Spatial and Temporal Variation Characteristics of Northwest Pacific Tropical Cyclone Activity in Global Warming Scenario

Xinyu Guo, Chenglin Gu*, Bei Li and Wenwen Zhang

Jiamusi University Department of Resources and Environment, Faculty of Science, Jiamusi, 154007, China
*Corresponding E-mail: 1293225883@qq.com

Abstract. Utilizing the Joint Typhoon Warning Center (JTWC) TC best-track data covering the period of 1951-2015, spatial and temporal variation characteristics of Northwest Pacific tropical cyclone activity in global warming scenario is discussed. The annual frequency trend of TC in the Northwest Pacific is as follows: from the late 1950s to the early 1960s, there was an obvious upward trend, the late 1960s to the early 1980s showed a downward trend, the late 1980s to the mid 1990s showed an upward trend, and the mid-1990s to the late 2010s showed a downward trend. The frequency of super TY in the Northwest Pacific showed a rapid downward trend from the late 1960s to the early 1980s, and then changed to a slow upward trend. The region where the linear change of different stages of TC life cycle stage (genesis, development, mature, decay) frequency is approaching to central Asian coastline. Northwest Pacific TC activity decreases, but from the perspective of spatial distribution of linear changes, the threat of TC towards eastern Asia is enhanced. That is probably because the global warming scenario results in the increasing temperature gradient between Northwest Pacific and central and eastern Pacific, which leads to the strengthening of walker circulation. The strengthening walk circulation could increase the magnitude of the vertical wind sheer and the relative vorticity on the tropical Northwest Pacific, which affects the spatial variation of TC activity in Northwest Pacific.

1. Introduction
In the past few decades, revealing the causes of tropical cyclone’s (TC) formation, development and influence factors have been the meteorology's challenges. At the same time, the response of tropical cyclone (TC) activity to global warming remains controversial, in part because of uncertainty in historical TC records. [1] During the last two decades, an extensive literature has appeared attempting to answer this interesting but elusive question, Global warming has a pervasive influence on ocean SST and heat content, atmospheric temperature, water vapour, and atmospheric and oceanic general circulation patterns, all of which affect tropical cyclones in complex ways, which are not yet fully understood. Chan and Liu [2] showed that in the NWP basin there was no significant relationship between typhoon activity parameters (the annual frequency of typhoons, ratio of intense storms to the total number of tropical cyclones and its destruction potential) and the local SST warming during the period 1960-2003. Aspects of the association between global warming and tropical cyclones are uncertain in part because climate change is continuous, but irregular. Our basic conceptual understanding of cyclones suggests that there could be a relationship between cyclone activity and sea surface temperatures (SST). It is an established fact that SST 26°C is a requirement for tropical cyclone formation in the current climate. As the SST become warmer, certain tropical ocean basins
may face more and more intense tropical cyclones. Elsner and Kocher [3] determined that tropical ocean SST have been increased by approximately 0.5°C between 1970 and 2004. Anthes et al. [4] thought that We could expect that a warmer and moister environment would have an enhanced overall cyclone activity, tropical cyclones form only over warm oceans from which they gain energy. Emanuel et al. [5] applied this approach to quantify the possible influence of global warming on TC activity, suggesting that global warming should reduce the global frequency of hurricanes, though their intensity may increase in some locations. Knutson et al., Knutson and Tuleya [6] conducted hurricane model simulations with large-scale thermodynamic conditions (atmospheric temperature and moisture profiles, and SST) derived from global warming experiments and found that hurricanes simulated in warming conditions are stronger and have higher precipitation rates than under present-day conditions. Tropical SST have trended upward over the past 50 years. The warming trend, which is generally believed to be associated with the ongoing global warming since the 1970s [7]. In the Western North Pacific (WNP) basin, upward trends were found over the past three decades in the proportion of intense typhoons with a maximum wind speed larger than 59 m/s [8]. According to Trenberth [9], there is building up of an evidence that global warming enhances a cyclone’s damaging winds and flooding rains. Elsner et al. [10] found that the strongest tropical storms are getting stronger, with the most notable increases in the north Atlantic and northern Indian Oceans. Emanuel demonstrated that the annual accumulated PDI has increased markedly in the north-west Pacific and north Atlantic basins since the mid-1970s and attributed the upward trend to both longer storm lifetimes and greater storm intensities.

