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Laboratory for Atmospheric Research, Department of Physics and Materials Science,
City University of Hong Kong, Hong Kong, China

Interannual and interdecadal variations of tropical cyclone activity over the western North Pacific

Johnny C. L. Chan

With 10 Figures

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Summary

This paper reviews the interannual and interdecadal variations in tropical cyclone (TC) activity over the western North Pacific (WNP) and the possible physical mechanisms responsible for such variations. Interannual variations can largely be explained by changes in the planetary-scale flow patterns. Sea-surface temperatures (SSTs) in the WNP, however, do not contribute to such variations. Rather, SSTs in the central and eastern equatorial Pacific are significantly correlated with TC activity over the WNP. Causality can be established: changes in the SST in the equatorial Pacific are related to the El Niño/Southern Oscillation (ENSO) phenomenon, and modifications of the planetary-scale flow associated with ENSO alter the conditions over the WNP and hence TC activity there. Variations in annual TC activity are also associated with different phases of the stratospheric quasi-biennial oscillations due to its modification of the vertical wind shear of the environment in which TCs form. Interdecadal variations in TC activity are apparently related to the location, strength and extent of the North Pacific subtropical high. However, the mechanisms responsible for modifying these characteristics of the subtropical high have yet to be identified.

1. Introduction

The western North Pacific (WNP) is the only ocean basin in the world in which tropical cyclones (TCs) can form throughout the year. The average number of TCs per year is ~30 (see Sect. 2), which is the highest among all ocean basins where TCs occur, and exceeds 30% of the global total of ~80. Such high activity mainly results from the frequent occurrence of favorable thermodynamic and dynamic conditions for TC development (Gray, 1979). Such occurrence, however, can vary significantly from year to year, which results in a large variation in the annual number of TCs (see Sect. 2). In addition, with a long enough time series, many recent studies have pointed out the existence of an appreciable interdecadal variation in the TC activity.

This paper presents a review of the interannual and interdecadal variations of TC activity over the WNP and the possible mechanisms responsible for such variations. Much of the material to be presented is from published literature. An overview of these variations is first given in Sect. 2. The interannual variations and the associated physical mechanisms are described in Sect. 3. The interdecadal variations are then examined in Sect. 4. Because only recently have interdecadal variations been studied, the physical mechanisms proposed by various researchers should be considered to be preliminary. Nevertheless, these hypotheses are also discussed. A summary of our current knowledge of the interannual and interdecadal variations is then given in Sect. 5, together with a discussion of possible future work.

2. Overview

The TC data used in this study are extracted from the website of the Joint Typhoon Warning Center[1]. Although the available data span from 1945–2003, only those from 1959 are used because some of the TCs before this time were likely missed due to the lack of satellite information.

The average monthly distribution of TCs within this period (Fig. 1) shows that the monthly frequency is lowest between January and March, then rises to a peak in August and decreases in the boreal autumn and winter. Yumoto and Matsuura (2001) found that the shape of this distribution remains largely the same for epochs with different TC occurrence frequency (see Sect. 4) except that the number of TCs in the high frequency periods between the months of July and October is higher than that in the low-frequency periods.

As pointed out by Chan (1985) and Chan and Shi (1996), the annual number of TCs has very significant interannual and interdecadal variations (Fig. 2). The number has a relative maximum in the 1960s, and then decreases to a minimum in the late 1970s to mid 1980s, rises again to another peak in the mid 1990s and then decreases since then. According to Yumoto and Matsuura (2001), the average number of tropical storms and typhoons (i.e., excluding tropical depressions) during the period 1961–72 is 30.2, that during 1973–85 25.3 and that during 1986–94 29.8. In addition to the interdecadal variations, the change in this number from year to year can also be very large. For example, the number of TCs in 1967 is 41, but drops to 23 in 1969 and rises to 37 again in 1971 (Fig. 2a). Such large-amplitude variations can also be seen in the number of tropical storms and typhoons (Fig. 2b) as well as the number of typhoons (Fig. 2c). A remarkable example in the latter is the number of typhoons in 1997 versus that in 1998, being 23 and 9, respectively.

In the following sections, more detailed explorations of these interannual and interdecadal

