**DECADAL VARIATIONS OF INTENSE TYPHOON OCCURRENCE IN THE WESTERN NORTH PACIFIC**

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**Summary**

The causes of a major oscillation period of 16-32 years of the frequency of intense typhoon (Category 4 and 5 in the Saffir-Simpson scale) occurrence for the period 1960-2005 in the western North Pacific (WNP) are studied in this paper. In the southeastern part of the WNP (5-20°N, 150-180°E), the following features are observed during periods with above-normal frequency of intense typhoon occurrences: slightly higher sea-surface temperature, higher moist static energy, a more negative vertical gradient of saturated moist static energy in the lower troposphere, a negative maximum in the low-level streamfunction anomalies and a relatively weak vertical wind shear between 200- and 850-hPa. All these are more conducive to the development of tropical cyclones. As these cyclones move northwestward, the favourable dynamic conditions continue to be present so that they can intensify further. The steering flow ensures many of these typhoons will stay over water for an extended period of time through low-latitude recurvature. As a result, they can intensify to become Category 4 or 5 typhoons. The conditions during the below-normal periods are generally opposite.

A major conclusion from the results of this study is that the frequency of intense typhoon occurrence does not exhibit a linear increasing trend. Rather, it undergoes a strong multi-decadal (16-32 years) variability due to similar variations in the planetary-scale oceanographic and atmospheric conditions that govern the formation, intensification and movement of tropical cyclones.

**Keywords**  
global warming, tropical cyclones, decadal variations

1. **Introduction**

In the last few years, many papers have been published to address the issue of whether a link exists between global warming and the frequency of occurrence of tropical cyclone (TC) activity or of intense TCs. Some have suggested an increase in frequency of occurrence of intense TCs in the past 30 years and related this increase to a concomitant increase in sea-surface temperature (SST) caused by global warming (e.g., EMANUEL 2005a, b; WEBSTER et al. 2005; HOYOS et al. 2006; WEBSTER et al. 2006; HOLLAND et al. 2007). Others argued such an upward trend in intense TC occurrence frequency is actually part of a multi-decadal oscillation in the frequency of TC occurrence (e.g., LANDSEA 2005; CHAN 2006). Some others pointed out that the crude data and estimation techniques in the earlier years of the satellite era (mid 1960s to late 1980s) may not allow the identification of intense TCs, especially in ocean basins where aircraft reconnaissance was not routinely available (LANDSEA et al. 2006), and thus errors in such estimates tend to be large. For example, both KAMAHORI et al. (2006) and WU et al. (2006) showed that the data from the US Joint Typhoon Warning Center (JTWC) give an upward trend in the number of intense TCs while the data from the Japan Meteorological Agency and the Hong Kong Observatory give a downward trend. KNAPFF et al. (2006, 2007) further showed that by using a consistent wind-pressure relationship throughout the data period, the upward trend, though still exists, is much reduced. Results from the modeling of future climate consistently suggested a decrease in the frequency of occurrence in all
basins except the Atlantic (e.g., BENGTSSON et al. 1996; SUGI et al. 2002, 2004; OOUCHI et al. 2006) but the number of intense TCs is predicted to have a slight increase (e.g. KNUTSON et al. 2004; OOUCHI et al. 2006).

It is obvious from this brief review that no consensus has been reached as to whether a trend of intense TCs exists during the last few decades. This is indeed the conclusion of the recent Sixth International Workshop on Tropical Cyclones of the World Meteorological Organization\(^1\). In addition, the Workshop pointed to the existence of a multi-decadal variability of TC activity although the causes have yet to be determined. The objective of this study is therefore to investigate the possible causes of the multi-decadal variability in intense TC occurrence in the western North Pacific (WNP).

Section 2 describes the data and methodology used in this study together with a preliminary analysis of the periodicities of the time series of intense TC occurrence. Analyses of thermodynamic and dynamic variables are presented in sections 3 and 4 respectively. The results from these two sections suggest a further examination of the number and track distributions of the intense TCs, which are discussed in section 5. All the results are summarized in section 6. Based on these results, the decadal variations in intense typhoon occurrence are explained and discussed in relation to the global warming issue.

