Comparison of the effect of easterly and westerly vertical wind shear on tropical cyclone intensity change over the western North Pacific

Wei Na1,3, Zhang Xinghai1,2, Chen Lianshou1 and Hu Hao1

1 State Key Laboratory of Severe Weather, Chinese Academy of Meteorological Sciences, Beijing, 100081 People’s Republic of China
2 China Electronics Technology Group Corporation, Glaron Group Co., Ltd, Nanjing, People’s Republic of China
3 Author to whom any correspondence should be addressed.

E-mail: weina@cma.gov.cn

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Abstract

The effects of vertical wind shear (VWS) with different directions on tropical cyclone (TC) intensity change are compared in this statistical study based on TCs occurring between 1982 and 2015 over the western North Pacific (WNP). Results show that a westerly VWS has a much higher correlation (−0.36) with change in TC intensity than an easterly VWS (−0.07) over the WNP, especially south-westerly VWS (−0.43). Sea surface temperature (SST) is found to modulate the effect of VWS on TC intensity change as it has a close relationship with zonal VWS (−0.48). The favorable effect of SST, which increases with increase in easterly VWS, could offset the detrimental effect of VWS, leading to a relatively low correlation coefficient between easterly VWS and TC intensity change. By contrast, westerly VWS increases with decreasing SST, and the largest correlation coefficient appears when SST is around 301 K. Therefore, it is suggested that the direction of VWS as well as its value is taken into consideration in models used to predict TC intensity.

1. Introduction

Strong environmental vertical wind shear (VWS) is one of the most detrimental factors for intensification of tropical cyclones (TCs) (e.g. Gray 1968, Merrill 1988, McBride and Zehr 1981, DeMaria 1996, Wang and Wu 2004). Statistical studies have shown that there is a significant negative correlation between VWS and the TC intensification rate (DeMaria 1996, Paterson et al 2005, Zeng et al 2007, 2008, 2010, Wang et al 2015). Thus, VWS was selected as one of the key predictors for TC intensity change in many statistical forecasting models (DeMaria and Kaplan 1999, Knaff et al 2005, Kaplan et al 2015).

The mechanism of how VWS effects change in intensity of TCs has been thoroughly explored and the ventilation theory has been proposed and well accepted to explain the main disadvantageous effect of VWS on TC intensification. Gu et al (2015) suggested the shear-induced updraft could reduce the radial gradient of entropy by enhancing outer rainband activities to weaken the TC. Ventilation was found not only at upper levels (Gray 1968, Frank and Ritchie 2001) but also at mid-levels (Tang and Emanuel 2010) and low levels (Riemer et al 2010). In recent years, some sensitivity studies (Zeng et al 2010, Wang et al 2015, Finocchio et al 2016) have been carried out to find better layers for calculating VWS in order to obtain a closer relationship with TC intensity change. Wang et al (2015) found that conventional VWS of between 200 and 850 hPa is less representative of the attenuating deep-layer shear effect than VWS between 300 and 1000 hPa found over the western North Pacific (WNP).

Similar to the layering of VWS, the direction of VWS has also been looked at in recent years. Some statistical studies mentioned that easterly shear (i.e. the direction of the VWS zonal component is easterly) is more favorable to TC intensification than westerly shear (e.g. Shu et al 2014). Some studies (Ritchie and Frank 2007, Zeng et al 2010) attributed this to the beta-induced north-westerly shear within the inner core of the TC. Shu et al (2014) argued that easterly shear could induce asymmetric inflow which can help bring warm moist air from the south and south-east quadrants of the TC and be favorable for TC intensification. Over the North Atlantic (NA), Zeng et al (2010)
found a higher correlation coefficient between westerly shear and TC intensity change than for easterly shear. One of the questions this study aims to answer concerns the relationship between TC intensity change and various directions of VWS over the WNP. The detailed characteristics of VWS over the WNP and its relationship to TC intensity change is demonstrated in section 3 after the introduction of data and methodology in section 2.

A further investigation of the reasons for the relationship is presented in section 4. Unlike the previous studies that considered VWS alone (Ritchie and Frank 2007, Zeng et al 2010, Shu et al 2014), we discuss the how VWS works with other environmental factors. The most important factor is sea surface temperature (SST). A high SST is the key factor behind the intensification of TCs (e.g. Emanuel 1988), and SST and VWS are the most significant factors determining TC development (Tao and Zhang 2014). Since a high SST is conductive to TC intensification while a high VWS is destructive, whether SST plays any role in the relationship between VWS with different directions and TC intensity change is explored in section 4. Finally, the conclusion and discussion are given in section 5.

