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EFFECTS OF VERTICAL WIND SHEAR ON TROPICAL CYCLONE INTENSITY CHANGE

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Abstract: The effects of vertical wind shear on tropical cyclone (TC) intensity change are examined based on the TC data from the China Meteorological Administration and the NCEP reanalysis daily data from 2001 to 2006. First, the influence of wind shear between different vertical levels and averages in different horizontal areas are compared. The results indicate that the effect of wind shear between 200 and 850 hPa averaged within a 200-800 km annulus on TC intensity change is larger than any other calculated vertical wind shear. High-latitude and intense TCs tend to be less sensitive to the effects of VWS than low-latitude and weak TCs. TCs experience time lags between the imposition of the shear and the weakening in TC intensity. A vertical shear of 8-9 m/s (9-10 m/s) would weaken TC intensity within 60 h (48 h). A vertical shear greater than 10 m/s would weaken TC intensity within 6 h. Finally, a statistical TC intensity prediction scheme is developed by using partial least squares regression, which produces skillful intensity forecasts when potential predictors include factors related to the vertical wind shear. Analysis of the standardized regression coefficients further confirms the obtained statistical results.

Key words: tropical cyclone intensity change, statistical analysis, environmental vertical wind shear, TC intensity prediction scheme
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1 INTRODUCTION

Observational and model studies have showed that environmental vertical wind shear is an important environmental dynamical control on tropical cyclone (TC) genesis and intensity changes (Gray[1]; DeMaria[2]; Frank and Ritchie[3]; Wong and Chan[4]; Lu and Wu[5]; Li et al.[6]; Chen [7]; Jia et al.[8]; Huang et al.[9]; Chen et al.[10]; Gu et al.[11]). It is found that the environmental wind shear can significantly affect the uncertainty in forecasts of TC intensity (Emanuel et al.[12]; Zhang and Tao [13]). Numerous results indicate a clear negative correlation between vertical shear and TC intensity change (Frank and Ritchie[14]). However, Corbosiero and Molinari[15] demonstrated that a moderate shear in the low-level is more favorable for the formation and development of TC than having no shear. Black et al. [16] determined that Hurricane Jimena (1991) maintained a constant, or slightly weakened, intensity in 13-20 m/s easterly shear, and that Hurricane Olivia (1994) intensified in an 8 m/s easterly shear and weakened as the shear reversed to a westerly shear larger than 15 m/s.

Many observational studies have demonstrated that TCs would be weakened once the vertical wind shear exceeded a critical value. Zehr[17] observed that TCs did not develop when the shear exceeded 10 m/s in the Atlantic Ocean and 12.5 m/s in the western North Pacific. An observational study by Gallina and Velden[18] determined the critical shear value is 7-8 m/s in the Atlantic Ocean and 9-10 m/s in the western Pacific. Zhao et al.[19] suggested that the average shear of TC that can develop into a typhoon (tropical depression or tropical storm) is below 7 m/s (above 8 m/s). Paterson et al.[20] investigated that the shear of less than 10 m/s favor intensification, with values between 2 and 4 m/s favoring rapid intensification. Shear greater than 10 m/s is associated with weakening, with values greater than 12 m/s favoring rapid weakening. Although vertical shear can inhibit TC genesis and intensification, large, well-developed TCs may be able to resist a relatively quite strong vertical shear (DeMaria[2]; Wong and Chan[4]).

A time lag appears to exist between the onset of increased vertical wind shear and the onset of TC weakening. DeMaria[2] determined that the negative correlation between 200 and 850 hPa wind shear and TC intensity change was most significant during the next 36 h when TC is in the low latitudes (<20° N). Moreover, Palmer and Barnes[21] determined that a single maximum shear value of 17–20 m/s within 7° of the TC center can trigger TC decay within 12–24 h. Frank and Ritchie[3] performed a series of numerical simulations of

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TCs in idealized large-scale environments to examine the effects of wind shear on the structure and intensity change of hurricanes. Their results indicate that TCs would be weakened within a few hours when TC is placed in significantly strong (15 m/s) shear. TCs with the 5 m/s shear case showing no sign of weakening until more than 36 h after the shear is applied.