2. Data, methodology and preliminary analysis

The TC data from 1960 to 2005 are extracted from the JTWC website\(^2\). Despite the findings of KAMAHORI et al. (2006) and WU et al. (2006) that the data from JTWC differ from those of other warning centres in Asia, the JTWC data are still chosen for two reasons. One is that this study examines the multi-decadal variation and not the trend and so their result is not directly applicable here. The other reason is that because JTWC uses one-minute average wind speeds, which is the basis for the Saffir-Simpson scale (see below), no conversion is necessary if this scale is used to represent TC intensity. All atmospheric data are from the US National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NACR) reanalyses and the SST data from the US National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST dataset\(^3\).

Many metrics have been used to represent TC intensity on annual time scales. For example, BELL et al. (2000) calculated the accumulated cyclone energy (ACE), which is defined as the sum of the square of the maximum wind speed of a TC at each 6-hourly interval during the lifetime of the TC, and summed over all TCs during the year. Another metric is the power dissipation index (PDI) proposed by EMANUEL (2005a), which is defined as the cube of the maximum wind speed, instead of the square as in the case of ACE. Although both indices are biased towards the more intense TCs, it has been suggested that a slightly-weaker TC lasting for a long time, or many more such weak TCs, would also contribute as much as a short-lived intense TC. Thus, the simplest representation of the annual frequency of intense TC occurrence is used in this study – the annual number of Category 4 and 5 TCs (hereafter for simplicity referred to as Cat 4/5 typhoons and the number as NCat45) on the Saffir-Simpson hurricane scale.\(^4\) It is worth noting that the correlation between the ACE and NCat45 series for the 1960-2005 period is 0.82.

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\(^1\) http://www.wmo.int/web/arep/press_releases/2006/iwtc_statement.pdf
\(^2\) http://www.npmoc.navy.mil/jtwc/best_tracks/wpindex.html
\(^3\) http://dss.ucar.edu/pub/reanalysis/
\(^4\) http://www.aoml.noaa.gov/general/lib/laescae.html
The multi-decadal variation in NCat45 is obvious from its time series (thick solid line in Fig. 1b), with higher values in the 1960s, lower values in the 1970s and 1980s, higher values again in the 1990s, lower during the La Niña period of 1998 to 2000 and higher again after about 2001. Note that even if underestimates in the NCat45 values exist prior to the late 1980s, this multi-decadal variation will still exist, as the NCat45 values in the 1960s are consistently much larger than those in the 1970s and 1980s.

![Wavelet analysis](image)

Fig. 1. (a) The normalized local wavelet power spectrum of the standardized NCat45 series using the real-valued Mexican hat wavelet (derivative of a Gaussian; DOG m=2). The thick curve on either end indicates the edge effects. (b) The normalized reconstructed time series of typhoon numbers at 2-7-yr (thin long-dashed, values multiplied by 2) and 16-32-yr (thick long-dashed, values multiplied by 10) periods, and of the Nino3.4 index at 2-7-yr (thin dotted) and 16-32-yr (thick dotted, values multiplied by 10) periods. The original standardized NCat45 series is also shown (thick solid).

A wavelet analysis of the standardized NCat45 time series using the real-valued Mexican hat wavelet (derivative of a Gaussian; DOG m=2) gives two distinct periodicities: 2-7 years and 16-32 years (Fig. 1a). The annual variation of NCat45 is therefore a superposition of a 2-7-year cycle onto a multi-decadal (16-32-year) cycle (Fig. 1b). Indeed, the variances of the original NCat45 series explained by the reconstructed 2-7-year and the 16-32-year time series are 59% and 39% respectively. The prominence of the 16-32-year cycle displayed in Fig. 1b also supports the argument in CHAN (2006).
that the increasing trend in the NCat45 values after 1970 found by WEBSTER et al. (2005) is actually part of the multi-decadal variation in these values. In addition, this “increasing trend” is most evident during the period from the mid 1970s to the mid 1990s. If the period up to 2005 is considered, this trend is much smaller.

