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Interannual variations of intense typhoon activity

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ABSTRACT

This study attempts to determine the possible causes of the interannual variations of intense tropical cyclones (TCs, or typhoons) in the western North Pacific (WNP, defined here as the region 0–40°N, 120–180°E). It is found that such variations cannot be explained by those of sea-surface temperature averaged over the same region. Rather, in years with a high frequency of occurrence of intense typhoons (inferred from high values of accumulated cyclone energy, or ACE), both the dynamic and thermodynamic conditions in the atmosphere, especially in the southeastern part of the WNP, are favourable for the formation of TCs. On the other hand, these conditions are not conducive for TC formation in years with small number of intense typhoons (low values of ACE). The temporal coefficients of the empirical orthogonal functions of the relative vorticity anomalies in the lower troposphere, the vertical zonal shear and the moist static energy correlate very well with ACE. The ACE is also significantly correlated with the Nino3.4 SST anomalies. It is concluded that the interannual variations of intense typhoons in the WNP are likely caused to a large extent by changes in the planetary-scale atmospheric circulation and thermodynamic structure associated with the El Niño phenomenon.

1. Introduction

Two recent papers (Emanuel, 2005; Webster et al., 2005) have claimed that the recent increase in sea-surface temperatures (SSTs) as a result of global warming is likely to be responsible to the concomitant increase in either the power dissipation (Emanuel, 2005) or the number of intense hurricanes and typhoons (Webster et al., 2005) through a direct forcing of enhanced thermodynamic energy supply. However, many papers in the past have failed to identify such relationships. For example, Evans (1993) found no relationship between SST and the maximum intensity of tropical cyclones (TCs). More recently, Wang and Chan (2002, hereafter WC02) found that SST anomalies (SSTAs) in the western North Pacific (WNP) have no relationship with the location of TC formation over the same region. Chan and Liu (2004, hereafter CL04) actually found a negative relationship between TC number and SST in the WNP. The latest paper by Michaels et al. (2006) further pointed out the lack of correlation between TC intensity and SST especially for intense TCs. Because of these apparently contradictory results, it is important to re-examine the variations of the activity of intense TCs to determine the possible causes of such variations.

Most of these recent discussions focus on the low-frequency, or decadal, variations of intense TC activity. One contentious issue is the data quality prior to and in the early days of the satellite era (see, for example, the report by Kerr, 2006). Because this has yet to be resolved, only the high-frequency, or annual, variations are investigated in this paper. The objective here is to determine the possible physical causes responsible for the interannual variations of the activity of intense typhoons in the WNP (here defined as the region 0–40°N, 120–180°E). The reason for choosing the WNP is because of the relatively large number of intense TCs in this ocean basin so that the signal may be more robust. The data and methodology are described in Section 2. Relationships between the activity of intense typhoons and SST as well as various atmospheric quantities are presented in Sections 3 and 4. The results are further discussed in Section 5 together with a summary and conclusion.

2. Data and methodology

The best-track data are extracted from the website of the Joint Typhoon Warning Center.[1] SST data are from the Extended SST data set of the U.S. National Centers for Environmental Prediction/National Center for Atmospheric Research while those of atmospheric variables are from the re-analysis data set ERA40 of the European Centre for Medium-range Weather Forecasts.

Several indices have been used to represent the activity of intense TCs. Emanuel (2005) defined a power dissipation index

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

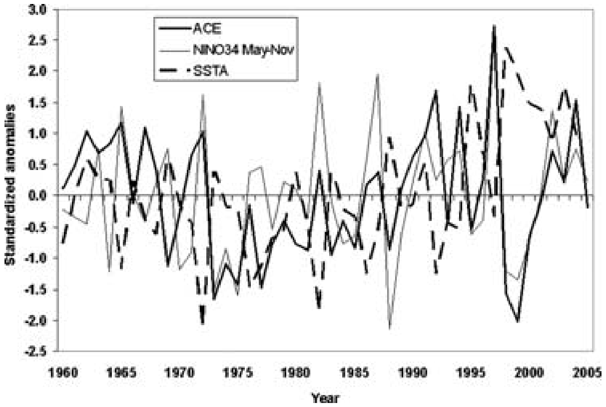

Fig. 1. Time variations of annual ACE (thick solid), Nino3.4 SSTA (thin solid) and SSTA within the region (5–30°N, 120–180°E) (thick dashed). Both SSTA values are averaged between May and November. All values for the three curves have been standardized. Abscissa is year.