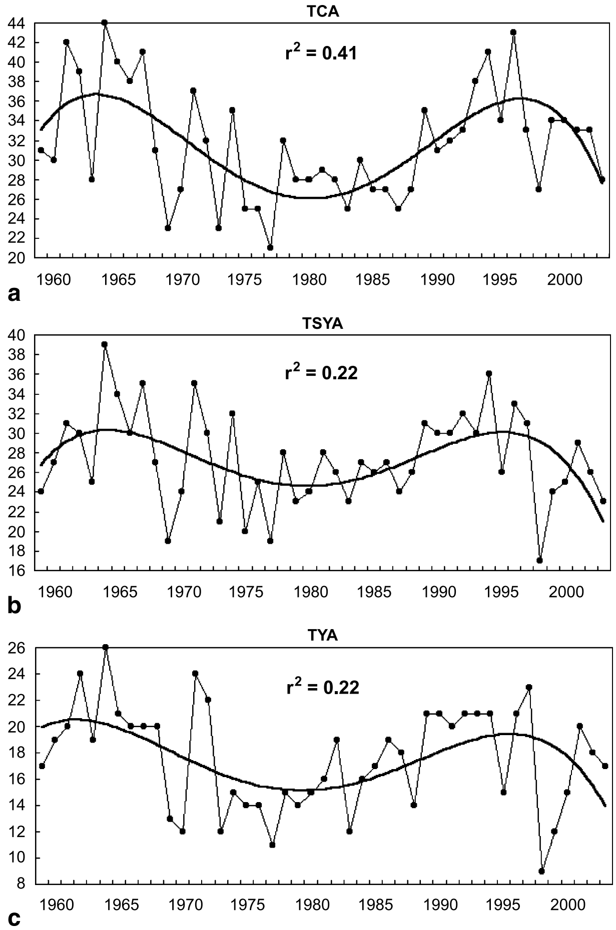

Fig. 2. Annual number of (**a**) all tropical cyclones, (**b**) tropical storms and typhoons, and (**c**) typhoons over the western North Pacific from 1959 to 2003. The curved line in each figure indicates a fourth-order polynomial fit to the time series. The value of r^2 in each figure is the percent of variance explained by the polynomial

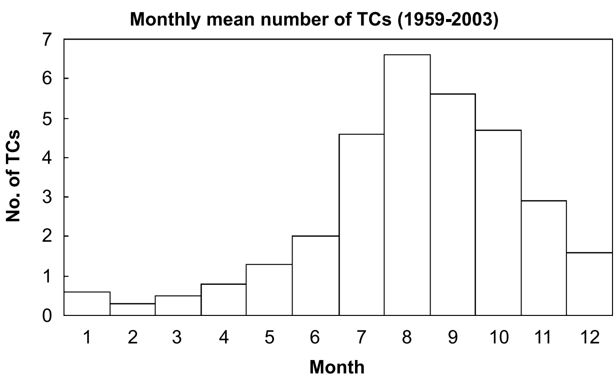

Fig. 1. Average monthly number of tropical cyclones over the western North Pacific based on the data 1959–2003 from the Joint Typhoon Warning Center. Month 1 is January, 2 is February etc

[1] http://metoc.npmoc.navy.mil/jtwc/best_tracks/wpindex.html

variations are made, together with some proposed mechanisms to explain such variations.

3. Interannual variations

Chan (1985) was the first to identify significant spectral peaks of 2 and 3.5 years in the time series of the annual number of TCs over the WNP. He suggested the former to be related to the stratospheric quasi-biennial oscillation (QBO), which was later found to be the case (Chan, 1995), and the latter to the El Niño/Southern Oscillation (ENSO). Chan and Shi (1996) extended the time series and found major periods of 2 and 7 years, the latter again attributed to ENSO. Further details of the relationships between TC activity and these two oscillations are discussed below.

3.1 Relationships with ENSO

3.1.1 Observed relationships

Chan (1985) found that the annual number of typhoons over the WNP correlates significantly with the Southern Oscillation Index (SOI) at the 3 to 3.5-year period, with the SOI leading by about one year. In other words, a decrease in SOI [corresponding to an El Niño (EN) event] is likely to be followed by a decrease in TC activity in the next year. Further, the number of TCs that form east of 150° E during an EN year tends to be above normal. Chan (1985) attributed these relationships to changes in the Walker circulation associated with ENSO. However, Lander (1994) disputed the existence of an ENSO signal in TC activity by identifying two EN events during which TC activity did not follow these general relationships. He nevertheless concurred with Chan's (1985) finding that more TCs tended to form in the eastern part of the WNP during an EN event. Dong (1988) and Dong and Holland (1994) also drew a similar conclusion. Using a coarse-grid general circulation model, Wu and Lau (1992) were able to simulate shifts in the location of TC formation in association with the migration of the sea-surface temperature (SST) anomalies in the equatorial Pacific (which can be used as proxies for the occurrence of an ENSO event).

Chan (2000) further examined TC activities in the year prior to, during and after an EN event and a La Niña (LN) event and found that during the year before an EN event, the number of TCs to the southeast of Japan tends to be below normal (Fig. 3a). The activities during and after an EN event (Fig. 3b and c) are consistent with the results obtained by Chan (1985). During the year prior to a LN event, the area east of the Philippines tends to have above-normal TC activity (Fig. 3d). However, these anomalies do not pass a significance test. In a LN year, the distribution of TC activity is generally opposite to that in an EN year, with fewer TCs over much, and especially the eastern part, of the WNP but more over the South China Sea (Fig. 3e). The entire WNP generally has above-normal TC activity during the year after a LN event (Fig. 3f).

Chan (2000) found that such anomalous TC activities during EN and LN events do not occur throughout the year, but only in certain months. During these months, the circulations that govern either TC genesis/development (850 hPa) or motion (500 hPa) have significant deviations from climatology, in association with the different phases of ENSO. In fact, most of the TC anomalies can be explained by such deviations. In other words, changes in the planetary-scale circulation from before to after the occurrence of an ENSO event modify to a large extent the locations where TCs form and intensify, as well as the TC tracks.

