A Statistical Analysis on the Effect of Vertical Wind Shear on Tropical Cyclone Development*

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ABSTRACT

Using tropical cyclone (TC) best track and intensity of the western North Pacific data from the Joint Typhoon Warning Center (JTWC) of the United States and the NCEP/NCAR reanalysis data for the period of 1992-2002, the effects of vertical wind shear on TC intensity are examined. The samples were limited to the westward or northwestward moving TCs between 5°N and 20°N in order to minimize thermodynamic effects. It is found that the effect of vertical wind shear between 200 and 500 hPa on TC intensity change is larger than that of the shear between 500 and 850 hPa, while similar to that of the shear between 200 and 850 hPa. Vertical wind shear may have a threshold value, which tends to decrease as TC intensifies. As the intensifying rate of TC weakens, the average shear increases. The large shear has the obvious trend of inhibiting TC development. The average shear of TC which can develop into typhoon (tropical depression or tropical storm) is below 7 m s^{-1} (above 8 m s^{-1}).

Key words: vertical wind shear, tropical cyclone (TC), statistical analysis

1. Introduction

Many factors can influence the intensity change of tropical cyclone (TC), and the vertical wind shear is one of the most important factors. As early as 1968, Gray (1968) found that most TCs formed on the poleward side of the equatorial troughs where the vertical wind shear was small, and TC was easy to develop in the region with small vertical wind shear. By comparing the developing and non-developing TCs, McBride and Zehr (1981) found that the vertical wind shear was greater than that of the non-developing TCs. Frank and Ritchie (1999, 2001) modeled a TC's development under different shears by using Mesoscale Model version 5 (MM5). The results showed that a shear of 5 m s^{-1} would cause TC to weaken within 36 h, a shear of 10 m s^{-1} would cause TC to weaken within 24 h, and a shear of 15 m s^{-1} would cause TC to weaken immediately. DeMaria and Kaplan (1994) made a correlation analysis for TCs in different regions. They found that there is an obvious negative correlation between vertical wind shear and TC intensity change. However, Corbosiero and Molinari (2002) showed that it is more avail to TC's formation and developing with a moderate shear in the low-level than with no shear.

It can be seen that there are controversial arguments on the relationship between vertical wind shear and TC intensity. Thus, in this paper, we will analyze the impact of vertical wind shear on TC intensity in the developing period in order to have a better understanding of the problem.

2. Data and analysis method

Best track data of TC in the western North Pacific from the Joint Typhoon Warning Center (JTWC) of the United States are used to get TC positions and intensities.

Palmer and Barnes (2002) figured out that the SST isotherms run essentially east to west in the eastern North Pacific between approximately 5°N and 20°N. The distribution of SST isotherms is much the same in the western North Pacific. In order to minimize the thermodynamic effects, the samples in this study are limited to the westward and northwestward moving TCs in this region and the total 90 TCs are qualified.

Wind data are from the NCEP/NCAR reanalysis

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qualified data for the period of 1992-2002, and their horizontal resolution is 2.5°×2.5°.

Vertical wind shear is calculated by vws=$\sqrt{(u_a-u_b)^2+(v_a-v_b)^2}$, where the "vws" means vertical wind shear; u and v are the zonal and meridional wind components averaged in a 10°×10° square area centered at TC position; a and b denote different levels in the troposphere.

Generally, vertical wind shear is always calculated between 200 and 850 hPa. But we do not know exactly the shear of which level affects TC intensity most significantly. Thus, first of all, the shears between 200 and 500, 500 and 850, 200 and 850 hPa are analyzed respectively to find out which is most closely related to TC intensity change. Then, that shear is used to analyze the effects of shear on TC intensity in detail.

3. Sample characteristics

In the 90 TCs, 43 (accounting for about 47.8%) reach typhoon (TY) intensity, 37 (~41.1%) tropical storm (TS), and 10 (~11.1%) tropical depression (TD).

By defining one "case" to be the observation every 6 h with TC intensity stronger than 12 m s^{-1}, 1309 cases are qualified, including 500 cases (accounting for about 38.2%) of TD intensity, 505 cases (~38.6%) of TS intensity, and 304 cases (~23.2%) of TY intensity.