Because the El Niño/Southern Oscillation (ENSO) also has a 2-7-year cycle, it might be natural to conclude that the variations in NCat45 are related to ENSO. However, as can be seen from Fig. 1b, the reconstructed ENSO (as represented by the standardized Nino3.4 index averaged between May and December) and NCat45 2-7-year cycles are not necessarily in phase. In fact, the correlation between these two time series is only 0.44. On the other hand, the correlation between the ENSO and NCat45 16-32-year cycles is 0.60, which suggests the multi-decadal variation of the ENSO cycle is likely to be related to that of NCat45. The relationships between ENSO and WNP TC occurrence (CHAN 1985, 2000; WANG et al. 2002; CHAN et al. 2004) and intensity (CHAN 2007) found in previous studies are therefore likely a combination of the 2-7- and 16-32-year cycles. As the focus of the current study is on the multi-decadal variability, only the 16-32-year oscillation will be considered in this paper. Based on the reconstructed 16-32-year series of NCat45, the period of 1960-2005 is divided into three sub-periods: 1960-1970 (period A1, above normal), 1971-1986 (period B, below normal) and 1987-1997 (period A2, above normal). As the values from 1998 to 2000 are nearly zero, and the period from 2001 to 2005 is too short, these years are ignored in the subsequent analyses. All oceanographic and atmospheric data averaged within each of these three periods are examined in the next three sections.

3. Thermodynamic factors

3.1. SST

The SST anomalies (SSTAs) averaged between May and November (during which most of the intense TCs occur) for period A1 are positive in the eastern half and negative in the western half of the WNP, with maximum anomalies > 0.3°C occurring in the southeastern part of the WNP (Fig. 2a). Note that much of the central North Pacific (CNP) also had positive values of SSTA. In Period B, the SSTAs are generally smaller throughout the entire ocean basin, with the maximum anomalies around -0.1 to -0.2°C, again in the southeastern part of the WNP (Fig. 2b), which appears to be an extension of the extensive anomalies present in the CNP. SSTAs are generally above normal in the tropical WNP in period A2 (Fig. 2c). The maximum anomalies occur near the equatorial region in the eastern part of the WNP, and again appear to be an extension of the warm anomalies present in the CNP.

The composite SSTA patterns in these three periods suggest that the main difference in SSTA between the above-normal and below-normal periods occurs in the southeastern part of the WNP. Indeed, the average SSTA within the box (5-20°N, 150-180°E, the thick rectangle in each of the panels in Fig. 2, to be referred to as the key area) for the periods A1, B and A2 are 0.17, -0.09 and 0.10°C respectively.

3.2. MSE

The 1000-500 hPa mean MSE averaged over the WNP (0-30°N, 120-180°E) and between May and November shows a general linear increase with time, which might be contributed by the global increase in temperature and/or moisture (not shown). Differences in MSE between the three periods will therefore be masked by this background increase. A better way is to examine the principal components (PC) of MSE.
Fig. 2. Sea-surface temperature anomalies over the North Pacific for each of the three periods: (a) A1 (1960-70), (b) B (1971-86), and (c) A2 (1987-1997). Contour interval: 0.1°C. The thick rectangle indicates the key area discussed in the text.

As expected, the first PC of MSE, which explains 51% of the variance, gives below-normal values in period A1 and positive in periods B and A2 (not shown). However, the second PC, which explains 22% of the variance and is distinct from the first PC based on the NORTH et al. (1982) test, shows very distinct discerning features among the three periods, with positive maximum anomalies in periods A1 and A2 in the key area and negative maximum anomalies in period B (Figs. 3a-c). Thus, the atmosphere within the key area is more thermodynamically energetic during the periods when the NCat45 values are higher. Note that this result is consistent with that found by Chan (2007) in studying the annual variations of ACE.