(PDI), which is the cube of the maximum wind speed summed over the lifetime of a TC. Such an index can have significant errors especially if estimates of the TC intensity have large uncertainties. Webster et al. (2005) examined the number of hurricanes that are in the Categories 4 and 5 of the Saffir–Simpson scale.[2] However, because such categorization is 'quantized', a slight underestimate of the maximum winds would categorize an actual Category 4 TC as a Category 3, and hence not counted. Therefore, in this study, a more conservative quantity, the accumulated cyclone energy (ACE, Bell et al., 2000) is employed, which is defined as the square of the maximum wind speed summed over the lifetime of a TC. Such an index is biased towards the more intense TCs but any error in the intensity estimates will not be multiplied significantly as the PDI, and it does not suffer from the 'quantization' problem associated with using the number of TCs in Categories 4 and 5.

To make comparisons among the various time series easier, each variable to be examined is standardized. For simplicity, all discussions of the time series in the rest of the paper refer to the standardized values unless otherwise stated.

3. Time series analysis

The time series of the annual ACE over the WNP (Fig. 1) shows a maximum in 1960s, a minimum in 1970s and early 1980s, another maximum in the early 1990s and a general decrease from 1997 to the present. The time series of the annual SST averaged between May and November and within the region where most of the TCs form and develop (5–30°N, 120–180°E) shows the same general trend until the 1990s when the SST continues to rise. A detailed examination of the two time series actually suggests an out-of-phase relationship between them. Indeed, the correlation between the two series is −0.30, which however is not statistically significant at the 95% level. This is similar to and consistent with the results of CL04 who examined the relationship between TC activity and SST. Their further result that TC activity correlates well with the SST in the Nino3.4 region is also found for the ACE, as can be seen from the time series of Nino3.4 SSTA (averaged between May and November) in Fig. 1. The correlation between the ACE and Nino3.4 series is 0.60, which is significant at the 99% level.

Therefore, at least for the WNP, the annual ACE, and thus likely the annual number of intense TCs, is apparently not related to the May–November mean SST averaged over the entire tropical WNP. This is similar to the conclusion of WC02 and CL04 who pointed that annual TC activity in the WNP is not regulated by the SST in the region but rather controlled by the atmospheric circulation in the WNP, which is related to the Nino3.4 conditions.

4. Differences between high and low ACE years

To investigate further the relationship between ACE and SST and other meteorological variables, the sample is divided into three groups based on the standardized values of ACE: high ACE years in which the ACE values are $\geq 0.5\sigma$ (σ being the standard deviation), low ACE years in which the ACE values are $\leq -0.5\sigma$ and the rest being the normal ACE years. Composites are then made of SST and other variables for the high and low ACE years.

4.1. SST

The composite SST for high ACE years show very weak negative anomalies over the entire WNP but an area of positive anomalies with a maximum value of around 0.5 °C is found in the Nino3.4 area (Fig. 2a). On the other hand, the opposite situation occurs in low ACE years, with very weak positive anomalies over the WNP and negative anomalies in the equatorial central and eastern Pacific (Fig. 2b). These results are therefore consistent with the conclusion in the last section that on interannual time-scales, SST anomalies averaged over the entire tropical WNP are not likely to be a factor in determining the intense TC activity there.

However, it is noted that in high ACE years, the SST anomalies in the southeastern part of the WNP are weakly positive (Fig. 2a), and the opposite is true in low ACE years (Fig. 2b). Indeed, a correlation between ACE and the SST anomalies within the region (5–15°N, 160–180°E) gives a coefficient of 0.31. The SST anomalies in this region are clearly an extension of those in the Nino3.4 area and are therefore associated with the El Niño/Southern Oscillation (ENSO) phenomenon. Thus, while the variations of SST over the entire tropical WNP apparently do not contribute to those of ACE on interannual time-scales, SST changes in the southeastern part of the WNP do have a contribution. A physical explanation of these results will be given later.