The average intensity of all cases is 25 m s^{-1} (Table 1), with the standard deviation 14.7 m s^{-1}. Also shown in Table 1 are the averages of the shear between 200 and 850 hPa, 500 and 850 hPa and 200 and 500 hPa. It can be seen that the average shears of 200 and 850 hPa and 200 and 500 hPa are larger than 500-and 850-hPa shear. Therefore, the distribution of wind in the middle and low troposphere is relatively uniform with small variability, and the shear in the middle and upper troposphere is much larger with values similar to that in the whole troposphere.

Correlation coefficients are calculated between vertical wind shear in different levels (200 and 850 hPa, 500-850 hPa, and 200-500 hPa) and TC intensity change in 6, 12, 24, 36, 48, 60, and 72 h (Fig.1).

Table 1. The statistics of all the 1309 cases

	Average (m s^{-1})	Standard deviation (m s^{-1})
TC intensity (m s^{-1})	25.0	14.7
Shear between 200 and 850 hPa	7.6	4.0
Shear between 500 and 850 hPa	3.8	2.2
Shear between 200 and 500 hPa	6.2	3.4

T-test shows that all of the coefficients are significant at 99% level. It can be seen that the coefficients of 200-850-hPa shear and 200-500-hPa shear are much larger than those of 500-850-hPa shear. Further analyses show that there is a quite high correlation (0.98) between the curve of 200-850-hPa shear and that of 200-500-hPa shear.

The largest coefficients for 200-850-hPa and 200-500-hPa shear both appear at 36 h with values of -0.34 and -0.32, respectively. DeMaria (1996) made coefficient analysis on the effects of 200-850-hPa shear on TC intensity change using data from 1989 to 1994. He also found that the negative correlation was the most significant for TC intensity change during the next 36 h when TC in low latitudes (<20°N).

From the above results, the coefficient is quite similar between 200-500-hPa shear and 200-850-hPa shear, thus we use 200-850-hPa shear to do our

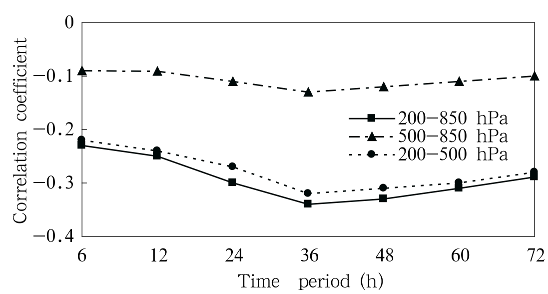

Fig.1. Correlation coefficients between vertical wind shears at different levels and TC intensity change during different time periods (6, 12, 24,$\cdots$, 72 h).

analysis below.

Table 2 shows the distribution of three kinds of cases, i.e., TD, TS, and TY. Here we define the small (or weak) shear to be vws$\leqslant$5 m s^{-1}, large (or strong) shear to be vws$\geqslant$10 m s^{-1}, and others are moderate shears. It can be seen that the percentages of TD and TS are essentially similar for the same shear group. For TY, the percentage in weak shear group is a bit higher than that for TD and TS, while that in strong shear group is smaller.

Figure 2 depicts the case distribution of different vertical wind shears and TC intensities, showing that the vws is generally under 11 m s^{-1} when TC intensity is stronger than 35 m s^{-1}, except for 22 cases (~1.7%) with vws larger than 12 m s^{-1}. But for cases weaker than 35 m s^{-1}, large shear cases are obviously increasing. It is speculated that some weak TCs can develop in the large vertical wind shear environment. However, when the shear is larger than 18 m s^{-1}, the TC intensity is hardly to beyond 25 m s^{-1}.

Table 2. The distribution of three kinds of TC cases

	TD		TS		TY	
	Number	Percentage (%)	Number	Percentage (%)	Number	Percentage (%)
Total	500		505		304	
Weak Shear	137	27.4	139	27.5	94	30.9
Moderate Shear	241	48.2	246	48.7	150	49.4
Strong Shear	122	24.4	120	23.8	60	19.7

Gray (1968) pointed out that TC would weaken obviously if its shear was larger than 10 m s^{-1}, and Chen and Ding (1979) had the similar opinion. According to a modeling study, Frank and Ritchie (1999) got a threshold value of 12.5 m s^{-1}. Gallian and Velden (2002) found that the threshold values are different in the Pacific and Atlantic Oceans, and they are about 7-8 m s^{-1}, and 9-10 m s^{-1} in the Atlantic and the Pacific, respectively. According to our analysis, the threshold value of vertical wind shear seems to change with TC intensity, which is 8-10 m s^{-1} when TC intensity weaker than 35 m s^{-1}, and 12-14 m s^{-1} when TC intensity stronger than 35 m s^{-1}. Thus, the threshold value of vertical wind shear tends to decrease as TC intensifies.