Fig. 3. 1000-500 hPa mean MSE anomalies over the WNP averaged between May and November reconstructed from the second principal components for each of the three periods: (a) A1 (1960-70), (b) B (1971-86), and (c) A2 (1987-1997). Unit: J kg⁻¹. The thick rectangle indicates the key area discussed in the text.
Convection also depends on the vertical gradient of the saturated MSE (SMSE, see HOLTON 1992). An examination of the vertical variation of SMSE averaged over the WNP shows that it decreases from the surface to around 600 hPa before increases again, which is typical for tropical regions. The vertical difference in SMSE between 1000 and 600 hPa is therefore computed. It is found that the atmosphere is more convectively unstable within the key area in periods A1 and A2 but not in period B (not shown). Therefore, not only is the atmosphere more energetic in periods A1 and A2 than in period B, it is also more convectively unstable.

3.3. Discussion

Results from the previous two sub-sections suggest that the atmosphere is likely to be more convectively unstable during periods A1 and A2. This assertion has been tested by examining the amount of strong convection in the WNP based on the precipitation rate anomalies (PRA). For period A1, The PRA are found to be positive within the key area and negative in the western part of the WNP for periods A1 and A2, but they are mostly negative within the key area (not shown). In fact, if the same DOG wavelet analysis (see section 2) is performed on the time series of PRA within the key area, the 16-32-year reconstructed series has a correlation coefficient of 0.87 with the 16-32-year reconstructed NCat45 time series (not shown). That is, convection is more prevalent in the key area during periods A1 and A2 than during period B.

Thus, from the thermodynamic point of view, during periods of above-normal NCat45 (periods A1 and A2), the SST within the key area is higher than normal, which probably contributes to a higher MSE, and a more negative vertical gradient of SMSE. All such features would result in more convection in this area. If the dynamic conditions are also favourable, it is likely that the convective clusters developed in this area will become TCs. Because they form in the southeastern part of the WNP, if they can continue to be over the ocean for a long period and at the same time under favourable dynamic conditions, they are more likely to develop into more intense typhoons. On the other hand, during period B, the SST is below normal and the vertical gradient of SMSE is less negative. As a result, the atmosphere is less conducive to intense convection. In this case, TCs tend to develop further westward. As they spend less time over the ocean, they are less likely to become very intense. This hypothesis will be demonstrated in the next two sections.

4. Dynamic conditions

4.1. Streamfunction

A parameter that represents the large-scale vorticity is the streamfunction. The low-level (at 0.995 sigma) streamfunction anomalies for period A1 shows minimum anomalies, corresponding to maximum rotation, extending from the key area northwestward to Taiwan (Fig. 4a), which suggests that TCs that form within the key area are likely to be under favourable conditions when moving northwestward, which is the typical track. For period B, the maximum streamfunction (and thus minimum rotation) anomalies appear within the key area while the minimum anomalies are to the southwest of the key area (Fig. 4b). The band of minimum anomalies stretches from about 5°N, 157°E northwestern to the east of central Philippines. Another area of minimum exists just south of Taiwan. For period A2, the minimum anomalies are again found in the key area (Fig. 4c). In fact, the broad area east of ~ 130°E in the tropical WNP can be considered to have anomalous cyclonic vorticity. These results therefore suggest that during periods of above-normal NCat45, the key area also has above-normal cyclonic vorticity and thus convection developed there has higher potential to become TCs. Furthermore, as these TCs move northwestward, they continue to be in a favourable cyclonic
environment. On the other hand, in the period of below-normal NCat45, TCs can only form further westward where the dynamic conditions are favourable.

Note also from Fig. 4 that the genesis locations of these Cat 4/5 typhoons mostly all fall within the area where the streamfunction anomalies are a minimum, further highlighting the importance of a favourable dynamic condition. In addition, more TCs that eventually became Cat 4/5 typhoons have their genesis location in the key area in periods A1 and A2 than in period B.