For example, during the late season in an EN year, low-level anomalous westerlies are found in the equatorial regions in the eastern part of the WNP (Fig. 4). This creates positive relative vorticity anomalies, which therefore provide a favorable environment for TC genesis so that more TCs form in the latter part of an EN year in the southeastern part of the WNP (see also Wang and Chan, 2002). Another example is the change in the steering flow. During the late season of an LN year, an anomalous anticyclone is found at 500 hPa over the East China Sea with significant easterly anomalies to its south (Fig. 5). As a result, TCs that form east of the Philippines have a tendency to enter the South China Sea (Fig. 6). Other examples of the association between TC activity anomalies and those of the large-scale atmospheric circulation can be found in Chan (2000), and Wang and Chan (2002). All these results therefore reinforce the existence of a relationship between ENSO and TC activity.

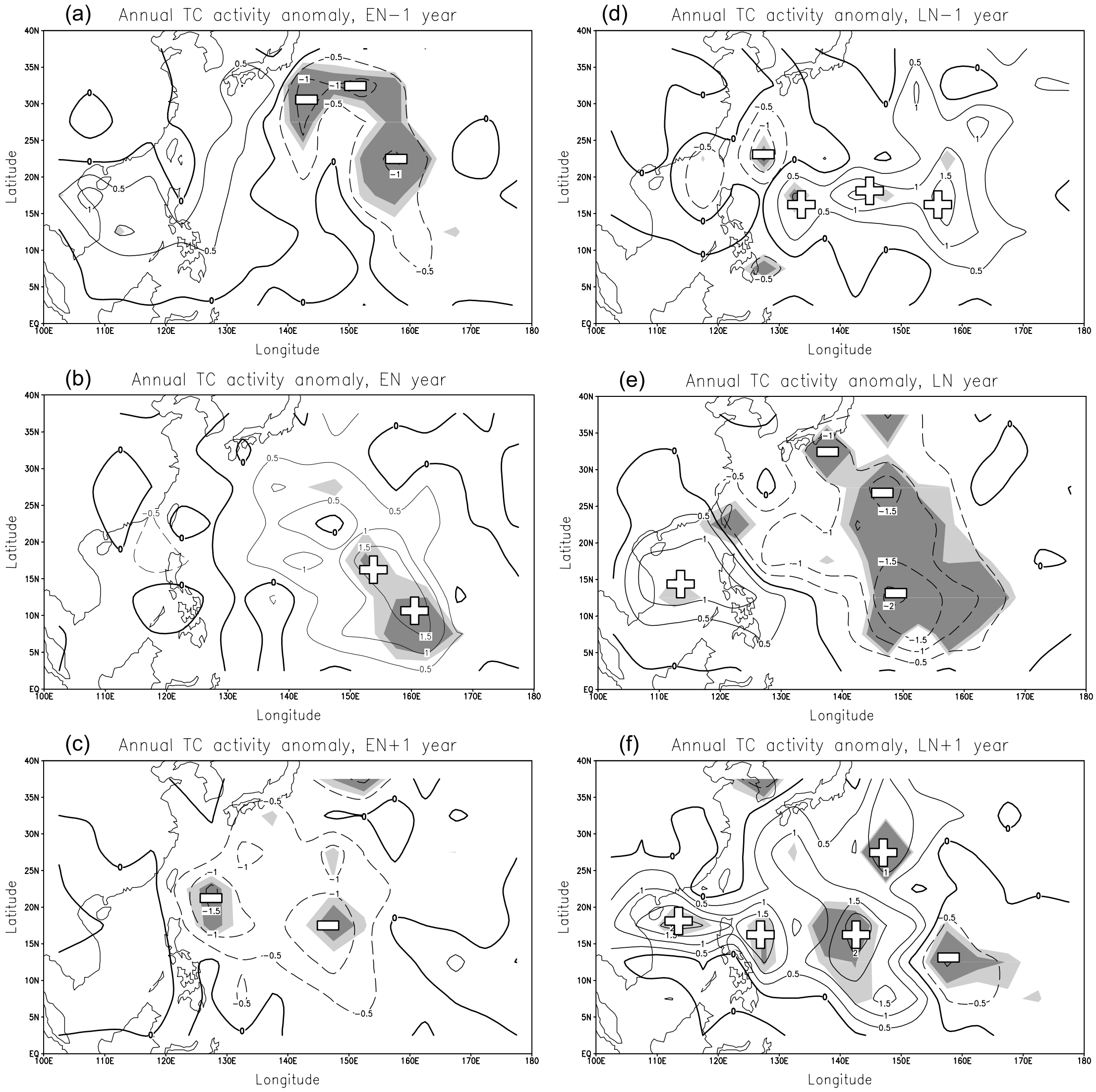

Fig. 3. Composite anomalies of the annual TC activity during (**a**) EN − 1, (**b**) EN, (**c**) EN + 1, (**d**) LN − 1, (**e**) LN, and (**f**) LN + 1 years over the western North Pacific. Solid (dashed) lines indicate positive (negative) anomalies, with the plus (minus) signs indicating the approximate locations of the maximum (negative maximum) values. Contour interval: 0.5. Light and dark shades indicate areas where the *t*-test is significant at the 90% and 95% level, respectively (from Chan, 2000)

