Environmental Influences on the Intensity Change of Tropical Cyclones in the Western North Pacific

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ABSTRACT

The atmospheric and oceanic conditions are examined during different stages of the lifecycle of western North Pacific tropical cyclones (TCs), with the intention to understand how the environment affects the intensity change of TCs in this area. It is found that the intensification usually occurs when the underlying sea surface temperature (SST) is higher than 26℃. TCs usually experience a rapid intensification when the SST is higher than 27.5℃ while lower than 29.5℃. However, TCs decay or only maintain its intensity when the SST is lower than 26℃. The intensifying TCs usually experience a low-to-moderate vertical wind shear (2–10 m s^{-1}). The larger the vertical wind shear, the slower the TCs strengthen. In addition, the convective available potential energy (CAPE) is much smaller in the developing stage than in the formation stage of TCs. For the rapidly intensifying TCs, the changes of SST, CAPE, and vertical wind shear are usually small, indicating that the rapid intensification of TCs occurs when the evolution of the environment is relatively slow.

Key words: tropical cyclone, sea surface temperature, convective available potential energy, vertical wind shear

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1. Introduction

Over the past several decades, there are vast improvements in the tropical cyclone (TC) track prediction, due mostly to the acquisition of better observations, advances in numerical weather prediction models and data assimilation schemes (Wang and Wu, 2004). However, there are little improvements in skills in predicting TC intensity change (Elsberry et al., 2007). The current official operational forecast of TC intensity still relies on statistical prediction models (Knaff et al., 2005). In the statistical models, a majority of the predictors are environmental factors depicting the thermodynamic and dynamical status of the atmosphere and the underlying ocean. It is now recognized that certain environmental conditions may have decisive influences on TC intensity change, although the latter involves a complex array of physical processes (Cheung, 2004).

Chan et al. (2001) found that TC intensity change is very sensitive to the variation of sea surface temperature (SST), and the response is nearly simultaneous. They also found with their idealized model that SST should be larger than 27℃ in order for TCs to intensify. He et al. (2006) analyzed the Geostationary Meteorological Satellite (GMS) high-resolution SST dataset and its relation to TC formation and maintenance in the western North Pacific (WNP). Their results suggest that the lower bound of SST for TC to form and maintain is 28℃; TCs do not form or decay rapidly when the underlying SST is lower than this threshold.

The convective available potential energy (CAPE), which is a measure of the instability of atmo-

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spheric stratification, is another important thermodynamic factor that affects the TC intensity change (Cheung and Elsberry, 2002). When the environmental CAPE is larger, the organized convective process within the TC circulation becomes more active, and more energy is released to feed the system, which is beneficial to the intensification of TCs.

The vertical shear of environmental wind is considered as an important dynamical factor in close relation to TC intensity change. Several earlier studies suggested that weak vertical wind shear (VWS) is favorable for TCs to intensify (e.g., DeMaria, 1990; Wu and Cheng, 1999; Emanuel et al., 2004). Holland and Wang (1999) found that the presence of VWS only reduces the intensification rate of a TC, and the TC would eventually attain its maximum potential intensity. Moreover, Zehr (2003) showed that few TCs form in the WNP when the environmental VWS is larger than 12.5 m s^{-1}. The statistical analysis of Zhao et al. (2006) also found that TCs reach typhoon strength only when the environmental VWS is less than 7 m s^{-1}. Paterson et al. (2005) analyzed TCs in the Australian Ocean and found that weak VWS of 2–4 m s^{-1} is a necessary condition for the TC rapid intensification.

The above-mentioned studies provide insight into the important environmental factors modulating TC intensity. However, further understanding of environmental control of TC intensity change is required. The current study extends previous studies by exploring the environmental influences on TC intensity change during different stages of the TC lifecycle. The remainding of this paper is organized as follows. The data and methodology are described in Section 2. Section 3 examines the characteristics of SST, CAPE, and VWS during the developing and weakening stages of TCs. Section 4 applies the analyses in Section 3 to TCs with different intensity categories. The main conclusions are summarized in Section 5.