The different results of vertical wind shear effects on TC intensity change in previous studies may be caused by two reasons. First, the wind shear effects on TC intensity change are different when TCs have different intensities, or they are located in different latitudes. Second, these studies have different definitions for vertical wind shear. One traditional measurement of generalized shear is the magnitude of wind difference between vertical layers; another one is the zonal component of the generalized shear. The shears between different vertical layers and within different horizontal areas have been suggested in numerous previous studies as well. For example, Gallina and Velden[18] and Paterson et al.[20] selected two mass-weighted layer-mean wind differences between the lower layer (700–925 hPa) and the upper layer (150–350 hPa) as the vertical wind shear measurements. Other studies chose the shear between two particular levels, namely, 500–850 hPa (Knaff et al.[22]) and 200–850 hPa (Zhao et al.[19]; Zeng et al.[23]). The averaged horizontal area of the shear is different as well, which could be within a circle in 3° radius and 6° radius (Elsberry and Jeffries[24]; Franklin et al.[25]), an annulus of 200–800 km from the TC center (Knaff [26]), a 3°x3° and 10°×10° square area centered at the TC center (Paterson et al.[20]; Zhao et al.[19]). To date, the possible dependences of the vertical wind shear effects with different definitions on TC intensity change have not been analyzed statistically from observations. In the current study, we first compare the effects of the different shears on TC intensity change and analyze the most significant one. Thereafter, a TC intensity change prediction model will be developed that considers the vertical wind shear effects.

2 DATASETS AND ANALYSIS METHOD

The TC data are obtained from the best track data issued by the Shanghai Typhoon Institute of the China Meteorological Administration (CMA). The environmental data are gathered from the NCEP/NCAR reanalysis daily data from 2000 to 2006. The horizontal resolution is 1°x1°.

The different vertical wind shear definitions used in this study are listed in Table 1, which include the generalized wind shear (GVWS for short, including GVWS1, GVWS2, and GVWS3) and the zonal component of the shear (UVWS for short, including UVWS1, UVWS2, and UVWS3). The averaged areas include a circle in the 800 km radius (GVWS1 and UVWS1), an annulus of 200–800 km from the TC center (GVWS2 and UVWS2), and a 10°×10° square area centered at the TC center (GVWS3 and UVWS3). Moreover, GVWS are calculated between the different vertical layers, which include 200–850 hPa, 500–850 hPa, and 200–500 hPa. GVWS and UVWS are calculated by

$$\mathrm{GVWS}=\sqrt{(U_{200}-U_{850})^2+(V_{200}-V_{850})^2} \quad (1)$$

$$\mathrm{UVWS}=|U_{200}-U_{850}| \quad (2)$$

where U_{200}, U_{850}, V_{200} and V_{850} are the zonal and meridional wind components at 200 hPa and 850 hPa, respectively.

3 EFFECTS OF THE VERTICAL WIND SHEAR ON THE TC INTENSITY CHANGE

There are 197 TCs genesis in western North Pacific during 2000 to 2006, including 101 typhoons (TYs with maximum wind speed ≥32.6 m/s), 84 tropical storms and severe tropical storms (TSs with maximum wind speed between 17.2 m/s and 32.5 m/s), and 12 tropical depressions (TDs with maximum wind speed <17.2 m/s). One case is defined as the observation every 6 h in the best track data. The total number of cases is 5 871, including 1931 cases (~32.9%) of TD intensity, 2 135 cases (36.4%) of TS intensity, and 1 805 cases (30.7%) of TY intensity.

T-tests indicate that the correlation coefficients between all VWS (Table 1) of 200–850 hPa and the TC intensity change in 6–72 h is significantly negative at the 99% level (Fig.1). The correlation coefficients between TC intensity change and GVWS are always larger than that of UVWS when they are calculated within the same horizontal areas. Among all the GVWS definitions, the coefficient of GVWS2 is largest, and that of

Table 1. Different vertical wind shear definitions used in this study.

Generalized wind shear(Eq.1)	Zonal wind shear(Eq.2)	Vertical layers	Averaged horizontal area
GVWS1	UVWS1	200-850 hPa	Circle in 800 km radius
GVWS2	UVWS2		Annulus of 200–800 km
GVWS3	UVWS3		10° × 10° square area
GVWS1-L	UVWS1-L	500-850 hPa	Circle in 800 km radius
GVWS2-L	UVWS2-L		Annulus of 200–800 km
GVWS3-L	UVWS3-L		10° × 10° square area
GVWS1-H	UVWS1-H	200-500 hPa	Circle in 800 km radius
GVWS2-H	UVWS2-H		Annulus of 200–800 km
GVWS3-H	UVWS3-H		10° × 10° square area

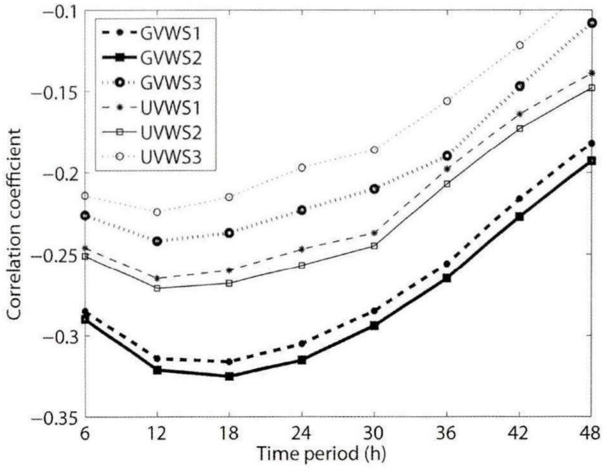


Figure 1. Correlation coefficients between the vertical wind shear of the different definitions and the TC intensity change during different time periods.