Chen et al (1998) found that the locations of TC genesis during June to August differed between years when the SST in the NINO3 region (4° N–4° S, 150–90° W) was significantly above normal and those when the SST in this region was below normal. Specifically, when the SST was above normal (i.e., an EN event), TCs tended to form at lower latitudes and further eastward (Fig. 7). On the other hand, during an LN event (SST below normal), more TCs occurred at higher latitudes and further westward. Wang and Chan (2002), who extended Chen et al's (1998) study to include more recent events, also identified such a southeast–northwest difference between warm and cold years. In addition, Chen et al (1998) found similar but less pronounced east–west differences for the fall season (September to November).

Wang and Chan (2002) further noted that because TCs form farther to the southeast during warm years, they tend to last longer, with a mean life span of 7 days versus only 4 days for TCs in cold years. This also leads to a larger average number of days of tropical storm occurrence in warm years (159), almost twice the number in cold years (84). In addition, the tracks also differ

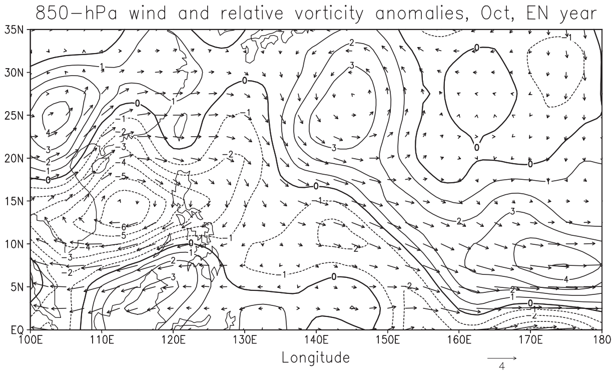

Fig. 4. 850-hPa wind (vector, scale indicated on lower right of diagram; unit: $m\,s^{-1}$) and relative vorticity (contour line, unit: $10^{-5}\,s^{-1}$, contour interval: $1 \times 10^{-5}\,s^{-1}$) anomalies during an EN year for the month of October (adapted from Chan, 2000)

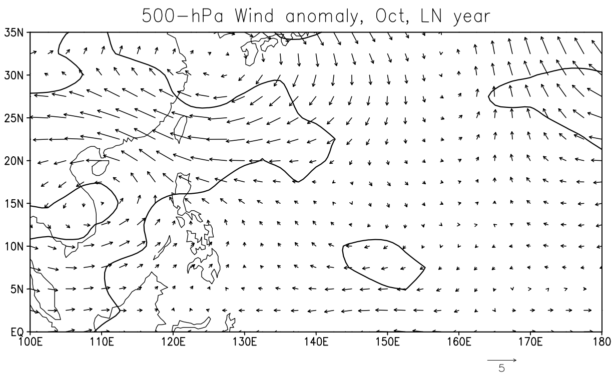

Fig. 5. Anomalous 500-hPa wind vectors (scale indicated on lower right of diagram; unit: $m\,s^{-1}$) during an LN year for the month of October. Contour lines indicate 80% wind steadiness of the composite (adapted from Chan, 2000)

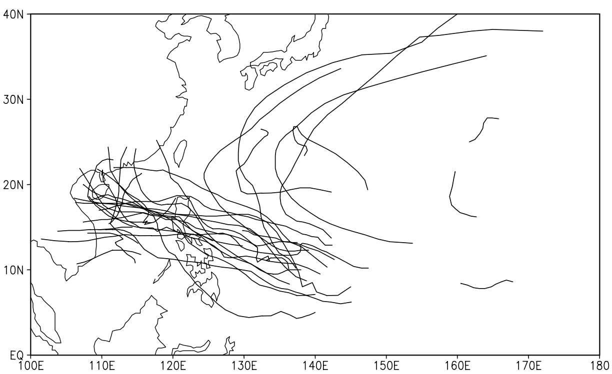

Fig. 6. Tracks of TCs in Oct of all the LN years between 1959 and 1997 (from Chan, 2000)

between warm and cold years. During the peak season (July to September), more TCs take on recurving tracks in warm years but those in cold