Based on the recommendations of the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC 2013), Although on the long-term scale (century) changes, the fact of enhanced TC activity is low reliability, since 1970, the fact of enhanced Atlantic tropical cyclone activity is almost certain [11].

To sum up, in global warming scenario, the increased trend of the Atlantic TC activity is for sure, but how does the TC activity change in the Northwest Pacific has not been determined. In global warming scenario, the TC activity changes, such as the numbers may increase, the life cycle stage is likely to grow, the intensity might change, can be predicted by climate patterns. However, at present, there are still a lot of uncertainties, such as the global or regional frequency, geographical distribution, path changes, the landfall frequency and intensity in coastal areas. It is still hard to draw a definite result. This study is based on the spatial and temporal variation of TC activity (occurrence frequency, super typhoon frequency, life cycle duration, annual average strength, annual maximum strength, track density and different stages of TC life cycle stage), to explore variation characteristics and the possible mechanism of Northwest Pacific tropical cyclone activity in global warming scenario.

2. Materials and method

We utilized the Joint Typhoon Warning Center (JTWC) TC best-track data covering the period of 1951-2015 sets in the WNP basin. (http://weather.unisys.com/hurricane/w_pacific/index.php), The data sets commonly include the locations of TC centers and maximum sustained wind speeds at 6 h intervals, etc.

SST is obtained from the University of Maryland (UMD) and the University of Texas A&M (TAMU) reanalysis products SODA_2.2.4, the vertical resolution is the unequal spacing, a total of 40 levels. The SODA-2.2.4 SST data, covering the period 1951-2010, has 0.5°×0.5° horizontal resolution. (http://dssrs.atmos.umd.edu/DATA/soda_2.2.4/), Closing to 100m’s depth, 1-9 level (0-96.92 m) is selected in the study to calculate the Pacific surface temperature. Wind field data is from Reanalysis 2 of the general circulation model from National Centers for Environmental Prediction and Department of Energy (NCEP/DOE). (http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis2.html), Horizontal/vertical winds and geopotential height, at 37 pressure levels and surface with 2.5° x 2.5° horizontal resolution for the period 1951-2015.

TC intensity changes in a complete life cycle. In order to analyze the TC’S spatial and temporal variations in different stages, TC life cycle duration can be divided into four different stages: 1) Genesis: TC genesis is defined as occurring when a TC reaches wind speeds of at least 17 m/s, 2) Development: The development stage is a time when the central pressure decreases continuously,
including a temporary period when the central pressure does not change, 3) Mature: The mature stage is defined as the period from the end of the development stage to the beginning of the decay stage and 4) Decay: The decay stage is a period during which the central pressure rises monotonically. Here, each TC central position over the Northwest Pacific ocean is counted in 5° × 5° bins to calculate the ratio of the numbers of TC in each life stage: TC genesis, development, mature, and decay stages in the whole TC numbers over the Northwest Pacific.

3. Results and discussion

3.1. Statistical characteristics of northwest Pacific TC activity
The time variation of TC activity intensity in the Northwest Pacific can be examined by four parameters, namely, the generation frequency, the super typhoon frequency, the annual peak intensity (the annual average of the maximum wind speed of TC), the intensity (the annual average of the average wind speed of TC).

3.1.1 Interannual variation characteristics of TC frequency in the Northwest Pacific
TC frequency that occurred in the Northwest Pacific (including the South China Sea) from 1951 to 2015 was counted. A total of 1912 TC were generated in 65 years. Among them, 1666 TC occurred in the Northwest Pacific, including 439 cases of super TY (maximum wind speed exceeding 51 m/s); 246 cases of TC occurred in the South China Sea, including 6 cases of super TY. The peak annual frequency of TC in the Northwest Pacific appeared in 1964 with a value of 45 cases, and the minimum value appeared in 1951 with a value of 17 cases and an annual average of 29.36 cases.