2. Data and methodology

The best-track data for TCs in the WNP basin are obtained from the Joint Typhoon Warning Center (JTWC). The data contain storm location (longitude and latitude), maximum sustained wind speed (VMAX), and minimum sea level pressure at 6-h intervals. TCs are classified into 7 categories based on their VMAX values: tropical depression (TD; VMAX $\leqslant$ 33 kt), tropical storm (TS; 34 $\leqslant$ VMAX < 63 kt), category 1 (CAT1; 64 $\leqslant$ VMAX < 82 kt), category 2 (CAT2; 83 $\leqslant$ VMAX < 95 kt), category 3 (CAT3; 96 $\leqslant$ VMAX < 113 kt), category 4 (CAT4; 114 $\leqslant$ VMAX $\leqslant$ 135 kt), and category 5 (CAT5; VMAX > 135 kt). The analysis in the present study covers the period 2000–2010. The 6-h zonal (u) and meridional (v) wind fields from the NCEP global final (FNL) reanalysis dataset with a horizontal resolution of 1°×1° are used to quantify the environmental VWS. The VWS is calculated as the difference of wind vectors between 200 and 850 hPa:

$$\mathrm{VWS} = \sqrt{(u_{200} - u_{850})^2 + (v_{200} - v_{850})^2}.$$

Similarly, the vertical shear of zonal wind (VWS$_u$) and the vertical shear of meridional wind (VWS$_v$) are defined as

$$\mathrm{VWS}_u = u_{200} - u_{850},$$
$$\mathrm{VWS}_v = v_{200} - v_{850}.$$

The CAPE data are provided by the US National Oceanic and Atmospheric Administration (NOAA) with a horizontal resolution of 2°×2°. The daily NOAA/AVHRR SST data on a 0.25° longitude-latitude grid are used as observations. The VWS, CAPE, and SST data are averaged within a radius of 5° from the storm center to characterize the storm environment.

This study divides the lifecycle of each TC into two stages, i.e., the developing stage and the decaying stage. The developing stage is defined as from the genesis of a TC to the time it reaches its maximum intensity, and the rest of the lifecycle is taken as the decaying stage. In general, the average duration of the developing stage is longer than that of the decaying stage in the whole lifetime of the TC. Therefore, the sample number is different in the above two stages. For the observational records of 265 TCs in the WNP during the period of 2000–2010, there are 5197 samples in the developing stage and 2984 samples in the decaying stage, with 6-h sampling time intervals. If the ith record of the maximum wind speed for an individual TC is denoted as VMAX(i), the intensity change of the TC over the next 6 hours is defined as ΔVMAX(i) = VMAX(i+1)–VMAX(i). The TC is intensifying if ΔVMAX(i) > 0; maintaining its strength if ΔVMAX(i) = 0; and weakening if ΔVMAX(i) < 0. It is well known that in the developing (decaying) stage, storms are not always intensifying (weakening) during the 6-h intervals. In these 11-yr samples, there exist 107 (2%) weakening samples in the developing stage and 119 (4%) intensifying samples in the decaying stage. These samples are neglected in the following investigation since their percentages are relatively small. In the next section, the relationship between the environmental factors (i.e., SST, CAPE, and VWS) and TC intensity change during the developing and decaying stages is explored in detail.

3. Effects of environmental factors on TC intensity change

3.1 SST

Figure 1a shows the cumulative number of cases in the developing stage of TCs as a function of SST. From the TC genesis to the time of its maximum intensity, the mean value of the underlying SST is 28.7℃, and the standard deviation is 0.8℃. Most of the samples (3823 cases, i.e., 72.7% of all the cases in the developing stage) correspond to SST values of 28–29.5℃. The distribution of SST as a function of TC intensity is shown in Fig. 1b. It can be seen that the SST is usually larger than 26℃ when TC intensity is lower than 34 kt, which is consistent with the lower bound of SST for the transformation of tropical disturbances into tropical storms. It is also seen in Figs. 1a and 1b that the number of samples, especially the number of intense TCs, is fewer when SST is higher than 30℃. For most of the cases with intensity higher than 95 kt (CAT3 and above), the underlying SST is lower than 30℃. Moreover, there are few cases with intensity higher than 82 kt (CAT2 and above) when the underlying SST is lower than 26℃. In fact, most of the 36 cases with SST lower than 26℃ is near the end of their lifecycles.

The TC intensity change during the developing stage and its relationships to SST and SST change are shown in Fig. 2. It can be found that TCs generally maintain their intensity when the underlying SST is lower than 26℃ (Fig. 2a). For TCs with larger intensification rates, the variation of SST is smaller. For example, the variation of SST is concentrated within the range of 27.5–29.5℃ for TCs with intensification rates larger than 20 kt (6 h)$^{-1}$. The relation between the TC intensity change and the SST change shown in Fig. 2c indicates that the large variation in SST is not favorable for TCs to intensify. Therefore, small variation of SST is a necessary condition for larger TC intensification rate.