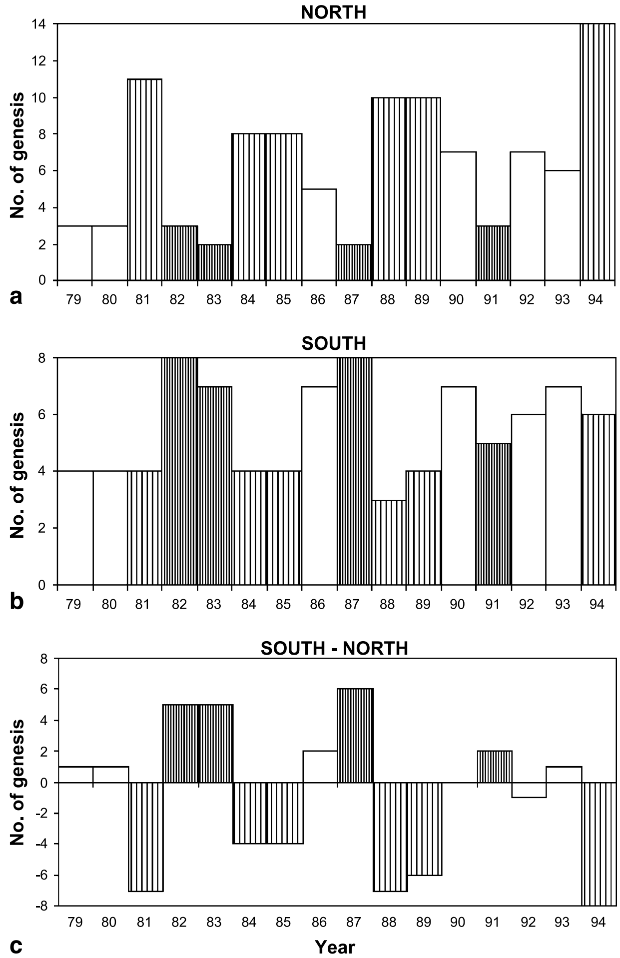

Fig. 7. Tropical cyclone genesis frequency of every summer (June–August) during 1979–94 over (**a**) 15–30° N, 120° E–180° (the North region) and (**b**) 0–15° N, 120° E–180° (the South region). The difference between South and North regions (south minus north) is shown in (**c**). Light (heavy) stripped bars indicate summers with NINO3 SSTA below (above) normal. (re-drawn from Chen et al, 1998)

years tend to move more northward after forming at locations further north than normal (Fig. 8). In the late season (October to December), recurving TCs continue to dominate in warm years but those in cold years have generally westward-moving tracks. As a result, the SCS experiences more TCs, which is consistent with the results of Chan (2000).

3.1.2 Physical mechanism

Most of the studies on the relationship between ENSO and TC activity show consistent results that can be physically explained by the changes in the planetary-scale circulation associated with ENSO. The following summarizes the consensus

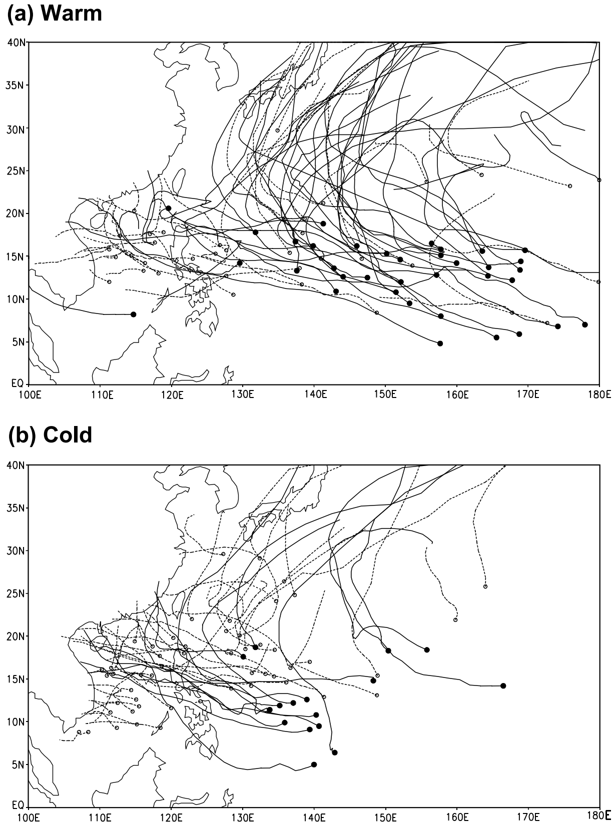

Fig. 8a. September–November TS tracks during the six strongest warm years (65, 72, 82, 87, 91, 97). Genesis locations (tracks) of the long-lived (life span exceeding 7 days) tropical storms formation are marked by heavy solid dots (solid lines). Genesis locations (tracks) of other storms are denoted by open circles (dashed lines). (**b**) The same as in (**a**), but for six strongest cold years (70, 73, 75, 88, 98, 99). (adapted from Wang and Chan, 2002)

explanations given by the various researchers (Chan, 1985; 2000; Wu and Lau, 1992; Lander, 1994; Chen et al, 1998; Wang and Chan, 2002).

Before the mature stage of the EN, strong westerly anomalies in the western equatorial Pacific have already extend to the dateline and beyond. These anomalies, when coupled with the trade winds, enhance the cyclonic shear so that the monsoon trough is located at lower latitudes and extends further eastward, which results in more TCs forming in the southeastern region of the WNP. This situation begins to occur from the early (April to June) to peak season (depending on the onset time of the warm event – see Xu and Chan, 2001) of an EN year (defined as the year in which SST anomalies in the eastern equatorial Pacific first reach a maximum). Because the TCs form further to the southeast, they tend to last longer when moving westward. At the same time, the subtropical high tends to be not as strong so that westerly troughs are more likely to penetrate southward, which results in more recurving TCs.