![Fig. 4. Streamfunction anomalies at 0.995 sigma over the WNP for each of the three periods: (a) A1 (1960-70), (b) B (1971-86), and (c) A2 (1987-1997). Contour interval for the three periods are respectively 2x10^5, 5x10^4 and 1x10^5 m^2 s^-1. The thick rectangle indicates the key area discussed in the text. Each typhoon symbol represents the genesis location of a Cat 4/5 typhoon during that period.](image)

### 4.2. Vertical wind shear

Vertical wind shear is one of the dynamic factors related to TC development, with a small wind shear over the area where TCs develop being favourable (GRAY 1979). The patterns of the 200-hPa minus 850-hPa vertical zonal wind shear averaged between May and November for each of the three periods are very similar (not shown). To compare the differences among the three periods, the vertical zonal wind shear of period B is used as a reference for subtraction from that of the other two periods. Compared with period B, the vertical zonal wind shear in period A1 is smaller over much of the weak shear area (Fig. 5a). A similar situation can be found when comparing the shear between periods A2 and B (Fig. 5b). The average values of the vertical zonal wind shear within the key area for periods A1, B and A2 are 6.0, 7.3 and 6.6 m s^-1 respectively. Therefore, it appears that the low-level vorticity and the vertical wind shear both favour TC development in periods A1 and A2 but less so in period B.

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5 Zonal shear instead of total shear is examined because the meridional winds tend to small and could produce large errors.
Fig. 5. Differences in May-November averaged vertical (200-hPa minus 850-hPa) zonal wind shear between period B (1971-86) and period (a) A1 (1960-70), and (b) A2 (1987-1997). Unit: m s$^{-1}$. The thick rectangle indicates the key area discussed in the text.

4.3. Summary

The dynamic conditions associated with periods A1 and A2 in the key area are thus more favourable for TC intensification. Furthermore, these conditions extend northwestward into the western part of the WNP so that TCs that develop and move northwestward will continue to be under these favourable conditions.

5. Location of Cat 4/5 typhoons

The results in sections 3 and 4 suggest that in periods A1 and A2, convection is more likely in the key area. Because the dynamic conditions also favour TC development in this area, more TCs will develop in this area. Furthermore, these dynamic conditions continue to be favourable to the northwest of this area. Because most TCs tend to move northwestward, they are more likely to intensify. The longer these TCs can stay over water and under favourable conditions, the higher potential they will have to become Cat 4/5 typhoons. This section therefore further examines the locations of the Cat 4/5 typhoons to see if this is the case.

The tracks of all TCs that eventually became Cat 4/5 typhoons for each of the three periods suggest that while a majority of the tracks are west-northwestward, more of such typhoons appear to be recurving northeastward in periods A1 and A2 (Figs. 6a-c). To get a more quantitative view of this result, the number of such typhoons passing through each 5$^\circ$ latitude x 5$^\circ$ longitude box is counted. It is obvious from the patterns of this number distribution for the three periods (Figs. 6d-f) that more such TCs tend to recurve in periods A1 and A2 than in period B. Note also the much smaller number within the key area in period B. The slightly larger numbers in the latter period at around 12$^\circ$N, 140$^\circ$E is consistent with the area of minimum streamfunction anomalies shown in Fig. 4b.

Because TC movement is generally determined by the mid-tropospheric flow (CHAN et al. 1982), the tracks and number distributions of such typhoons should be consistent with such a flow, which is indeed the case when the mid-tropospheric geopotential height anomalies are examined (not shown). These results show that during periods when NCat45 values are above normal, the Cat 4/5 typhoons tend to stay over water for a longer period of time because (1) they form further southeastward, and (2) more of them tend to recurve due to the large-scale steering flow. As a result, they have more time to intensify.
Fig. 6. Tracks of Cat 4/5 typhoons for (a) period A1 (1960-70), (b) period B (1971-86), and (c) period A2 (1987-1997). The typhoon symbol indicates the formation location of each of these typhoons. Number of Cat 4/5 typhoons (times 10) occurring in each 5°latitude x 5°longitude box for (d) period A1 (1960-70), (e) period B (1971-86), and (f) period A2 (1987-1997).