It can be seen from Figure 1(a) that the long-term variation trend of TC frequency from 1951-2015 (green dotted line) showed a slight upward trend, but failed to pass the significance level test of 0.05, and the black dotted line was the significance level reliability line of 0.05 (U0.05=1.96). From the late 1950s to the early 1960s, the generation frequency showed an obvious upward trend, a downward trend from the late 1960s to the early 1980s, an upward trend from the late 1980s to the mid-1990s, and then a downward trend. From the M-K test, it can be seen that the frequency of TC formation in the Northwest Pacific underwent a sudden change around 1957, that is, a shift from a partial period before 1957 to a partial period, but the increase trend only passed the significance level test of 0.05 in the two stages from the early 1960s to the early 1970s, and from the late 1990s to the early 2000s.

The maximum value of super typhoon in the Northwest Pacific was 12 cases in 2004, and the minimum value was 1 case in 1966, 1985 and 1999, and the annual average value was 6.63 cases.

It can be seen from Figure 1(b) that there was no significant change in the long-term trend of super typhoon frequency (green dotted line) from 1951 to 2015. From the late 1960s to the early 1980s, the frequency of super typhoon in the Northwest Pacific showed a rapid decline, then changed to a slow rise. The M-K test of the time series of the generation frequency of super typhoon shows no climatic change.
Figure 1. 1951-2015 Temporal variation of TC activity in the Northwest Pacific and M-K test curve
(a) Frequency of TC in the Northwest Pacific. (b) Frequency of super TY in the Northwest Pacific 0.05 Significant horizontal reliability line (U0.05=1.96). (c) The intensity of TC in the Northwest Pacific. (d) The peak intensity of TC in the Northwest Pacific. 0.01 significant horizontal reliability line (U0.01=2.576).

3.1.2 Characteristics of Interannual Variability of TC Intensity in the Northwest Pacific
The highest value of the peak intensity of TC appeared in 1958 with a value of 56.95 m/s, and the lowest value appeared in 2015 with a value of 14.87 m/s, and the annual average value was 40.28 m/s. The highest value of the intensity of TC appeared in 1958 with a value of 38.56 m/s, and the lowest value appeared in 2015 with a value of 12.29 m/s, and the annual average value was 25.04 m/s.

Figure 1(c) and Figure 1(d) show that from the early 1950s to the late 1950s, the annual peak and annual intensity of TC in the Northwest Pacific showed a short-term strengthening trend, and then a long-term weakening trend. The black dashed line is the 0.01 significant horizontal reliability line (U0.01=2.576).

On the whole, the average annual peak intensity and annual intensity of TC in the Northwest Pacific showed a significant downward trend (passed the 0.05 significant level test). The intensity had a sudden change around 1972, indicating that the intensity decreased significantly after 1972. A sudden change in the peak intensity occurred around 1968, indicating a significant decrease in the peak intensity after 1968.

Wu et al. used the Japan Meteorological Administration’s Tokyo Typhoon Center (JMA RSMC TOKYO) and the China National Meteorological Administration’s Shanghai Typhoon Institute (CMA-STI) best path data sets from 1975 to 2007, and also considered that the annual intensity of TC and the annual average The peak intensity began to decline in the mid-1970s. This conclusion is basically consistent with the change in the intensity of this study. At the same time, it is also found that the frequency of super TY has obviously declined from the late 1950s to 2005, which is different from the conclusion of this study. This difference may be due to the selection of different observation systems and analysis methods for different data sets.