Wang et al (2000) suggested that during the year after the mature stage of a warm event, an anomalous anticyclone tends to form just to the east of the Philippines where TC formation is climatologically a maximum (Xue and Neumann, 1984). This anticyclonic flow suppresses the formation and development of TCs. As a result, TC numbers in the year after a warm event tends to be below normal.

If an LN event develops, easterly anomalies are present near the dateline. This is especially the case after the LN event has fully developed. These easterly anomalies then reduce the cyclonic shear. As a result, conditions in the southeastern region of the WNP become unfavorable for TC genesis and TCs can only form much further to the west. At the same time, the subtropical high tends to be enhanced, which suggests a northward displacement of the monsoon trough so that more TCs form in the northwestward quadrant. Because these TCs are already closer to land, they tend to have a shorter life span.

Thus, TC activity is being modulated to a certain extent by the occurrence of an ENSO event. Using a limited sample, Zhang et al (1990) showed that the SOI could explain about 40% of the variance of TC activity in the WNP. Prediction studies (e.g., Chan et al, 1998; 2001; Liu and Chan, 2003) also indicate that ENSO is one of the predictors of TC activity in the WNP. Of course, ENSO is not the only factor in causing the interannual variations in TC activity. Other atmospheric or oceanographic conditions may also contribute to such variations, one of which is the QBO.

3.2 Relationship with QBO

Gray (1984) has linked Atlantic hurricane frequency to the QBO, with the frequency of intense hurricane occurrence during the westerly phase of the QBO being almost three times that during the easterly phase (Gray et al, 1992). The proposed explanation is that when the zonal winds are westerly in the lower stratosphere, the vertical wind shear in the upper troposphere off the equator tends to be smaller and therefore favors TC formation.

Zhang et al (1994) examined the annual number of TCs over the WNP during the period 1884–1988 and found that TC activity tends to be enhanced during the westerly phase of the zonal winds in the lower stratosphere. Chan (1995) further obtained a significant correlation between the time series of TC activity in the WNP and those of zonal winds at 30 and 50 hPa at the QBO frequency. The phase difference between the two time series is consistent with the explanation of Gray et al (1992) and Zhang et al (1994). That is, when lower stratospheric winds begin to strengthen from the west, TC activity over the WNP is likely to increase. However, Chan (1995) also found that this correlation sometimes weakened during ENSO years, which suggests again that more than one factor must be considered in understanding the low-frequency variability of TC activity.

3.3 Results

In this section, two atmospheric and oceanographic oscillations – ENSO and QBO – have been identified as important contributors towards the interannual variations in TC activity. However, other factors can also come into play, as evidenced by the predictors of the annual TC activity used by Chan et al (1998; 2001), which include the strength of the subtropical high, the India-Burma trough and others. However, the mechanisms through which these factors affect the annual TC activity have yet to be identified. In addition, it is obvious from Fig. 2 that the annual variations are "high-frequency" oscillations superimposed on the interdecadal variations. Therefore, a better understanding of the former must come from a detailed examination of the latter, which is presented in the next section.

4. Interdecadal variations

In analyzing the variation of annual TC frequencies during the period 1884–1988, Zhang et al (1994) found oscillations with periods of 31, 21, 15 and 6 years although no physical explanation was given. They also identified significant changes in 1931, 1959 and 1977.

Yumoto and Matsuura (2001) found that the annual number of tropical storms and typhoons can be grouped into high-frequency periods (HFPs) during which this number is enhanced, and low-frequency periods (LFPs) during which this number is reduced. The difference in this number between the HFPs (1961–72 and 1986–94) and the LFPs (1951–60 and 1973–85) mainly lies during the months of July to October. Within the HFP, the area of TC genesis shifts more eastward compared with the LFPs.

To understand why this might be the case, Yumoto and Matsuura (2001) examined the SST distributions and found that the main difference in the SSTs between the HFPs and the LFPs is east of $\sim 150°$ E, where the SST is about 0.2 °C higher during the HFPs. This result implies that over areas where most TCs form (i.e. east of the Philippines – see Xue and Neumann, 1984), the SST apparently plays no role in increasing or decreasing TC activity. Wang and Chan (2002) also drew a similar conclusion. In addition, this result is consistent with a recent study by Chan and Liu (2004) that the SST over the WNP is not correlated with annual TC activity if the correlation with the SST over the central and eastern equatorial Pacific (representing the ENSO signal) is removed. Matsuura et al (2003) suggested that the increase in SST in the central and eastern equatorial Pacific could lead to a strengthening of the tropical westerlies, which then results in an eastward extension of the monsoon trough and an anomalous cyclonic circulation east of the Philippines, and hence more TCs.