2. Data and methodology

The International Best Track Archive for Climate Stewardship (IBTrACS) datasets (Knapp et al 2010) are used to obtain best track data from the Joint Typhoon Warning Center (JTWC) over the WNP (0–60°N, 100–180°E; the domain in figure 1). The dataset contains 6-hourly TC position information and the maximum sustained near-surface wind speed \( V_{\text{MAX}} \), which is used to present TC intensity in this study. TCs with a maximum wind speed greater than 17 m s\(^{-1}\) between 1982 and 2015 are analyzed. To further exclude the influence of land, TC records having a storm center within 100 km of the coastline are not taken into
3. Statistical characteristics

There are 828 TCs with 19,548 records at 6 h intervals included in our analysis. Figure 1(a) shows the geographical frequency distribution of all records accumulated on the 1° × 1° grid and the corresponding ratio of TC records with westerly VWS (W-VWS). When the ratio is greater than 0.5 (indicated by red shading), the grid is dominated by W-VWS. It is clear that TCs are more likely to experience W-VWS when moving to the northern WNP, which may be attributed to the prevailing westerlies in the upper layer. By contrast, the grid with a ratio lower than 0.5 shows easterly VWS (E-VWS) to be predominant (indicated by blue shading). The eastern regions of the Philippines and the South China Sea are both included, which are most frequently affected by TCs. The ratio distribution is related to the large-scale circulation pattern in the active TC season over the WNP where the monsoon brings south-westerly flow at low levels over the low-latitude region, while for the high-latitude region westerly wind controls the upper levels.

Figure 1(b) shows the percentage distribution of zonal VWS with respect to magnitude. A positive VWS value denotes westerly shear while a negative one denotes easterly shear. In general, the frequency distribution is close to Gaussian, and the distribution is almost symmetric, as there are 10,948 samples with W-VWS and 8,591 samples with E-VWS. The average magnitudes of E-VWS (i.e. 5.2 m s⁻¹) and W-VWS (i.e. 6.8 m s⁻¹) are close. Figure 1(c) shows the seasonal distribution of zonal VWS. In all records of TC with E-VWS 54.5% are in summer (JJA), while for W-VWS 54.8% appear in the autumn (SON). This indicates that E-VWS is dominant in the early TC season while W-VWS is more common in the later TC season over the WNP.

The correlation coefficient between zonal VWS and 24 h intensity change is about -0.3, with significance at the 95% confidence level, indicating that VWS is detrimental to TC intensification overall. This is almost the same as for F-VWS, which may explain why zonal VWS has often been used instead of F-VWS in many studies. However, W-VWS presents a remarkably larger correlation coefficient (i.e. -0.36) with 24 h TC intensity change than E-VWS (i.e. 0–0.07) over the WNP, although both correlations are significant at the 95% confidence level. This is consistent with the result over the NA (Zeng et al. 2010), which suggests that E-VWS is less detrimental to TC intensification than W-VWS.

To further explore the influence of shear direction on TC intensity change, all records are divided into eight groups at a 45° interval from 0° to 360° according to shear angle. Shear angle is defined as the included angle between shear and due north, and increases as the shear rotates clockwise (figure 2). Note that the correlations are made using F-VWS instead of the zonal component of VWS. There are three groups with sample size percentages over 15%: 0°–45° (NNE), 45°–90° (ENE) and 225°–270° (WSW). This indicates that TCs over the WNP often experience south-west and north-east VWS, which may be attributed to the large-scale circulation pattern including monsoon, subtropical high and westerlies. The corresponding correlations between VWS and 24 h TC intensity change are shown in figure 2(b). Shear with a westerly component is overall more correlated with the following change in TC intensity. The correlations in WNW, WSW, SSW and SSE are over -0.2, much higher than for the other four groups. In particular, south-westerly shear has the highest correlation (up to -0.43), while the smallest one appears in ENE (only -0.13). Thus, over the WNP, south-westerly shear is much more related to TC intensity change than any other shear direction.

These results demonstrate that westerly shear is more detrimental for TC intensification, especially for south-westerly shear over the WNP. We now examine their relationship when the TC intensity changes at different rates. Figure 3 divides all records according to 24 h TC intensity change at 5 m s⁻¹ intervals and shows the corresponding mean VWS as well as its standard deviation (i.e. error bars). For F-VWS, the stronger the VWS the greater the rate of TC weakening. The only exception emerges for a TC weakening rate over 35 m s⁻¹ in 24 h, which is due to small sample size and is not significant at the 95% confidence level. The relationship between rate of intensification and F-VWS
Figure 2. (a) The percentage of samples with vertical wind shear with various shear angles and (b) the corresponding correlation coefficient with 24 h intensity change. Calculations are within eight bins at 45° intervals from 0° to 360° according to shear angle, which is indicated by a black number. The green numbers indicate the percentage and coefficient of each circle.