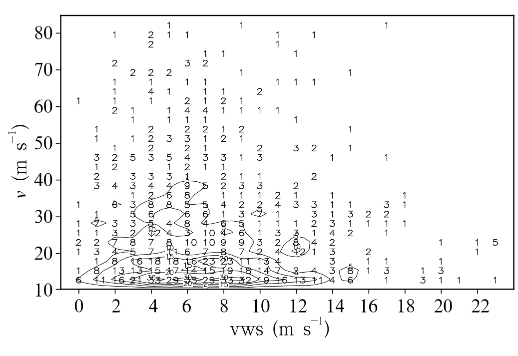

Fig.2. Case distribution of different vertical wind shears and TC intensities. Abscissa: vertical wind shear; ordinate: TC intensity.

4. Vertical wind shear in the development stage of TC

It can be seen from the above analysis that, the correlation between 200-850-hPa shear and TC intensity change in 36 h is the most obvious, thus we only analyze the effects of vertical wind shear on TC intensity change in 36 h as a representative in this part. There are totally 793 cases, including 734 (~92.6%) intensifying ones (ΔV_{36} >0, ΔV_{36}=V_{36}-V_0) and 59 (~7.4%) maintaining ones (ΔV_{36}=0). Here, we will focus on the intensifying cases.

Figure 3a shows that the intensifying cases are primarily crowded in the region where shears are small or moderate ($\leqslant$10 m s^{-1}), with percentage of about 86% (631). About 52.3% (384) of the cases experience a shear of 4-8 m s^{-1}. Only 103 cases (14%) can develop in the shear>11 m s^{-1}, but those TCs are almost weaker than 35 m s^{-1}. When the shear is above 16 m s^{-1}, there are only 7 TC cases.

From Fig.3b, we can find that TC intensifies fastest in the "region" where TC intensity is about 23-48 m s^{-1} and vertical wind shear about 1-5 m s^{-1}, with the maximum TC intensity change reaching 39 m s^{-1}/(36 h) and the average change 17.1 m s^{-1}/36 h. Very weak increasing trend can be observed for shear above 12 m s^{-1}, with the maximum intensity

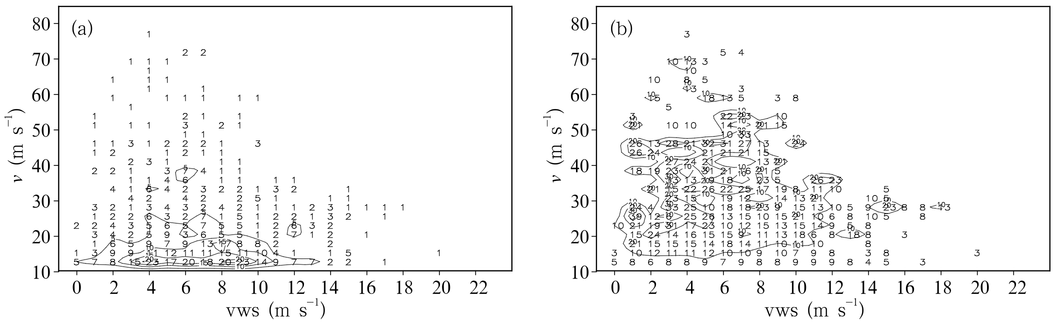

Fig.3. Distribution of intensifying TC cases (a) and TC intensity change in 36 h (b).

change 23 m s^{-1}/36 h and average value only 3.2 m s^{-1}/36 h. It is then assumed that TC is easy to develop in small vertical wind shear environment and it can intensify fastest with the shear of 1-5 m s^{-1}.

By defining "fast intensifying" TC and "not-fast intensifying" TC according to the averge intensity change, the average shear and TC intensity change are compared in Table 3. It can be seen that there are 105 "fast increasing" TC cases with average intensifying rate 29.4 m s^{-1}/36 h and average shear 6.0 m s^{-1}, much less than that of total cases (7.7 m s^{-1}). Among the "fast intensifying" cases, only 8 cases (7.1%) experience shears above 10 m s^{-1}.

