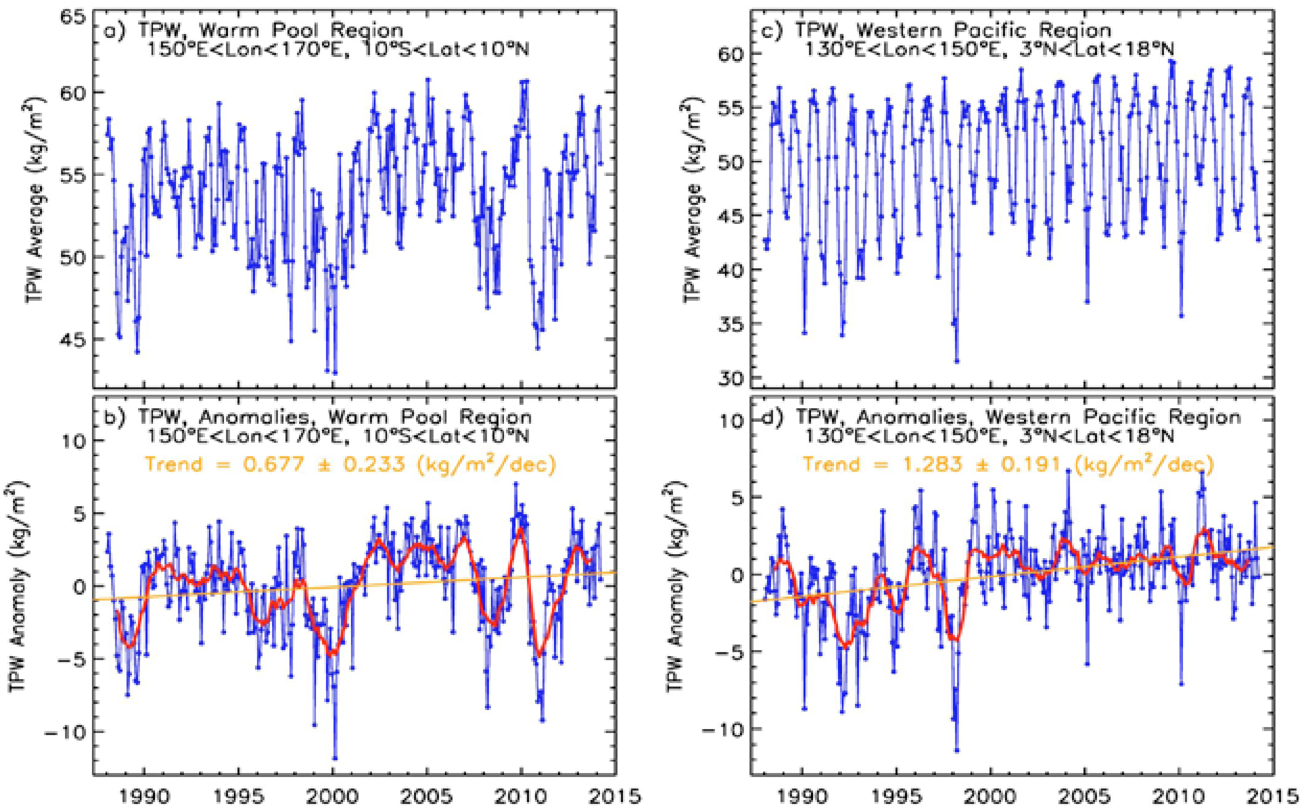

Figure 9. Monthly averages of total precipitable water in the trophosphere and monthly anomalies in (a, b) Warm Pool Region and (c,d) Western Pacific Region. Eleven month running averages are shown in red.