Figure 3. The average of (a) full wind speed VWS, (b) westerly shear, and (c) easterly shear with respect to various 24 h intensity changes. The error bars indicate the standard deviation.

value is not very obvious. The variation of averaged W-VWS against 24 h intensity change is highly consistent with F-VWS (figure 3(b)), indicating that W-VWS has a similar effect on TC intensity change as F-VWS. By contrast, E-VWS does not vary much with the rate TC intensity change and the average E-VWS remains at about 5 m s\(^{-1}\).

Rios-Berrios and Torn (2017) defined moderate VWS as 4.5–11 m s\(^{-1}\) corresponding to the 25th–75th percentiles of the global distribution of the magnitude of VWS around TCs. Therefore weak VWS below 4.5 m s\(^{-1}\) and strong VWS over 11 m s\(^{-1}\) are examined in our analysis. When the averaged VWS is over 11 m s\(^{-1}\), the 24 h intensity change of TCs exceeds 15 m s\(^{-1}\), which is close to the threshold of rapid weakening (RW; weakening by 30 knots in 24 h as defined by Wood and Ritchie 2015). This indicates that the phenomenon of RW is often accompanied by strong VWS. As we focus on the other side of rapid intensification (RI; intensifying by 30 knots in 24 h, following Kaplan and DeMaria 2003), the averaged VWS remains weak to moderate (about 5–6 m s\(^{-1}\)) and changes little as the intensification rate increases. This may indicate that RI is more influenced by internal dynamical processes (e.g. Montgomery and Smith 2014), provided that a pre-existing favorable environment exists (Hendricks et al 2010). In addition, cases with RI have a smaller standard deviation than cases with RW, which means there is stronger variability of VWS for RW than that for RI (figure 3). This suggests that for RI there are many favorable environmental factors and moderate to weak VWS should be a necessity, but RW might be induced by many factors and strong VWS is an optional one.

4. Reasons: VWS and SST

As mentioned in the introduction, the reason for the difference between the effects of W-VWS and E-VWS on TC intensity change is usually discussed in terms of considering VWS independently. But the intensity change is always induced by the composite influence of environmental factors, such as SST. The SST of samples with W-VWS and E-VWS is compared in figure 4. In general, the E-VWS samples present a higher local SST than W-VWS, as the averaged SST of samples with E-VWS is 301.9 K (28.9 °C) and 300.7 K (27.7 °C) for those with W-VWS. Actually, the correlation
The coefficient between zonal VWS and local SST can reach ~0.48, which is significant at the 95% confidence level. That is, as SST increases the zonal VWS tends to be easterly. The magnitude of VWS decreases as SST increases for W-VWS but the opposite is the case for E-VWS. The relationship between VWS and SST could be partially explained by the spatial distribution of W-VWS and E-VWS shown in figure 1. The area dominated by E-VWS is the warm pool over the WNP. By contrast, W-VWS is distributed in the northern region with a relatively cool SST. The northward transition from E-VWS to W-VWS may be due to the meridional SST gradient based on thermal wind theory. Since a higher local SST is more favorable for TC intensification, this suggests that local SST may play an important role in the response of TC intensity change to W-VWS and E-VWS.

Figure 5 shows the averaged local SST with respect to different TC intensifying/weakening rates for all samples and samples with W-VWS and E-VWS, respectively. The averaged SST of all intensifying samples is over 301 K but varies little as the intensification rate increases, even for RI. The averaged SST is lower during the TC weakening stage and decreases obviously as the weakening rate is 0–10 m s$^{-1}$ per 24 h. But it remains at 300 K when the weakening rate is 10–25 m s$^{-1}$ per 24 h. The average SST increases again when the storm weakening rate is over 25 m s$^{-1}$. Few TC samples with extreme weakening may be related to severe SST cooling due to a large SST horizontal gradient and cold SST wake. This may be the reason for the unusual increase in local SST with the extreme weakening of TCs. Similar to VWS magnitude, the variation of SST against rate of change of intensity for samples with W-VWS is close to that for all samples (figure 5(b)). However, the variation of SST for samples with E-VWS is in a smaller range but has higher values (i.e. 301–302 K). This suggests that in an E-VWS environment, there is a high enough SST for TCs to intensify with any intensification rate; this is also consistent with SST increasing as E-VWS increases, as shown in figure 4.