3.2. Spatial and temporal variation characteristics of northwest pacific TC activity
At present, most studies focus on the spatial and temporal variations of TC forming source location and influence factors. They did not study TC during a complete life cycle, so they cannot analyze spatial and temporal variations of TC activity intensity on the whole. From a point of view that TC has a complete life cycle, consisting of genesis, development, mature and decay stages, this study analyzes spatial and temporal variations of four stages.

Figure 2 illustrates the horizontal distribution of TC locations for each life stages. TC are frequently formed around 127.5°E to 145°E, 7.5°N to 145°N in the Northwest Pacific and around 115°E, 15°N to 20°N in South China Sea (Fig. 2(a)). The genesis location is different from the other scholars’ results, for example, Zhou Xu [12] thought that TC are frequently formed around 130°E, 12.5°N. The different results might be due to the different time scale and data sets. On the long-term changes, there is a trend of TC forming source location: a notable increase over the northeastern Philippine Sea, with a notable decrease over the southeastern Philippine Sea (blue shading), and there is no significant changes over South China Sea. Note that increasing occurrence frequency in a certain region could
reduce the average TC intensity over the local and surrounding regions because newly generated TC
usually have the weakest intensity, lower than 17 m/s. That means TC forming source location moves
towards northeast, which weakens the threat towards Philippine.
Figure 2 (b) illustrates TC development stages mainly locate over the eastern Philippine Sea. There is
a notable increasing trend over the west and the north (red shading) and a significant decreasing trend
over the east and the north (blue shading). By contrast, basically, TC development stages show no
spatial distribution change over the South China Sea, which shows that TC moves slowly over the
South China Sea.
Figure 2 (c) depicts that TC is in the mature stage, which exhibits the climatology of the location of
peak intensity (contour) and its long term change (shading). The mature stages mainly locate over the
western Philippine Sea (122°E, 22°N) and South China Sea (112°E, 17.5°N). The long-term change
shows an increasing trend (red and yellow shading), which mainly extends like a belt towards the west
and north along the coastline south of 30°N. There are two areas with significant linear changes:
Taiwan Island and coastline of northeastern Indo-China Peninsula. The mature location is approaching
to China’s coastline, which intensifies China’s risk of being attacked by typhoons. TC intensity starts
to decrease in the southern and northeastern part of the belt. The changes are statistically significant
over the 90% confidence level. These features confirm that the expected changes based on the changes
have indeed been occurring over the WNP basin. Except north of 30°N, TC intensity begins to
decrease in the southeast of Philippine (blue shading).
Figure 2(d) illustrates that TC decay stages mainly locate in the southeastern and southern coast of
China, Indo-China Peninsula and Hainan province, with its center in (20°N, 120°E). The long-term
changes are not notable. That exhibits that TC landfall locations are mainly in southeastern coastline
of China, Vietnam coastline, coast from Fujian province to Leizhou Peninsula and southern coast of
China. Most southern parts of China are affected. Another middle area (134°E, 32°N) is formed in
kyushu, Japan. Over the Sea of Japan (134°E, 37°N), north of that middle area, the increasing trend is
obvious.

3.3 Global Warming Influencing TC Activity
Region sea surface temperature determines the power input, which maintains the formation and
development of TC, at the same time it is an important factor of controlling TC intensity. The tropical
sea temperature rises by 0.25-0.5 degree since the middle of last century. High SST is a necessary but
insufficient condition for hurricane intensification. From the perspective of the global warming
scenario, TC intensity is influenced by energy input or upper troposphere thermal exchange. From the viewpoint of energy interchange, the east of Philippine Sea surface temperature trends upwards, while the TC activity trends downwards. That is probably because there are the adverse condition of heating power and motive power in this region.

Figure 3. (a) Temperature departure (contour) ($^\circ$C) and Linear trends in the SST ($^\circ$C decade$^{-1}$) over the Pacific during the period 1951-2010, (b) Linear trends of 850 hPa horizontal winds (vectors, m s$^{-1}$ decade$^{-1}$), (c) the vertical wind shear between 850 and 200 hPa (contours, m s$^{-1}$ decade$^{-1}$) and (d) relative vorticity over the WNP during the period 1951-2015. Blue arrows indicate the region by the 90% confidence level, the blue solid line surrounded by area, blue shadows said the region by the 95% confidence level.