As the decaying stage of TCs is concerned (figure omitted), about 71.6% of all the cases occur when the SST is in the range of 26–29℃. The SST value is systematically lower than that during the developing stage. For example, there are only 52 cases with SST higher than 29.5℃ during the decaying stage. The highest two cumulative numbers of cases appear in the SST range of 27.5–28.5℃, which is 1℃ lower than that

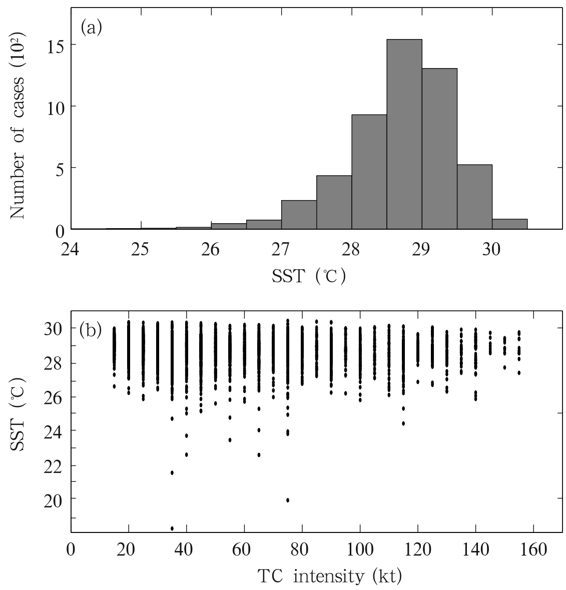

Fig. 1. (a) Cumulative number of samples in the developing stage of TCs as a function of SST (0.5℃ interval) and (b) distribution of SST as a function of TC intensity for the developing stage. Note: 1 kt = 0.514 m s^{-1}.

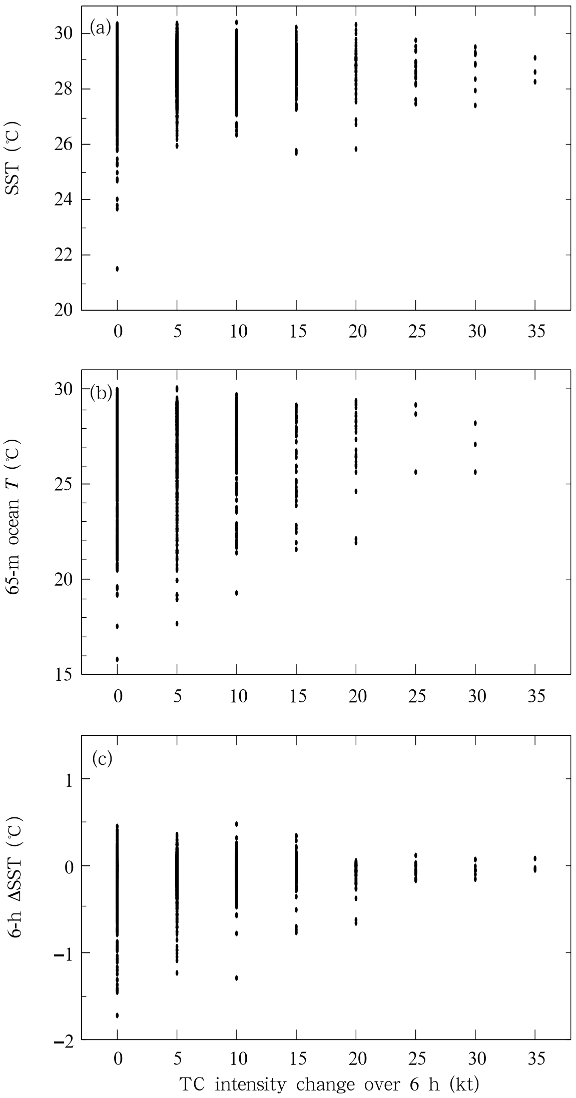

Fig. 2. Distributions of (a) SST, (b) ocean temperature (T) at 65-m depth, and (c) SST change (ΔSST) over 6 h as a function of TC intensity change over 6 h during the developing stage of TCs. Note: 1 kt = 0.514 m s^{-1}.

in the developing stage. With the lower SST, the heat and moisture fluxes into TCs are much reduced, which is not beneficial to the intensification of TCs. It is often the case that TCs recurve into high latitudes during the decaying stage. As TCs moving northward, the SST decreases steadily. This may largely explain why the SST is systematically lower during the decaying stage, and why the distribution of SST is not so concentrated as that during the developing stage (figure omitted).