[2]http://www.aoml.noaa.gov/general/lib/laescae.html

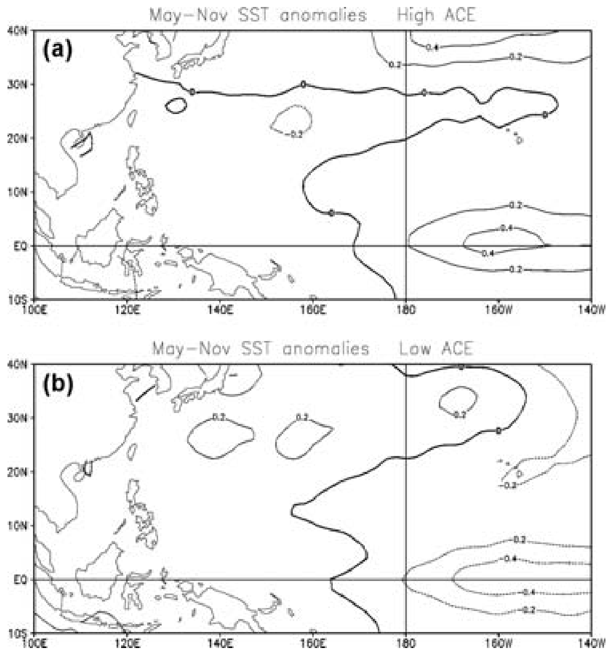

Fig. 2. Composite SSTA (unit: °C) averaged between May and November for (a) high and (b) low ACE years. See text for definition of high and low ACE years. Contour interval: 0.2 °C. Dashed contours indicate negative values.

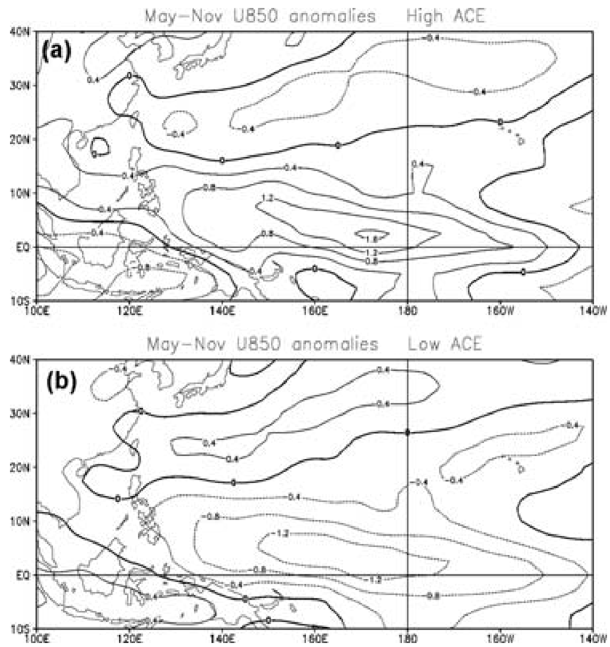

Fig. 3. As in Fig. 2 except for 850-hPa zonal wind anomalies. Unit: m s^{-1}, contour interval: 0.4 m s^{-1}.

4.2. 850-hPa zonal winds

As the 850 hPa winds provide the low-level cyclonic vorticity necessary for the spin-up of the TC vortices (Gray, 1979), it is useful to examine their patterns in relation to ACE. The composite 850-hPa zonal winds for high ACE years show anomalous westerlies over the entire tropical WNP, with a maximum of over 1.6 m s^{-1} just west of the dateline (Fig. 3a). At the same time, anomalous easterlies exist in the subtropical WNP. This pattern provides anomalous cyclonic vorticity especially over the eastern part of the tropical WNP, and is therefore more favourable for TC genesis there (Gray, 1979). Cyclones that form in this region generally have a longer lifetime (WL02) and hence a higher probability of being more intense.