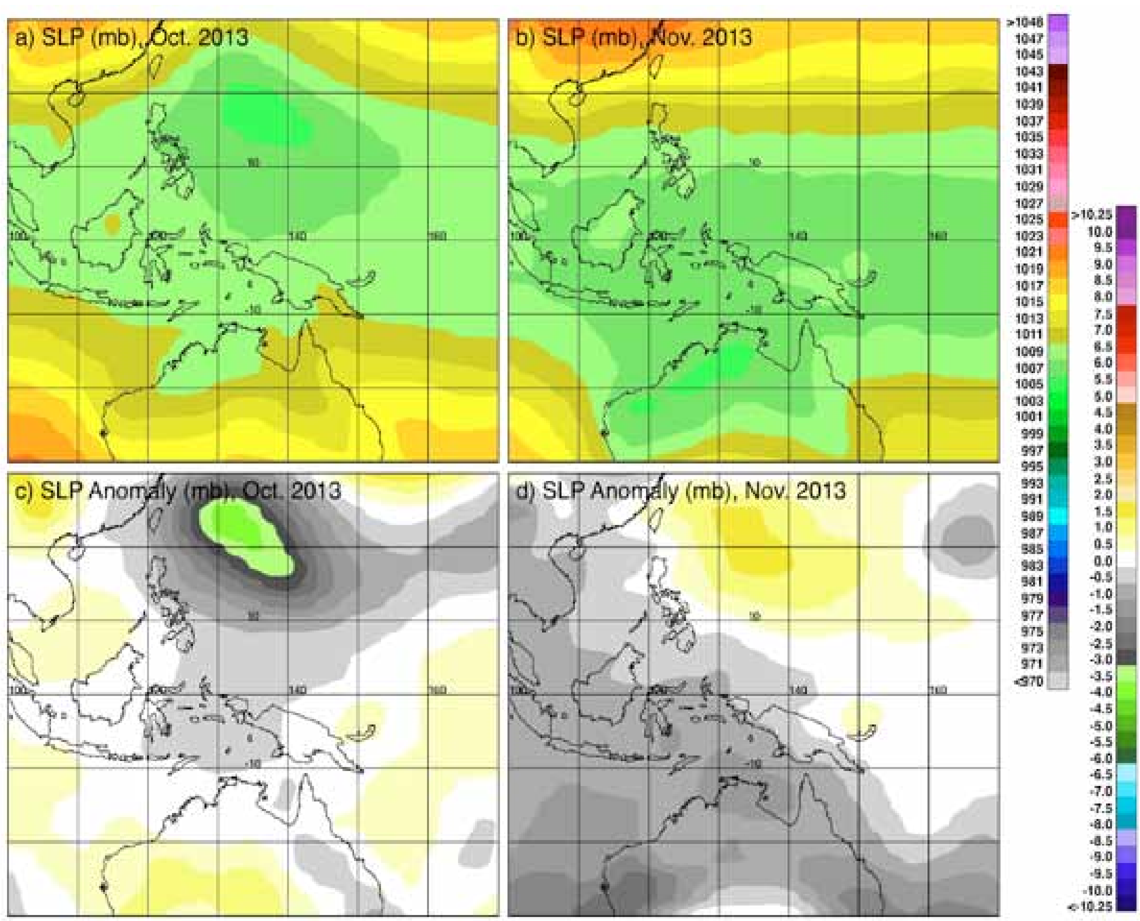

Figure 10. Monthly averages of sea level pressure in (a) October 2013 and (b) November 2013. Monthly averages of sea level pressure anomalies in (c) October 2013 and (b) November 2013.