6. Summary and discussion

6.1. Summary

This study attempts to identify the causes of the decadal variation of the frequency of intense typhoon occurrence in the WNP. The sea-surface temperature (SST) in the southeastern part of the WNP (5-20°N, 150-180°E) is found to exhibit a distinct signal, being slightly higher during the above-normal periods. Within this area, the moist static energy is also higher and the vertical gradient of saturated moist static energy in the lower troposphere is more negative during these periods. At the same time, the low-level streamfunction anomalies tend to have a negative maximum and the vertical wind shear between 200 and 850-hPa is also relatively small. The thermodynamic conditions suggest that in this
area, more convection tends to develop, as evidenced by the above-normal precipitation rate. Because the dynamic conditions are also favourable, the convection would likely develop into tropical cyclones. As they move northwestward, these favourable dynamic conditions continue to be present so that they can intensify further. The steering flow is such that many of these typhoons will stay over water for an extended period of time through low-latitude recurvature. As a result, they can intensify to become Category 4 or 5 typhoons. In the period when the frequency of intense typhoon occurrence is below normal, convection is not much favoured in the above “key” area and thus tropical cyclones tend to form further westward. Many of them also tend to continue westward without much recurvature because of a rather strong subtropical high to their north. As a result, their lifespan becomes shorter and hence they are less likely to intensify to Cat 4/5.

6.2. Discussion

A major conclusion from the results of this study is that the frequency of intense typhoon occurrence does not exhibit a linear increasing trend. Rather, it goes through variations on interannual (2-7 years) as well as multi-decadal (16-32 years) time scales. Causes of the interannual variations have been addressed in CHAN (2007). The multi-decadal variations are due to variations on similar time scales in the planetary-scale oceanographic and atmospheric conditions that govern the formation, intensification and movement of tropical cyclones. Although these conditions may have a linear trend as a result of global warming (e.g. SST, moist static energy), they also vary within the ocean basin in response to other factors that have oscillations on multi-decadal time scales. It is these latter oscillations that are responsible for the multi-decadal variation in the frequency of intense typhoon occurrence. Further, the favourable thermodynamic and dynamic conditions must occur within the same general area. In other words, even if global warming causes a general enhancement of the basin-wide thermodynamic conditions, and hence more favourable for intensification (as proposed by some researchers), without the coupling of the favourable dynamic conditions, the TCs will still not intensify significantly, as evidenced in what happens in period B (1971-86). Because no hypothesis has been proposed as to whether global warming would lead to a basin-wide enhancement of favourable dynamic conditions, it is difficult to conclude that global warming would lead to an increase in intense typhoon occurrence.

What are the possible multi-decadal oscillations that could contribute to multi-decadal variations in intense typhoon occurrence? One possibility is the Pacific Decadal Oscillation (PDO, MANTUA et al. 1997). For example, the SST anomalies shown in Fig. 2 appear to be extensions of those in the tropical and midlatitude central North Pacific, which may be related to the PDO. Changes in the atmospheric circulation may also be related to the forcing by the SST anomalies through air-sea interaction, or to other multi-decadal oscillations such as the North Atlantic Oscillation that causes changes in the atmospheric circulation in the Eurasian continent and perhaps subsequently the subtropical high in the North Pacific. Of course, these possibilities need to be examined through further data analyses.

To conclude, the rather simplistic view that global warming would lead to more intense tropical cyclones because of the enhancement of thermodynamic factors ignores the fact that for tropical cyclones to intensify significantly, the dynamic factors must “cooperate”. However, the latter has not been demonstrated to be enhanced basin-wide. Therefore, the more likely conclusion is that the frequency of intense tropical cyclone occurrence cannot have a simple linear trend and must go through variations in response to similar variations in the factors that govern the formation, intensification and movement of tropical cyclones.
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