The anomalous 850-hPa zonal wind pattern for low ACE years is almost the entire opposite (Fig. 3b), with strong easterly anomalies of >1.2 m s^{-1} in the tropical WNP east of $\sim$150°E and anomalous westerlies in the subtropical WNP. This creates anomalous anticyclonic vorticity in the area where TCs are most likely to occur. The broad easterly anomalies in the eastern part of the tropical WNP further discourage TC formation there. As a result, fewer TCs can form in this area and therefore the ACE tends to be lower in these years.

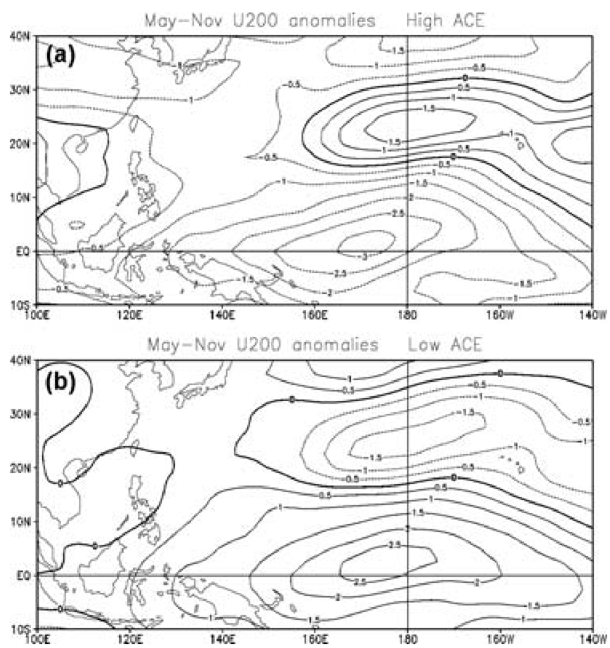

Fig. 4. As in Fig. 2 except for 200-hPa zonal wind anomalies. Unit: m s^{-1}, contour interval: 0.5 m s^{-1}.

4.3. 200 hPa winds

In high ACE years, strong upper tropospheric easterly anomalies are found in the tropical WNP and westerly anomalies in the subtropical WNP (Fig. 4a) so that anticyclonicanomalies exist in the WNP especially in the eastern part. This pattern, coupled with the lower tropospheric flow, is very favourable for TC formation there. On the other hand, upper tropospheric cyclonic anomalies are found over the WNP in low ACE years (Fig. 4b), with

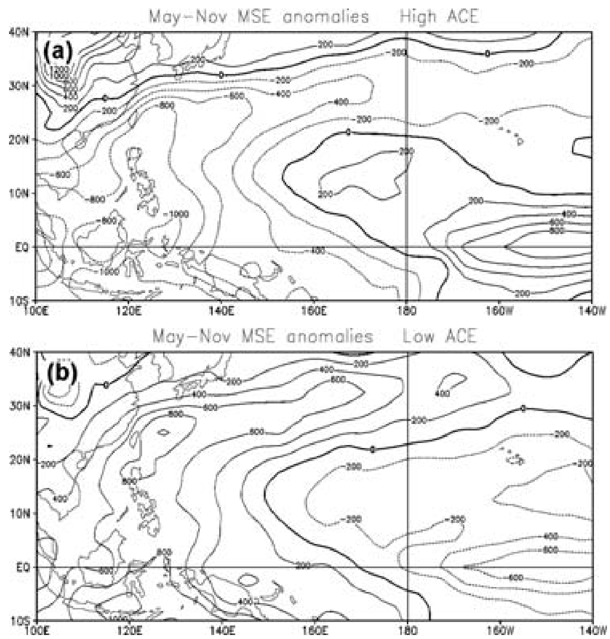

Fig. 5. As in Fig. 2 except for anomalies in moist static energy averaged between 1000 and 500 hPa. Unit: J kg^{-1}, contour interval: 200 J kg^{-1}.

westerly anomalies in the tropical WNP and easterly anomalies in the subtropical WNP.

4.4. Moist static energy

One parameter that CL04 found to be correlated with TC activity is the moist static energy (MSE). Therefore, it is useful also to examine this parameter here. In high ACE years, values of MSE (integrated between 1000 and 500 hPa and averaged between May and November) are anomalously high in the eastern and low in the western WNP (Fig. 5a). This pattern suggests that in these years, the atmosphere in the southeastern part of the WNP is particularly conducive to strong convection. In other words, both the dynamic and thermodynamic conditions in the atmosphere support the development of TCs especially in the southeastern part of the WNP. TCs that form in this area have a longer lifetime over the ocean and therefore are more likely to become intense, and hence the frequency of occurrence of intense TCs is likely to be higher in these years.