There are 629 "not-fast intensifying" TC cases with average intensifying rate 7.9 m s^{-1}/36 h and average shear 7.9 m s^{-1}, larger than that of total cases. Among these "not-fast intensifying" cases, 156 cases (24.8%) are in an environment shear>10 m s^{-1}.

By "time normalization" analysis, we define TC formation time to be 0 and the time when TC is the strongest to be 1. The other time levels between the formation and the mature stages can be converted to the numbers between 0 and 1.

Averagely (Fig.4), vertical wind shear at formation time (0) is a bit large: about 7.9 m s^{-1}. After that, the shear keeps about 7.5 m s^{-1} till 0.7 time level

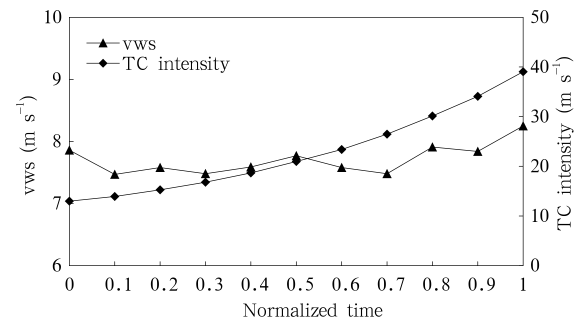

Fig.4. The average distribution of total cases' vertical wind shears and TC intensities during "time normalization" analysis.

and then begins to increase slowly to 8.3 m s^{-1} at 1 time level. Correspondingly, TC intensifies from 13.0 m s^{-1} to 39.0 m s^{-1}.

Figure 5 depicts the average distribution of vertical wind shear (a) and TC intensities (b) for different intensity groups (TD, TS, and TY). From Fig.5a, we can find that shear distribution of TD is similar to that of TS. During 0-0.7 time level, the shears are all about 8 m s^{-1}. However,the shear of TD is a little larger than TS after 0.4 time level, while a bit smaller than TS before that. After 0.7 time level, both the shears for TD and TS show a trend of increasing. More specifically, the shear for TD increases from

Table 3. The discriminants and statistics of "fast intensifying" TC and "not-fast intensifying" TC (unit of ΔV is m s^{-1}/36 h, $\Delta\bar{V}_{+}$is average intensity change of intensifying cases in 36 h, σ_{+} is standard deviation)

	"Fast intensifying" TC	"Not-fast intensifying" TC
Discriminant	$\Delta V > \Delta\bar{V}_{+} + \sigma_{+}$	$0 \leqslant \Delta V \leqslant \Delta\bar{V}_{+} + \sigma_{+}$
	ΔV >21.0	0$\leqslant$ ΔV $\leqslant$21.0
Number of cases	105	629
Average shear (m s^{-1})	6.0	7.9
Average intensity change	29.4	9.7

8.2 m s^{-1} to 9.1 m s^{-1}, and that for TS from 8.0 m s^{-1} to 8.7 m s^{-1}. The shear for TY is smaller than TD and TS at all time levels and is less than 7 m s^{-1} from 0.1 to 0.9, with the evolution trend similar to that of the total samples (Fig.4).

Figure 5b shows that the intensity of TCs in three groups are the same at 0 time level, and the difference becomes much larger as time goes. In the final time level, the average intensity of TY reaches 54.2 m s^{-1}, but that of TD is only 15.4 m s^{-1}. The sharp slow increasing trend of TY (TD and TS) corresponds quite well to the low (large) vertical wind shear.

The analysis above only reflects average status of TC development, some individual TCs have quite different features. Using the definition of average and standard deviation, we define "abnormally large" shear and "abnormally small" shear. T is defined to be the average shear of a certain time level, A is the standard deviation, and $t + a$ is the criterion for "abnormally large" shear, while $t - a$ is that for "abnormally small" shear.

Figure 6 shows the average and abnormal shear curves for TY,TS, and TD. Due to the fact that the shear distributions for TD and TS are quite similar. The two intensity groups are combined together to construct Fig.6a. It can be seen that TD and TS have an "abnormally small" shear of about 4 m s^{-1}, and the "abnormally large" shear is larger than 12 m s^{-1} most of time. The "abnormally large" shear for TY ranges from 10 m s^{-1} to 12 m s^{-1}. Totally, there are six "abnormally small" shears in TD and TS samples (12.8%) and five "abnormal large" shears of TY samples (11.6%).