Park et al. [13] thought that the spatial difference of power environment changes the relative TC intensity patterns. The global warming scenario in recent decades may affect the general circulation of atmosphere in large scale, which would result in the changes of vertical wind sheer and relative vorticity. In order to reveal the mechanism of TC activity changes, we could exam the changes of the environmental field in the process TC development. Shading in Figure 3 (a) shows the trend of tropical Pacific sea surface temperature. Over the past seven decades, the sea surface temperature became warmer obviously over the northwest Pacific, especially over the western Pacific warm pool. By contrast, the sea surface temperature decreases slightly over the middle and east tropical Pacific. This pattern of Pacific surface temperature changes must result in the increasing zonal temperature gradient between western Pacific and Middle Eastern Pacific. The spatial difference of sea surface temperature must lead to the TC change in large scale, which is the coupling process is strengthened near the equator. Such changed probably result in the strengthening of walker circulation. Figure 3 (b) shows the long-term change trend of low attitude circulation at the eastern pacific near the equator increases obviously, and decreases westwards. Such trends are through 90% confidence level.
Associated with this enhanced Walker circulation, dynamic environments relevant to the TC activity were also examined, such as the horizontal winds and relative vorticity at 850 hPa, and the magnitude of the vertical wind shear between 200 and 850hPa. The increasing low-level easterlies near the equator have formed the meridional wind shear, inducing the more anticyclonic low-level flows along the tropics including the eastern rectangle region. This kind of anomalous anticyclone may become an important factor of restraining the formation of TC. On the other hand, the strengthening of the Walker circulation also has increased the magnitude of the vertical wind shear in the tropical North Pacific. The region (137-145°E, 10-15°N) in Figure 3 (c) and (d) shows the increasing trend of the vertical wind shear and the decreasing trend of the relative vorticity. Though the changes of the vertical wind shear and the relative vorticity are not obvious, it is likely to be an important factor of encouraging TC activity to decrease. It is also can explain why TC genesis frequency and intensity decrease in eastern Philippine. In the subtropical zone of northern South China Sea, south of Taiwan and Japan, a large abnormal low level cyclonic wind flows and weakened vertical wind shear, in combination with the warmer SST, have encouraged TC to increase in strength. Therefore, when explaining TC observed intensity, spatial distribution pattern of track density, both thermodynamic and dynamic environments should be considered, but it seems that dynamic factor is more important than thermodynamic one.

4. Conclusions
Over the period of mid 1950s to early 1960s, occurrence frequency trended upwards, while from early 1960s to early 1980s, occurrence frequency trended downwards; over the period of early 1980s to mid 1990s, that trended upwards, since then, downwards again. Over the period of min 1950s to mid 1960s, the Northwestern Pacific super typhoon occurrence frequency trended upwards, from mid 1960s to late 1970s, that trended downwards; over the period of late 1970s to late 1990s, that trended upwards, from late 1990s to 2004, that trended upwards rapidly, while from 2004 to 2015, that trended downwards. The frequency of super TY in the Northwest Pacific showed a rapid downward trend from the late 1960s to the early 1980s, and then changed to a slow upward trend. Northwest Pacific TC activity decreases from the early 1960s, but from the perspective of spatial distribution of linear changes, the threat of TC towards eastern Asia is enhanced. But from the perspective of the peak intensity stage (mature), the regions where linear changes show as upward trend approach to eastern Asia land. That indicates that Northwest Pacific TC activity shows a decreasing trend, but the frequency of landfalls and intensity are probably strengthened. Therefore, the threat of TC towards eastern Asia is enhanced.
Over the past seven decades, the sea surface temperature became warmer obviously over the Northwest Pacific, especially over the western Pacific warm pool. By contrast, the sea surface temperature decreases slightly over the middle and east tropical Pacific. This pattern must result in the increasing zonal temperature gradient between western Pacific and Middle Eastern Pacific. This kind of changes probable leads to the strengthening of the Walker. Associated with this enhanced Walker circulation, dynamic environments relevant to the TC activity were also examined. The increasing low-level easterlies near the equator have formed the meridional wind shear, inducing the more anticyclonic low-level flows. On the other hand, the strengthening of the Walker circulation also has increased the magnitude of the vertical wind shear and decease the relative vorticity, which is likely to be an important factor of encouraging TC activity to decrease. In the subtropical zone of northern South China Sea, south of Taiwan and Japan, a large abnormal low level cyclonic wind flows and weakened vertical wind shear, in combination with the warmer SST, have encouraged TC to increase in strength.
5. References