The reverse is true in low ACE years in which values of MSE are anomalously low in the eastern and high in the western WNP (Fig. 5b). In this case, the atmosphere is less favourable for strong convection in the southeastern part of the WNP. That is, both the dynamic and thermodynamic conditions in the atmosphere do not support the development of TCs in this part of the ocean basin and TCs are more likely to form further west. These TCs will have a shorter lifetime over the ocean and hence the frequency of occurrence of intense TCs is likely to be lower in these years.

It is also noteworthy that the area where the MSE has above-normal values in high ACE years is also where the SST anomalies are positive (cf. Figs. 2a and 5a). Apparently, the increase in MSE is related to the rise in SST, which is what might be expected in the tropics. A similar but opposite situation occurs for the low ACE years (cf. Figs. 2b and 5b).

4.5. Correlations

To examine further the significance of these dynamic and thermodynamic factors in determining the ACE value, each of the factors is subjected to an empirical orthogonal function (EOF) analysis. However, instead of the 850- and 200-hPa zonal winds, the 850-hPa relative vorticity and the vertical (200 – 850 hPa) zonal shear are analysed as they actually provide more information than simply the zonal winds at one level. The temporal coefficients corresponding to each EOF are then correlated with the ACE values. For the two dynamic factors (850-hPa relative vorticity and vertical zonal shear), the first EOF correlates well with ACE, with correlation coefficients 0.58 and −0.67, respectively, both values being significant at the 99% level.

For MSE, the first EOF of MSE, which explains about 51% of the total variance, shows a broad pattern over the entire WNP, with larger values to the west and smaller values to the east (not shown). However, the correlation with ACE is −0.22, which is not statistically significant. The time series of the coefficients show a generally increasing trend (not shown), which suggests an overall increase in MSE in recent years. Whether such an increase is related to global warming is beyond the scope of this paper and will not be discussed. On the other hand, the second EOF, which explains 22% of the variance, has a pattern very similar to that shown in Fig. 5. Application of the test for degeneracy suggested by North et al. (1982) suggests that the eigenvalues associated with these two EOFs are well separated. Correlating the time coefficients of this second EOF with those of ACE gives a correlation coefficient of 0.72, which is significant at the 99% level.

A plot of the time series of the temporal coefficients of these three parameters against that of ACE clearly illustrates that all of them vary almost in tandem with ACE (Fig. 6), which further validates the composite results shown in the previous few subsections. It is also of interest to note from Fig. 6 that the correlations with ACE appear to be not as good prior to 1970 and become much better afterwards. Indeed, much higher correlation coefficients are obtained for all the three variables if only the latter years are included. For example, the correlation coefficients reach 0.64, −0.75 and 0.81 for the relative vorticity, vertical shear and MSE parameters, respectively, when using the time series from 1980 to 2005. These are likely related to the data quality in the early years, an issue that has recently been addressed by Knaff and Sampson (2006) and Knaff and Zehr (2007). Such an observation only further strengthens the

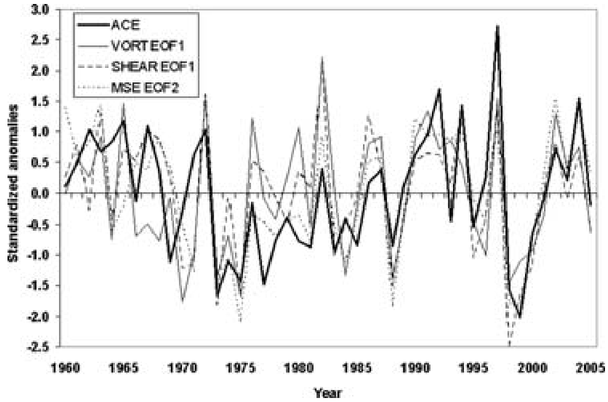

Fig. 6. Time variations of annual ACE (thick solid), coefficients of first empirical orthogonal function (EOF) of 850-hPa relative vorticity (thin solid), of vertical zonal wind shear between 200 and 850 hPa (dashed) and of second EOF of moist static energy (dotted). All EOFs are computed for the WNP region. The coefficients of vertical zonal shear have been multiplied by −1. Abscissa is year.

conclusion of this study. Nevertheless, as this is not the focus of the present study, it will not be discussed further.