3.2 CAPE

The CAPE values in the genesis, peak intensity, and decaying stage of TCs, and the maximum CAPE in TC lifetime are shown in Fig. 3. The mean CAPE during the genesis stage of the 265 TCs in the WNP during 2000–2010 is 1061 J kg^{-1} (Fig. 3a), and the mean maximum CAPE is 1213 J kg^{-1} (Fig. 3b). About 97% of the maximum CAPE values during the TC lifetime are found in the genesis stage, which is consistent with the results of Zehr (1992). Large CAPE leads to active convection, which is favorable for the genesis and development of TCs. Due to consumption of CAPE during the developing stage, the mean CAPE has decreased to 678 J kg^{-1} when TCs reach their maximum intensity (Fig. 3c). The CAPE value continues to decrease after the maximum intensity. For most of the 265 TCs, the CAPE value is below 500 J kg^{-1} and the mean CAPE is only 385 J kg^{-1} during the TC decaying stage (Fig. 3d).

Figure 4a demonstrates the relationship of TC intensity change to the value of CAPE during the TC developing stage. The minimum and maximum of CAPE occur only when the TC intensification rate is very slow. For the cases with large intensification rates, the range of CAPE is narrow and the mean CAPE is relatively large. The large CAPE implies more energy to be supplied to the TC system, which in turn leads to more rapid intensification of TC. For example, the CAPE value is 800 J kg^{-1} for the cases with intensification rate larger than 30 kt (6 h)$^{-1}$ while the CAPE value is only 600 J kg^{-1} for the cases with intensification rate larger than 20 kt (6 h)$^{-1}$. On the other hand, the intensification process consumes and decreases CAPE; thus, only moderate value of CAPE is found in TCs undergoing rapid intensification. The relationship of the TC intensity change to the variation of CAPE is given in Fig. 4b. It is clearly seen that the intensification rate is usually small when large variations in CAPE occur. For the cases with the large intensification rate, the range of variation in CAPE is relatively small. Therefore, relatively constant environmental CAPE is necessary for the rapid intensifi-