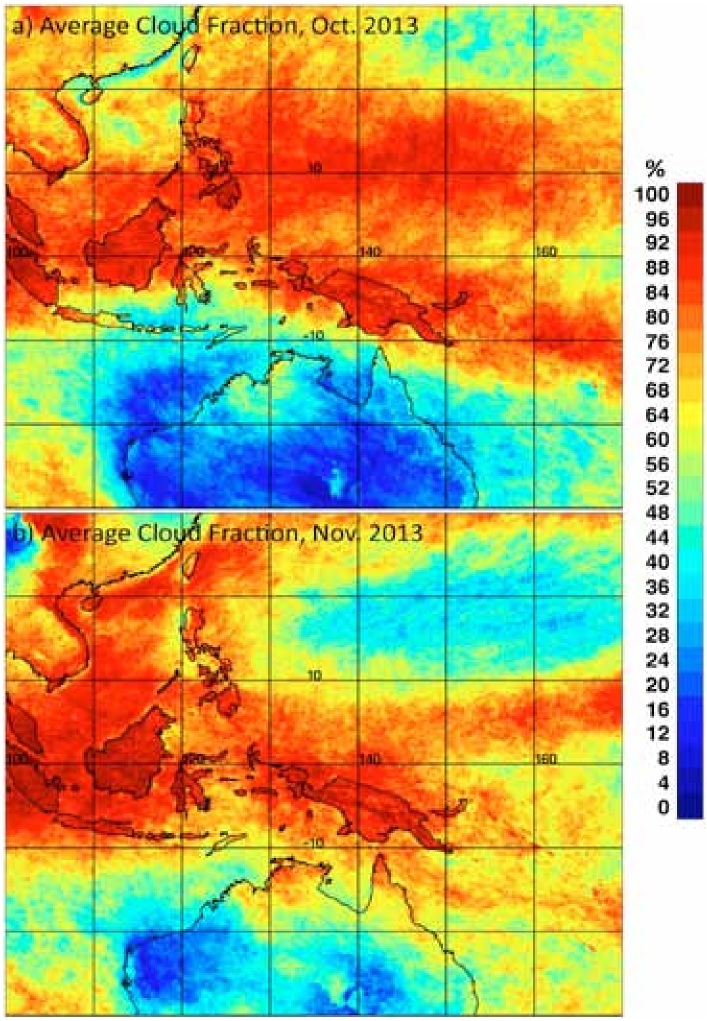

Figure 11. Monthly averages of cloud fraction over the Pacific Ocean region in (a) October 2013 and (b) November 2013.

depending on height and infrared emissivity and it has been reported that cirrus clouds showed cooling effects at mid-latitude and warming effect at tropical environments (*Cox 1971*). The observation of persistent cloud cover in October 2013 (**Figure 11a)** is concurrent with the observation of enhanced SST during the same month showing consistency with what is expected in a tropical environment (*Cox 1971*).

CONCLUSION AND RECOMMENDATION

The environmental factors that are likely to cause the unusual strength of Typhoon Haiyan have been evaluated and this study indicates that in 2013 the strongest environmental signal that may be associated with the typhoon is the SST in the Warm Pool and Western Pacific Regions. The most remarkable result is that the typhoon event coincided with the record high monthly average SST during the 1981 to 2014 study period over the Warm Pool Region. The highest monthly SST over the Warm Pool Region occurred in November 2013 while the 4th highest SST observed in the region during the same period occurred in October 2013. The monthly average SST in the Western Pacific region did not show a record high value in 2013 but the values were comparatively elevated and the region had a higher trend in SST than the Warm Pool Region.

The maximum and minimum values of the SST in the two regions have also been increasing with the minimum increasing faster than the maximum SST. This suggests that a conditioning in the temperature of the mixed layer has kept the SST in the more current decade from going below the minimum values in the previous decades. This implies that the temperature of the mixed layer of the ocean is likely increasing as well. Finally, a comparative analysis of SST with maximum winds of destructive typhoons in recent years shows a relatively good correlation with correlation coefficient of 0.7 in the Warm Pool Region and 0.4 in the Western Pacific Region. Statistical studies also show that the percentage of typhoons with associated wind speeds of at least 150 km hr^{-1} have also been increasing with the percentage being 29.6% for 1984 to 1993, 30.5% for 1994 to 2003 and 41.9% for the 2004 to 2013 period. These preliminary analyses indicate that increases in SST could cause not only stronger typhoons but also a larger percentage of them.

A main concern is the apparently significant positive trend of SST of about 0.2 ºC per decade over the Warm Pool and the Western Pacific Regions. More rigorous attribution studies are needed but the results from this study imply that such a trend could lead to the occurrence of future storms that are as intense or even stronger than Typhoon Haiyan. Since the Philippines contribute only a very small fraction of global emissions of greenhouse gases, the emphasis should be on risk assessment and adaptation. This includes the monitoring of SST in the Warm Pool and Western Pacific Regions as can be done with satellite data to be able to assess in advance the dangers of impending storms. It also requires resilience including the installation of strong foundations of the structure of buildings and residential areas to minimize the loss of lives and economic losses. However, some mitigation efforts to minimize the anthropogenic greenhouse warming, such as the reduction in the use of fossil fuels and the greater utilization of alternate source of energy, are highly desired, especially since the country's population is rapidly increasing in tandem with economic growth and industrialization.

REFERENCES

American Physical Society (APS). 2007. http://www.aps.org/policy/statements/07_1.

Comiso, J.C., 2010. Polar Oceans from Space, Springer Publishing, New York, doi 10.1007/978-0-387- 68300-3, 507pp.

Comiso, J. C., C. Blanche, V. Espaldon, F. Lansigan and T. Sarigumba, et al. 2014. Changing Philippine Climate: Challenges to Agriculture, Natural Resources and the

Environment, University of the Philippines Press, Diliman, QC, Philippines, 378pp.