Very recently, Ho et al (2004) found that summertime (June to September) tracks of tropical storms and typhoons also go through interdecadal changes, with the most significant decrease being in the number of TCs passing over the Philippine Sea (135–155° E, 5–15° N) during the period 1980–2001, at a rate of -9% per decade (Fig. 9b). Another area with a noticeable decrease is the East China Sea (125–135° E, 20–30° N), although the decrease is more of a transition than a continuous decrease (Fig. 9a). They attributed these decreases to an enlargement, strengthening as well as a southwestward extension of the subtropical ridge over the WNP since the late 1970s (Fig. 10). Such a change in the characteristics of the subtropical ridge then

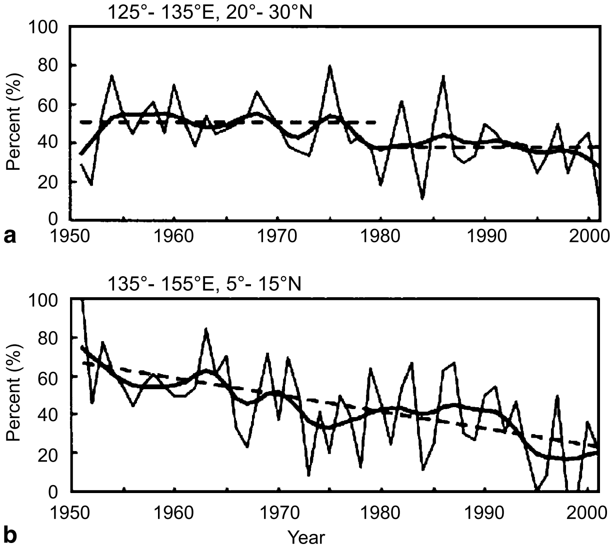

Fig. 9. Time series of frequency of passage of tropical storms and typhoons in two regions: (**a**) 125–135° E, 20–30° N, and (**b**) 135–135° E, 5–15° N. Heavy solid line denotes 9-point Gaussian filtered values. Dashed line denote in (**a**) the means for the period 1951–79 and 1980–2001, and in (**b**) the linear slope for the entire period (adapted from Ho et al, 2004)

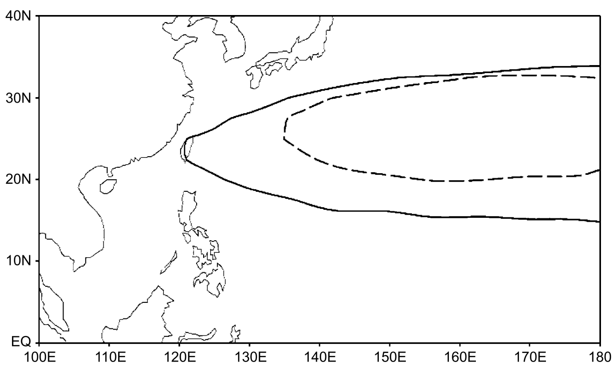

Fig. 10. Mean (June to September) position of the 5870 gpm contour for 1951–79 (dashed) and 1980–2001 (solid)

causes the location of TC formation and the subsequent tracks to be different.

The study by Matsuura et al (2003) suggested that the interdecadal TC variations may result from the forcing of the atmospheric circulation over the WNP by the SST over the central and eastern equatorial Pacific. However, the SST anomalies found by Yumoto and Matsuura (2001) covered a much larger area (see their Fig. 6), which corresponds to the location of the North Pacific subtropical high. As discussed above, Ho et al (2004) pointed out a correlation between changes in the subtropical high and those of TC activity. Thus, it appears that perhaps the SST forcing may not be limited to changing the strength of the tropical westerlies over the WNP.

A recent study by Chan and Zhou (2004) on the interdecadal variations in summer monsoon rainfall over South China suggested that such variations may be linked to the Pacific Decadal Oscillation, which is reflected in changes in SST over the WNP. They suggested that such changes cause variations in the strength of the subtropical high, which then modifies the rainfall over South China. In addition, Gong and Ho (2002) found a strong correlation between the strength of the subtropical high with the SST in the eastern tropical Pacific and tropical Indian Ocean. These two results may be complementary as Chan and Liu (2005) showed that SST over the WNP is negatively correlated with that over the central and eastern equatorial Pacific. Thus, it appears that while interdecadal variations in TC activity are perhaps largely related to the location, strength and extent of the North Pacific subtropical high, the mechanism responsible for modifying the latter needs to be further investigated.

5. Conclusions

This paper reviews the current state of understanding of the interannual and interdecadal variations in tropical cyclone (TC) activity over the western North Pacific (WNP). A significant proportion of the interannual variations can apparently be explained by the occurrence of the El Niño/Southern Oscillation (ENSO) phenomenon as well as changes in the phase of the stratospheric quasi-biennial oscillation (QBO). However, local sea-surface temperature appears to play no obvious role. The physical mechanism in the case of ENSO is that the changes in the atmospheric circulation associated with ENSO causes a shift in the location of the monsoon trough and a change in the location and intensity of the subtropical high, which then modify the TC formation locations, intensity and movement.

Different phases of the QBO provide different vertical shear profiles, which results in either a favorable or unfavorable environment for TC formation and development. While ENSO and QBO appear to be dominant factors in governing the interannual variability of TC activity over the WNP, they cannot explain all the variance, which suggests that other factors need to be identified and should be a subject for further investigation.