To determine how SST affects TC intensity change in relation to W-VWS and E-VWS, the moving correlations between TC intensity change and zonal VWS with respect to different SSTs are calculated (figure 6). The correlation coefficients for W-VWS and E-VWS show very different responses to change in SST. For W-VWS, the largest negative correlation coefficient (about ~0.27) occurs when SST is 301 K. When SST is below 301 K, as SST decreases W-VWS becomes less correlated with SST. This suggests that the local SST may have a greater effect on TC intensity change than W-VWS when SST is low. In contrast, the correlation becomes weaker as SST increases when SST is greater than 301 K. That is, high SST is conductive to intensification of TCs, which can partly offset the detrimental influence of W-VWS. Note that when SST is high enough large W-VWS is uncommon (figure 4). In a W-VWS environment, a very low or very high SST will have a dominant influence on TC intensification rate. For E-VWS there is no significant correlation coefficient when SST is below 301 K, due to small sample sizes. When SST is above 301 K, the negative coefficient fluctuates within the range ~0.09 to ~0.15. As shown in figure 4, E-VWS increases as SST increases. So when a high SST provides favorable thermal conditions, the dynamics of a strong E-VWS may offset this. Thus, when the relationship between E-VWS and TC intensity change appears weak and insensitive to changes in SST this may imply competition between favorable effects of SST and unfavorable effects of VWS. When SST is above 303 K, the
coefficients for E-VWS and W-VWS are similar and not very large, demonstrating that SST modulation has a similar and strong influence on the effect of E-VWS and W-VWS when SST is high enough. Thus, SST could modulate the effect of VWS on TC intensity change since there is a close relationship between SST and VWS when the zonal direction of VWS is considered. The shear decreases as SST increases for W-VWS, with the opposite for E-VWS, thus probably at least partially explaining the much stronger negative correlation between TC intensity change and W-VWS.

5. Conclusion and discussion

In this study, the relationship between different directions of VWS and TC intensity change is discussed in detail based on TCs over the WNP. In general, over the WNP, a westerly VWS has a much higher correlation ($-0.36$) with TC intensity change than an easterly VWS ($-0.07$). In particular, the correlation coefficient could reach $-0.43$ for a south-westerly VWS. SST can influence the effect of W-VWS and E-VWS on TC intensity change due to its large negative correlation ($-0.48$) with zonal VWS. E-VWS increases as SST increases. Competition between these opposite effects leads to a relatively weak correlation between E-VWS and TC intensity change. By contrast, when SST is increasing, W-VWS decreases. The favorable effect of SST amplifies the correlation between W-VWS and TC intensity change. Both very low and high SST seem to reduce the effect of W-VWS and dominate TC intensity change. The highest statistical correlation of W-VWS and TC intensity change is found when SST is around 301 K.

Thus, the high negative correlation highlights the importance of VWS in determining TC intensity change. But VWS with different directions have different effects on TC intensity change, partially due to the close relationship between SST and zonal VWS. In many statistical models used to predict TC intensity, VWS and SST are two key independent predictors (DeMaria and Kaplan 1999, Knaff et al 2005, Kaplan et al 2015). According to the results of our study we make two proposals: (1) the direction of VWS should be considered in predictive models; (2) the close relationship between SST and zonal VWS should be considered in predictive models. The cases of E-VWS and W-VWS should be treated separately when determining the significance of impact factors in predictive models. Other environmental factors, such as humidity, have not been considered and they should be examined in further work.

In addition, the performance of VWS and SST in extreme TC intensity change, i.e. RI and RW, is demonstrated in this study. Strong W-VWS is found in RW but is only one of many reasons for RW. By contrast, weak to moderate VWS and high SST seem necessary for RI. However, there is little difference in SST and VWS between TCs showing RI and TCs with small intensification rates. So a favorable SST and VWS environment is a precondition for RI but does not seem to determine the occurrence of RI. Furthermore, both RW and RI in an E-VWS environment seem to be difficult to predict using SST and VWS, since they are similar for TC samples with different intensification/weakening rates. Thus, it is far from sufficient to estimate extreme TC intensity change from SST and VWS alone and prediction of TC intensity should emphasize the internal dynamical processes of TCs.

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ORCID iDs

Wei Na @ https://orcid.org/0000-0002-5541-6068

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