5. Summary and discussion

The results of this study suggest that the variations of intense TCs (typhoons) in the WNP on interannual time-scales cannot be explained by those of SST averaged over the entire tropical WNP. In other words, the frequency of occurrence of intense typhoons in this region is not likely determined by the average SST over the region. Rather, in years with a high frequency of occurrence of intense typhoons, both the dynamic (relative vorticity in both the lower and upper troposphere as well as the vertical wind shear) and thermodynamic (as represented by the moist static energy in the low to mid troposphere) conditions in the atmosphere, especially in the eastern part of the WNP, are favourable for the formation of TCs. Once formed, these TCs tend to have longer lifetimes over the ocean, and therefore have a high chance to become more intense. The vertical shear conditions are also conducive for the maintenance of these TCs. On the other hand, relative vorticity anomalies are anticyclonic in the lower and cyclonic in the upper troposphere in years with small number of intense typhoons. The moist static energy is also anomalously low in the eastern part of the WNP. Thus, it is less likely that TCs can form in this region and hence most TCs form further west. They have less time to develop and therefore tend to be less intense. The temporal coefficients of the empirical orthogonal functions of the relative vorticity anomalies in the lower troposphere, the vertical zonal shear and the moist static energy correlate very well with the ACE, which is used as a proxy for the number of intense TCs.

In addition to these significant correlations, the ACE is also significantly correlated with the Nino3.4 SST anomalies. Indeed, the anomalies in SST (see Fig. 2) and those in zonal winds in the lower and upper troposphere in the WNP (see Figs. 3 and 4) in high ACE years are the patterns that are associated with El Niño conditions, and those in low ACE years with La Niña conditions. WC02 have pointed out that TCs in strong El Niño years tend to have longer lifetime because they tend to form in the southeastern quadrant of the WNP. On the other hand, the lifetime of TCs in strong La Niña years tends to be shorter as most of them form in the northwestern quadrant. The current results for the ACE are therefore very similar to theirs and can be similarly explained.

The relationship between SST and ACE needs to be discussed further. Because SST in the WNP is anti-correlated with the Nino3.4 SST, it could be argued that while the El Niño/Southern Oscillation phenomenon is the dominant factor controlling the interannual variability of intense TC activity in the WNP, it is possible that in situ SST could still have a secondary effect. However, CL04 has shown this not to be the case when they examined the interannual variation of TC activity. When the correlation between WNP SST and Nino3.4 SST is removed, the partial correlation between TC activity and WNP SST becomes very small, and remains negative. A similar result is found when using the ACE (not shown). The average SST over the entire tropical WNP does not appear to be one of the factors in directly determining TC intensity in the WNP on interannual time-scales because the SST is very high in this region throughout the year (>28.5 °C) so that slight variations in SST of a few tens of a degree do not have much of a contribution to the overall conditions necessary for TC formation and development.

However, the SST in the southeastern part of the WNP does correlate with ACE, though the statistical significance is not very high. This region is near the edge of the warm pool and thus fluctuations in the SST could likely cause changes in the convective stability of the local atmosphere, as evidenced by the variations in the MSE. The relationship between MSE and ACE is likely a reflection of such variations. Note that variations of SST in this region are an extension of those in the Nino3.4 area and hence are related to the ENSO phenomenon.

To conclude, the variations in the frequency of occurrence of intense typhoons on interannual time series are caused by changes in the planetary-scale circulations in the WNP mostly associated with the El Niño phenomenon. Such changes lead to variations in the local dynamic and thermodynamic conditions of the local atmosphere that become either more or less favourable for TC formation and development. It should be noted that because these conditions cannot explain all the variance in ACE, some other factors that control the variations of ACE still need to be identified.

6. Acknowledgments

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