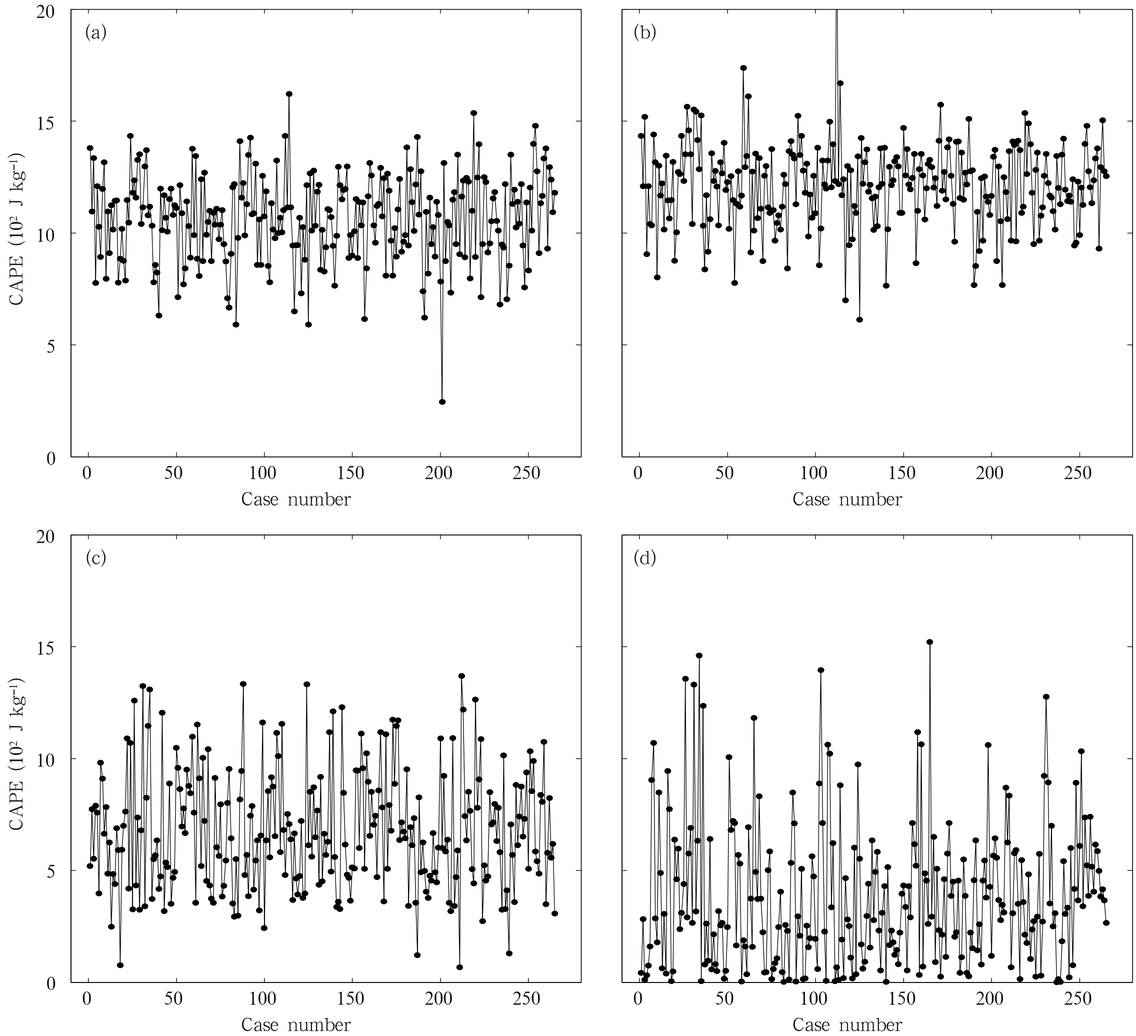

Fig. 3. CAPE in the (a) genesis, (c) peak intensity, and (d) decaying stages of TC, and (b) the maximum CAPE in TC lifetime.

cation of TCs.

3.3 VWS

Figure 5a shows the distribution of all the cases in the developing stage of TCs as a function of the VWS at an interval of 1 m s^{-1}. The mean value of VWS during the developing stage of TC is 7 m s^{-1}. There are 4097 cases (78.8%) concentrated within the range of 2–10 m s^{-1}. That is, the majority of TCs in the WNP experience a low-to-moderate VWS during their developing stage. There are 11 cases with VWS larger than 20 m s^{-1} and the maximum value of VWS is 26 m s^{-1}. Of all the cases during the developing stage of TCs, the VWS$_u$ is mainly easterly shear with the mean value of –6 m s^{-1} (∼70%). In contrast, the VWS$_v$ is centered about the zero point with the mean value of southerly (northerly) shear being 3.46 (3.44) m s^{-1}.

The range of VWS during the decaying stage is wider than that during the developing stage (Figs. 5a vs. 5b). 42.8% of all the cases in the decaying stage experience VWS larger than 10 m s^{-1}, and the mean value of VWS is about 10.2 m s^{-1}, which is 3.2 m s^{-1} larger than that during the developing stage. This is consistent with the viewpoint that large VWS plays an adverse role in the intensification of TCs and may lead to the decaying of TCs. For VWS$_u$, the percentage of easterly shear decreases from 70% during the