Cox, S. K. 1971. Cirrus clouds and the climate, *J.Atmos. Sci*., 28: 1513-1515.

Digital Typhoon. 2015. “Typhoon Images and Information,” Japan. Website: http://agora.ex.nii.ac.jp.digital-typhoon/(13 May 2015)

Dvorak, V. F. 1975. Tropical cyclone intensity analysis & forecasting from satellite imagery. Mon. Wea. Rev 103: 420–430.

Emanuel, K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years, *Nature*, 436(4): 686-688.

Emanuel, K. 1988. The maximum intensity of hurricanes, *J. Atmos. Sci*, 45(7): 1143-1155.

England, M. H., S. McGregor, P. Spence, G. A. Meehl, A. Timmermann, W. Cai, A. S. Gupta, M. J McPhaen, A Purich and A. Santoso. 2014. Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus, Nature Climate Change, 4: 222-227, doi:10.1038/nclimate 2106.

IPCC. 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T., D. Qin, G. Plattner, M. M. B. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P. M. Midgley (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1550 pp.

JTWC. 2015. Joint Typhoon Warning Center “Tropical Cyclone Best Track Data Site,” U. S. A. http://www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/best_tracks/

JTWC. 2013. Prognostic Reasoning for Super Typhoon 31W (Haiyan) Nr 19 (Report). Joint Typhoon Warning Center, United States Navy. November 7, 2013.

Kalnay E, R. Kanamitsu, R. Krisler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Wollen, Y. Zhsu, M. Chella, J. Janowlak, W. Eb., C. R. Ropelewski, R. Jenne. 1996. The NCEP/NCAR reanalysis project, *Bull. Amer. Meteor. Soc.*, 77: 437-479.

Knutson, T. R., J. L. McBride, J. Chan. K. Emanuel, G. Holland, C. Landsea, I. Held, J. P. Kossin, A. K. Srivastava and M. Sugi, 2010. Tropical cyclones and climate change, *Nature Geoscience,* doi:10.1038/NGEO779.

Lin, I. I., M. D. Chou, and C. C. Wu. 2009. The impact of warm ocean eddy on Typhoon Morakot, a preliminary study from satellite observations and numerical modeling, *Terrestrial Atmospheric and Oceanic Sciences* 22(6): 661-671, doi:10.19/TAO.2011.08.19.01(TM).

Moon, I. J., and S. J. Kwon. 2012. Impact of upper-ocean thermal structure on the intensity of Korean Peninsula landfall typhoons, Prog. Oceanogr., 105: 61-66.

NDRRMC. 2014. Updates of Effects of Typhoon YOLANDA (HAIYAN)". National Disaster Risk Reduction and Management Council. April 17, 2014.

Pun, I. F., I. I. Lin, M. H. Lo. 2013. Recent increase in high tropical cyclone heat potential area in the Western North Pacific Ocean Geophy. Res. Lett. 40: 1-5, doi:10.1002/grl_50548.

Halverson, J. B., and T. Rabenhorst. 2013. Hurrican Sandy: The science and impacts of a superstorm, *Weatherwise* 66: 14-23, doi: 10. 1080/00431672.2013.762838.

Reynolds, R. W., N. A. Rayner, T. M. Smith, D. C. Stokes, and W. Wang. 2002. An improved in situ and satellite SST analysis for climate. *J Climate* 15:1609-1625.

Trenberth, K. 2005. Uncertainty in hurricanes and global warming Science 308: 1753-1754, doi:10.1126/science.1112551.

Trenberth, K. E. and J. T. Fasullo. 2010. Tracking Earth’s Energy Science 328: 316- 2010.

Vecchi, G. A., A. Clement, and B. J. Soden. 2008. Examining the tropical Pacific’s response to global warming EOS Transactions 89(9): 81-83.

Wang, B., J. Liu, H. J. Kim, P. J. Webster, S. Y. Yim, B. Xiang. 2013. Northern Hemisphere summer monsoon intensified by mega-El Nino/Southern Oscillation and Atlantic multidecadal oscillation, PNAS 110(14): 5347-5352.

Webster, P. J., G. J. Holland, J. A. Curry and H. R. Chang. 2005. Changes in tropical cyclone number, duration and intensity in a warming environment Science 309: 1844-1846.

Zhao, H., L. Wu, R. Wang. 2014. Decadal variations of intense tropical cyclones over the western North Pacific during 1948-2010, *Advances in Atmospheric Sciences* 31(1): 57

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