[1] Kossin, J. P.; Knapp, K. R.; Vimont, D. J.; Murnane, R. J.; Harper, B. A., (2007). A globally consistent reanalysis of hurricane variability and trends. Geophys. Res. Lett., 34,L04815.

[2] Chan, J. C. L.; Liu, K. S., (2004). Global warming and western North Pacific typhoon activity from an observational perspective. J. Climate, 17, 4590-4602.

[3] Elsner, J. B.; Kocher, B., (2000). Global tropical cyclone activity: a link to the North Atlantic Oscillation. Geophys. Res. Lett., 27,129-132.

[4] Anthes, R. A.; Corell, R. W.; Holland, G.; Hurrell, J. W.; Mac Cracken, M. C.; Trenberth, K. E., (2006). Comments on hurricanes and global warming-potential linkages and consequences. Bull Am Meteorol Soc., 87, 623-628.

[5] Emanuel, K. A.; Sundararajan, R.; Williams, J., (2008). Hurricanes and global warming: results from downscaling IPCC AR4 simulations. Bull. Amer. Meteor. Soc., 89,347-367.

[6] Knutson, T. R.; Tuleya, R. E., (2004), Impact of CO2 induced warming on simulated hurricane intensity and precipitation: Sensitivity to the choice of climate model and convective parameterization. J. Climate, 17,3477-3495.

[7] Intergovernmental Panel on Climate Change IPCC (2001). Climate Change 2001: The Scientific Basis. Houghton, J.T.; Y.-H. Ding, D. J.; Griggs, M.; Noguer, P. J.; Van Der Linden; Dai, X.; Maskell, K.; Johnson, C. A., (Eds.), Cambridge University Press, 881.

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

[9] Trenberth, K., (2007). Warmer oceans stronger hurricanes. Scientific American. July issue, 45-51.

[10] Elsner, J. B.; Kossin, J. P.; Jagger, T. H., (2008). The increasing intensity of the strongest tropical cyclones. Nature, 455, 92-95.

[11] Intergovernmental Panel on Climate Change IPCC (2013). Climate Change 2013: the scientific basis. Thomas, F. S.; Dahe, Q.; Gian-Kasper, P.; Melinda, M. B. T.; Simon, K. A.; Judith, B.; Alexander, N.; Yu X.; Vincent, B.; Pauline, M. M. (Eds.), Cambridge University Press, 216-217.

[12] ZHOU Xu, YU Jinhua, WANG Zhifu,(2013). The climate change of tropical cyclone frequency and its relationship with environment factors in the western North Pacific. Journal of the Meteorological Sciences, 33(1): 43-50.

[13] Park, D. S. R.; Ho, C. H.; Kim, J. H.; Kim, H. S.,(2013). Spatially inhomogeneous trends of tropical cyclone intensity over the western North Pacific for 1977–2010. J. Climate, 26, 5088–5101.

Acknowledgements

This work was supported by the Jiamusi University Doctoral Special Research Fund Project (JMSUBZ2019-11), Heilongjiang Provincial Universities Basic Scientific Research Project (2019-KYYWF-1399). The authors are grateful to the editor and anonymous reviewers for their helpful comments and also acknowledge helpful comments by Chenglin Gu.