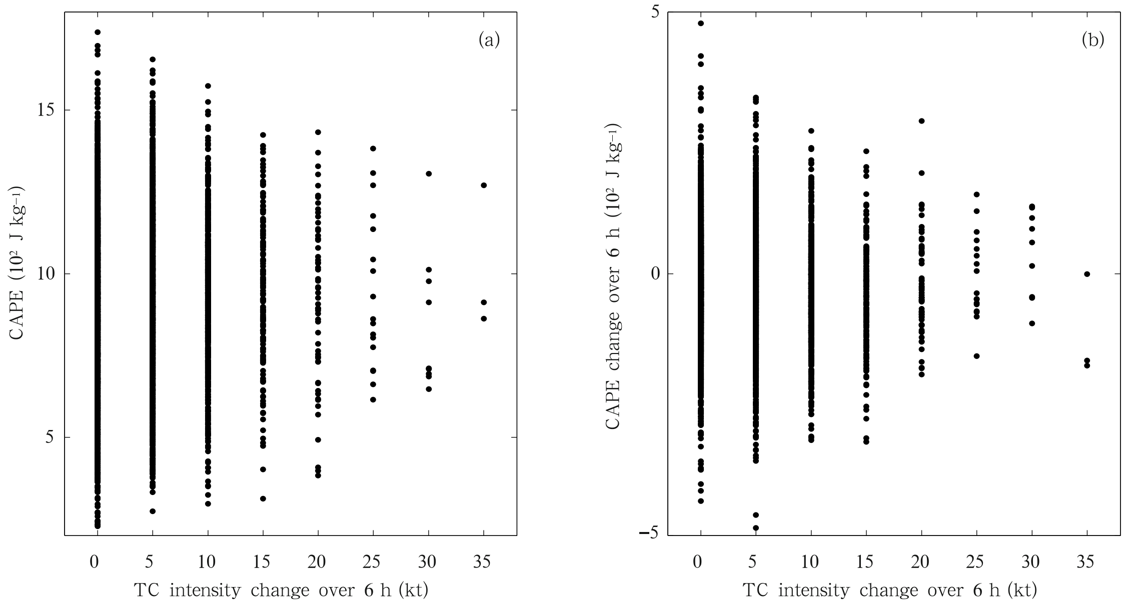

Fig. 4. Distributions of (a) CAPE and (b) CAPE change over 6 h as a function of TC intensity change over 6 h during the developing stage of TCs. Note: 1 kt = 0.514 m s^{-1}.

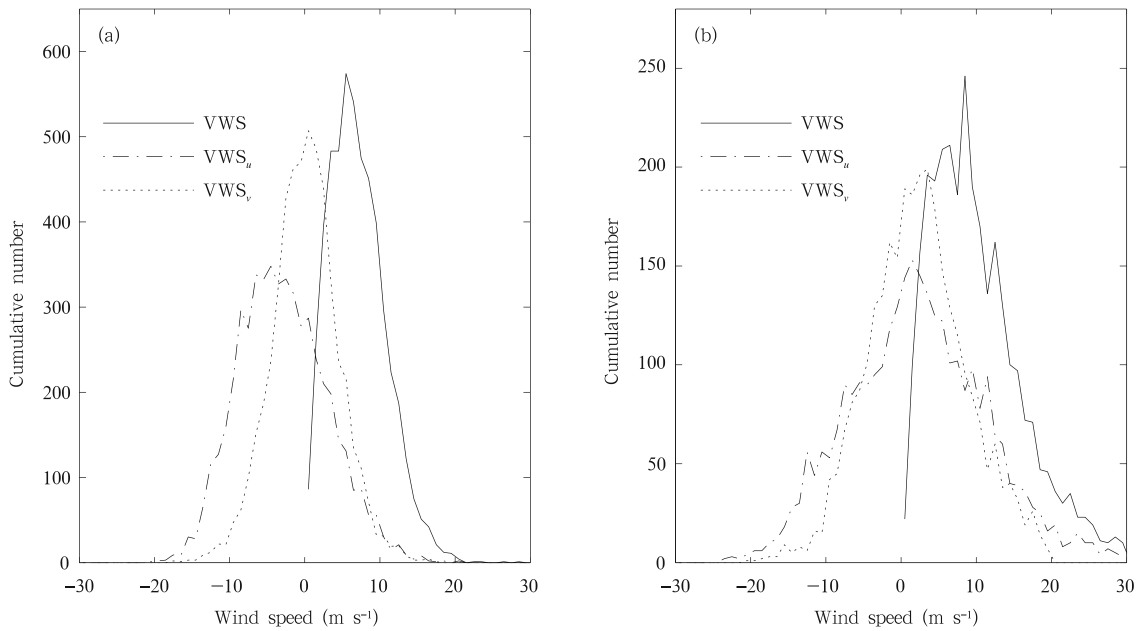

Fig. 5. Cumulative number of samples as a function of vertical wind shear (solid line), vertical shear of zonal wind (VWS_u; dot-dashed line), and vertical shear of meridional wind (VWS_v; dotted line) during the (a) developing and (b) decaying stages of TCs. The binning interval is 1 m s^{-1}.

developing stage to about 40% during the decaying stage. This indicates that a considerable part of easterly shear during the developing stage of TCs in the WNP turns into westerly shear during the decaying stage. This may be ascribed to the fact that TCs usually decay when they move into higher latitudes. The VWS_v is slightly biased to southerly shear during the decaying stage of TCs.