The controversial point for these cases is why some TCs cannot develop into TY even with small vertical wind shear less than 4 m s^{-1}, while some others can still develop into strong TY with shear larger than 10 m s^{-1} during their development periods? It is speculated that there are maybe some other influence factors which are needed for future studies.

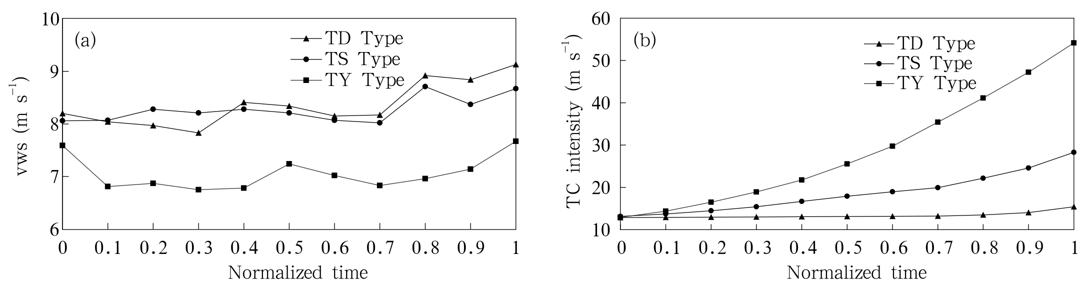

Fig.5. The average distribution of vertical wind shear (a) and TC intensities (b) for different intensity groups (TY, TS, and TD) in "time normalization" analysis.

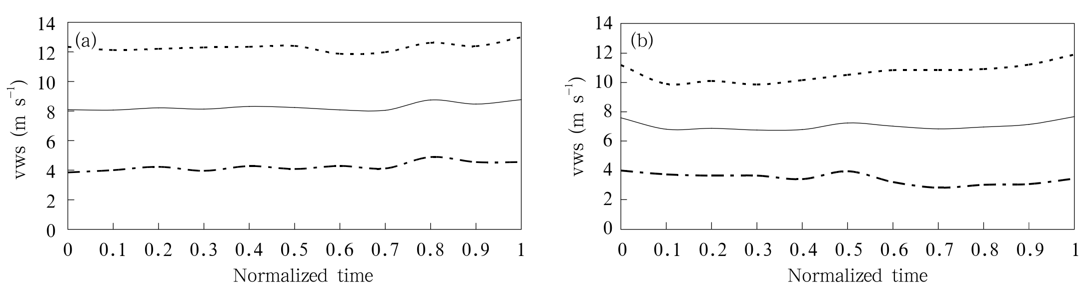

Fig.6. Distribution of the average shears (real line), "abnormally large" shear (dashed line), and "abnormally small" shear (dotted line) for TD,TS (a) and TY (b).

5. Conclusions

The 11-yr (1992-2002) data are used to analyze the effects of vertical wind shear on westward or northwestward moving TCs between 5°N and 20°N. Analyses have been carried out on correlation between vertical wind shear in different levels and TC intensity change, the relationship between vertical wind shear and TC intensity change in the developing period, and the distribution of vertical wind shear by "time normalization" analysis. It can be concluded below:

(1) The negative correlation between 200-500-hPa vertical wind shear and TC intensity change is significant and similar to that of 200-850-hPa shear. The shear of middle and upper troposphere can reflect the characteristics of the whole troposphere and the vertical wind shear which affects TC intensity should be mainly due to the great difference of wind in middle and-upper troposphere.

(2) Strong TC tends to appear in weak shear environment. There does exit a threshold value of vertical wind shear for TC development while it decreases for stronger TC.

(3) With weakening trend of TC, the average shear increases, implying that large shear tends to inhibit the development of TC or even cause it to weaken. The less the shear is, the better it is for the development of TC.

(4) By the "time normalization" analysis, it is found that the average shear of TC which can develop into TY is smaller than those can develop into TD or TS.

It is also found that some TCs cannot develop into TY intensity even with very weak shear, while some TCs can intensify rapidly even with large shear. The reason for that needs further studying. Furthermore, we only analyze TC in low latitudes in order to minimize thermodynamic effects in this paper. Further studies also need to be carried out to make clear whether there is difference in the effect of vertical wind shear on TC intensity in mid-latitude from that in low latitude.

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