Recent studies on interdecadal variations in TC activity and tracks over the WNP appear to converge to the idea that such variations result from changes in the location, strength and extent of the North Pacific subtropical high. However, the mechanism responsible for the modification of the subtropical high is still uncertain and more research is necessary.

To conclude, the interannual variations in TC activity over the WNP have been well documented and largely understood. On the other hand, much more work is needed in determining the physical mechanisms responsible for the interdecadal variations.

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References

Chan JCL (1985) Tropical cyclone activity in the northwest Pacific in relation to the El Niño/Southern Oscillation phenomenon. Mon Wea Rev 113: 599–606

Chan JCL (1995) Tropical cyclone activity in the western North Pacific in relation to the stratospheric quasi-biennial oscillation. Mon Wea Rev 123: 2567–2571

Chan JCL (2000) Tropical cyclone activity over the western North Pacific associated with El Niño and La Niña events. J Climate 13: 2960–2972

Chan JCL, Liu KS (2004) Global warming and western North Pacific typhoon activity from an observational perspective. J Climate 17(23): 4590–4602

Chan JCL, Shi JE (1996) Long-term trends and interannual variability in tropical cyclone activity over the western North Pacific. Geophys Res Lett 23: 2765–2767

Chan JCL, Zhou W (2005) PDO, ENSO and the summer monsoon over South China. Geophys Res Lett (in press)

Chan JCL, Shi JE, Lam CM (1998) Seasonal forecasting of tropical cyclone activity over the western North Pacific and the South China Sea. Wea Forecast 13: 997–1004

Chan JCL, Shi JE, Liu KS (2001) Improvements in the seasonal forecasting of tropical cyclone activity over the western North Pacific. Wea Forecast 16: 491–498

Chen T, Weng S-P, Yamazaki N, Kiehne S (1998) Interannual variation in the tropical cyclone formation over the western North Pacific. Mon Wea Rev 126: 1080–1090

Dong K (1988) El Niño and tropical cyclone frequency in the Australian region and the northwest Pacific. Aust Meteor Mag 36: 219–225

Dong K, Holland GJ (1994) A global view of the relationship between ENSO and tropical cyclone frequencies. Acta Meteor Sinica 8: 19–29

Gong D-Y, Ho C-H (2002) Shift in the summer rainfall over the Yangtze River valley in the late 1970s. Geophys Res Lett 29 (DOI:10.1029/2001GL014523)

Gray WM (1979) "Hurricanes: their formation, structure and likely role in the tropical circulation." In: Meteorology over the Tropical Oceans (Shaw DB, ed). Bracknell, England, Royal Meteorological Society, pp 155–218

Gray WM (1984) Atlantic seasonal hurricane frequency. Part I: El Niño and 30 mb quasi-biennial oscillation influences. Mon Wea Rev 112: 1649–1668

Gray WM, Sheaffer JD, Knaff JA (1992) Influence of stratospheric QBO on ENSO variability. J Meteor Soc Japan 70: 975–994

Ho C-H, Baik J-J, Kim J-H, Gong D-Y (2004) Interdecadal changes in summertime typhoon tracks. J Climate 17: 1767–1776

Lander MA (1994) An exploratory analysis of the relationship between tropical storm formation in the western North Pacific and ENSO. Mon Wea Rev 122: 636–651

Liu KS, Chan JCL (2003) Climatological characteristics and seasonal forecasting of tropical cyclones making landfall along the South China coast. Mon Wea Rev 131: 1650–1662

Matsuura T, Yumoto M, Iizuka S (2003) A mechanism of interdecadal variability of tropical cyclone activity over the western North Pacific. Climate Dyn 21: 105–117

Wang B, Chan JCL (2002) How does ENSO regulate tropical storm activity over the western North Pacific? J Climate 15: 1643–1658

Wang B, Wu R, Fu X (2000) Pacific-East Asian teleconnection: How does ENSO affect East Asian climate? J Climate 13: 1517–1536

Wu G, Lau NC (1992) A GCM simulation of the relationship between tropical storm formation and ENSO. Mon Wea Rev 120: 958–977

Xu J, Chan JCL (2001) The role of the Asian/Australian monsoon system in the onset time of El Niño events. J Climate 14: 418–433

Xue Z, Neumann CJ (1984) Frequency and motion of western North Pacific tropical cyclones. Tech Memo NWS NHC 23: NOAA, Washington, DC, 89 pp

Yumoto M, Matsuura T (2001) Interdecadal variability of tropical cyclone activity in the western North Pacific. J Meteor Soc Japan 79: 23–35

Zhang GZ, Drosdowsky W, Nicholls N (1990) Environmental influences on northwest Pacific tropical cyclone numbers. Acta Meteorol Sinica 4: 180–188

Zhang G, Zhang X, Wei F (1994) A study on the variations of annual frequency of tropical cyclone in northwest Pacific during the last hundred years. J Trop Meteor 11: 315–323

Author's address: Johnny Chan, Department of Physics and Materials Science, City University of Hong Kong, Tat Chee Ave., Kowloon, Hong Kong, China (E-mail: johnny.chan@cityu.edu.hk)