The relationship of TC intensity change to VWS during the developing stage is given in Fig. 6. It is

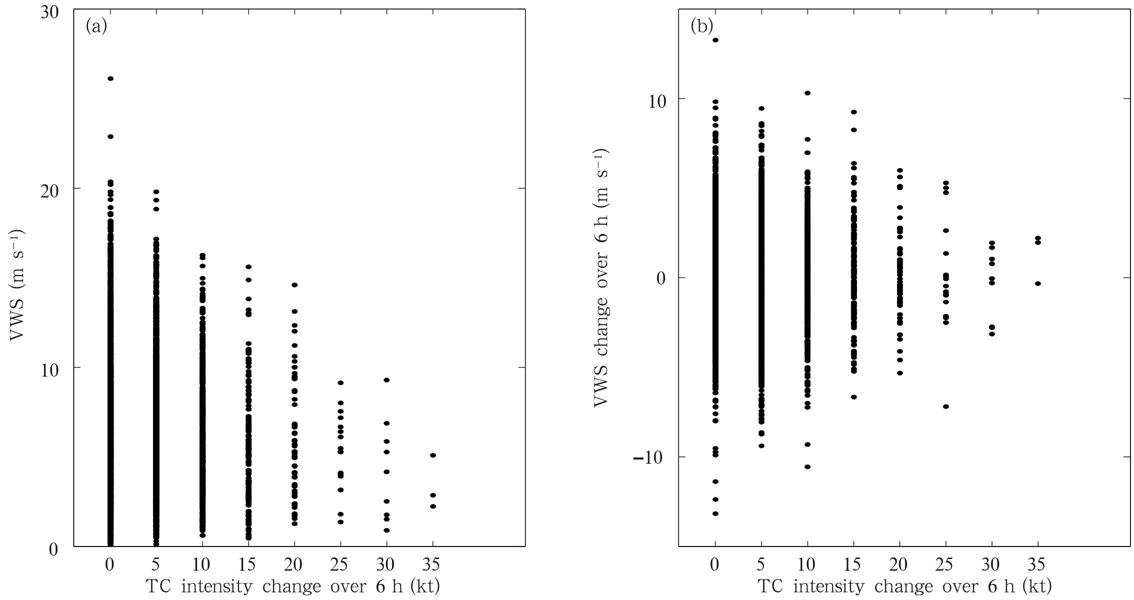

Fig. 6. Distributions of (a) VWS and (b) VWS change over 6 h as a function of TC intensity change over 6 h for the developing stage of TCs.

found that the large value of VWS only appears in the cases with relatively small intensification rates. For the cases with large intensification rates, the range of VWS and the maximum VWS are small. For example, the VWS is less than 10 m s^{-1} for all the cases with intensification rate larger than 20 kt (6 h)$^{-1}$. The decrease of VWS with increasing intensification rates in Fig. 6a confirms the results from previous studies that weak VWS is favorable for rapid intensification of TCs. Figure 6b shows the relationship of TC intensity change to VWS change during the developing stage of TCs. It is clear that the intensification rate is small when the change in VWS (no matter increase or decrease) is large. For the cases with larger intensification rates, the range of change in VWS is narrower. This indicates that a large change in VWS is not favorable for TCs to intensify rapidly.

4. Effects of environmental factors on TCs in different intensity categories

To better understand the roles of the environmental factors in the development of individual TC, the developing and decaying stages of TCs are evenly divided into three phases, respectively, represented by numbers 1–6 consectutively. In addition, the 265 TCs during the period of 2000–2010 are categorized into three groups according to their maximum intensity. The TS group includes all the tropical storms. The CAT1–3 group consists of category 1–3 TCs on the Saffir-Simpson hurricane intensity scale, while the CAT4–5 group consists of category 4–5 TCs. The distributions of SST, CAPE, and VWS during the different phases of TC lifecycle are shown in Fig. 7.

Figure 7a shows that TCs with stronger lifetime maximum intensity correspond to higher SST during the early phase of the developing stage. For example, the mean SST for CAT4–5 TCs during the early phase is 29.2°C, about 0.2°C higher than that of CAT1–3 TCs. The TS group has the lowest value of SST (28.8°C) during the early phase. In addition, TCs in the CAT4–5 group experience higher SST (than that in TS and CAT1–3 groups) during all the 3 phases of the developing stage. This result suggests that higher SST is advantageous for TCs to intensify into strong TCs.

Similarly, TCs with stronger lifetime maximum intensity have higher CAPE during the early phase of the developing stage (Fig. 7b). The CAT4–5 group has the largest CAPE, and the TS group has the low-

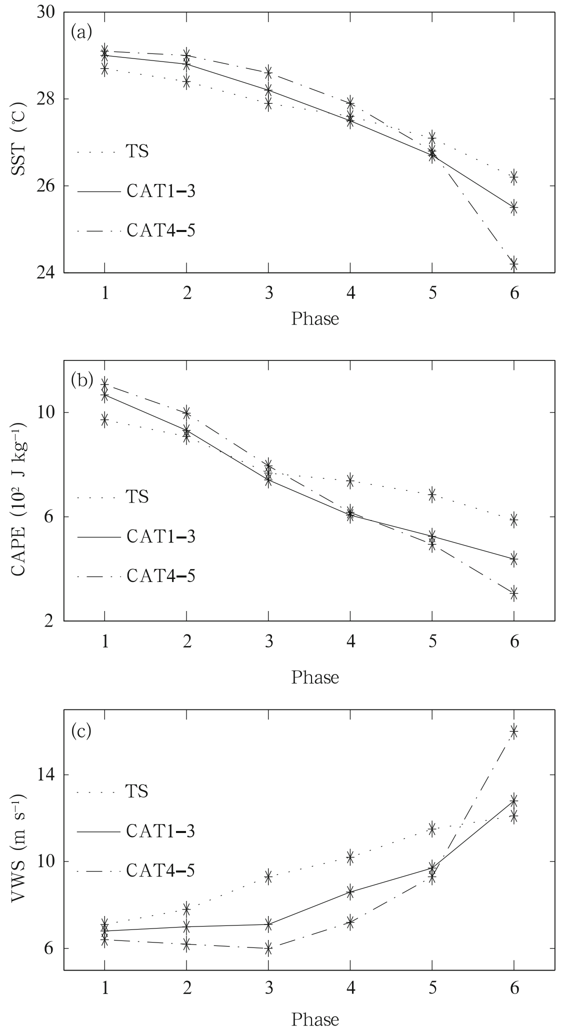

Fig. 7. Evolution of environmental factors in the different stages of TC lifecycle. (a) SST, (b) CAPE, and (c) VWS. The numbers 1–6 in the x-axis represent different phases within different stages of TC lifecycle. The developing stage (1–3) and decaying stage (4–6) are evenly divided into 3 phases.

est CAPE during the early phase. Near the end of the developing stage, all the three groups have similar value of CAPE. This indicates that more CAPE is released during the development of stronger TCs.

During the early phase of the developing stage, the VWS of all the three groups is relatively weak (about 7 m s^{-1}; Fig. 7c). The VWS in the TS group increases with time, while the VWS in the CAT1–3 (CAT4–5) group generally maintains (decreases slowly with time). On average, TCs in the CAT4–5 (TS) group experience smaller (larger) VWS than those in the CAT1–3 group. This is consistent with the notion that weak VWS is conducive to rapid intensification of TCs, while the development of TCs is restrained in the presence of significant VWS.

5. Concluding remarks

The possible relationship of TC intensity change to certain important environmental factors (SST, CAPE, and VWS) is explored through the detailed statistical analysis of 265 TCs in the WNP during the period of 2000–2010. Different from the previous studies, the samples in this study are categorized into groups according to the stages of TC lifecycle. It is found that, during the developing stage of TCs, the critical value of SST for TC intensification is about 26°C. TCs strengthen rapidly when the value of SST is between 27.5 and 29.5°C; otherwise, the intensification rate is much slower. In addition, the rapid intensification of TCs usually occurs when the variation of SST is small. Moreover, the underlying SST of TCs decreases steadily during the decaying stage of TCs. Therefore, the low value of SST usually leads to the weakening of TCs. As regards to the CAPE in the evolution of TCs, the results show that the average CAPE is about 1061 J kg^{-1} for TC genesis in the WNP. This indicates that the large CAPE in Northwest Pacific is beneficial to TC genesis for the strong atmospheric instability.

Strong VWS is found to be adverse to the intensification of TCs while small-to-moderate environmental VWS (2–10 m s^{-1}) favors the intensification of TCs in the WNP. TCs strengthen more rapidly with increasingly smaller VWS.

The analyses on the environmental factors in the different developing stages of TCs show that, for TCs undergoing rapid intensification, the variations of SST, CAPE, and VWS are usually small, which suggests that strong variations of the environment within which TCs are embedded are not favorable for TCs to intensify. For strong TCs, the SST and CAPE are usually high and the VWS is low during their developing stage. Therefore, under the conditions of high SST, high CAPE, and weak VWS, TCs are more easily to intensify into strong TCs.

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