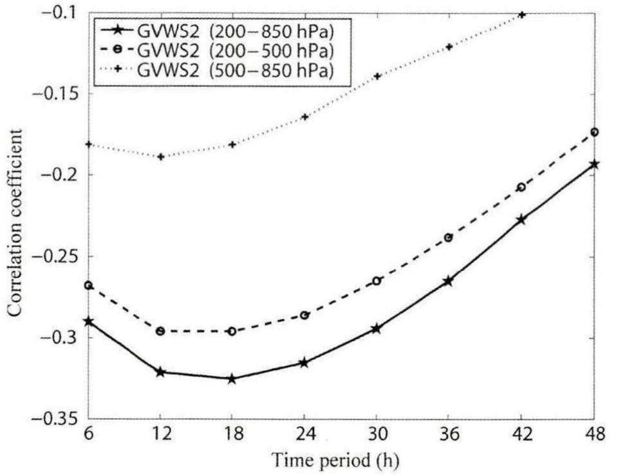


Figure 2. Correlation coefficients between GVWS at different levels and the TC intensity change during different time periods.

GVWS3 is smallest. Therefore, GVWS2, which is 200-850 hPa vertical shear averaged in an annulus of 200-800 km from the TC center, is selected in the following study.

The correlation coefficients between GVWS at different levels and TC intensity change during different time periods are shown in Fig.2. The largest coefficient for 200-850 hPa GVWS appears at 18 h with a value of -0.33. The coefficients decrease after 24 h because the case numbers become small and other factors (e.g., landfalling and extra-tropical transformation) become more important after 24 h. The curve of 200-500 hPa GVWS is similar to that of 200-850 hPa GVWS, which is significantly larger than that of 500-850 hPa. The largest coefficient for 500-850 hPa GVWS appears at 12 h, which is 6 h earlier than that of 200-500 hPa GVWS.

Table 2 shows the average TC intensity changes during the different time periods of different GVWS2 groups. The positive (negative) values of the TC intensity change with GVWS2 smaller (larger) than 10 m/s indicates that a larger vertical shear can inhibit TC intensification. A GVWS2 of 8-9 m/s (9-10 m/s) would cause TC to weaken within 60 h (48 h), and a GVWS2 larger than 10 m/s would cause TC to weaken within 6 h. This result suggests that TC experiences time lags between the imposition of larger GVWS2 and the resulting decrease in TC intensity; the lag is significantly shorter in strong GVWS2. This result confirmed the model outputs of Frank and Ritchie[14].

Table 2. Average TC intensity changes during the different periods of the different GVWS2 groups. GVWS2 indicates the 200-850 hPa generalized wind shear averaged within an annulus of 200-800 km from the TC center.

GVWS2/(m/s)	TC intensity change during different time periods (m/s)									
	6 h	12 h	18 h	24 h	30 h	36 h	42 h	48 h	60 h	72 h
0～1	1.09	1.82	2.62	3.47	4.68	5.25	4.72	5.47	3.50	4.86
1～2	1.04	2.02	2.69	3.19	4.33	4.71	4.22	3.90	4.20	2.35
2～3	0.64	1.30	1.88	2.42	3.42	2.97	2.45	2.79	2.49	1.94
3～4	0.73	1.39	2.21	2.73	3.60	3.88	2.72	2.78	1.52	1.18
4～5	0.66	1.30	1.89	2.48	3.40	3.33	2.77	2.85	0.24	0.08
5～6	0.57	1.06	1.61	1.92	2.34	2.42	1.79	2.66	1.22	0.65
6～7	0.42	0.74	0.95	1.16	1.99	2.04	0.88	1.56	1.10	1.38
7～8	0.01	0.28	0.35	0.40	1.27	1.18	0.58	0.90	0.15	0.71
8～9	0.22	0.32	0.35	0.65	0.99	1.23	0.33	0.74	-0.26	-0.41
9～10	0.09	0.14	0.21	0.07	0.46	0.37	0.14	-0.18	-0.01	-0.99
10～11	-0.19	-0.60	-1.06	-1.19	-0.72	-0.20	-1.48	-1.48	-1.82	-0.84
11～12	-0.62	-1.19	-1.68	-2.20	-1.80	-2.00	-2.70	-1.64	-2.70	-2.64
12～13	-0.79	-1.29	-2.01	-2.56	-2.32	-2.19	-3.29	-4.04	-3.48	-2.86
13～14	-0.52	-0.98	-1.23	-1.99	-1.61	-1.37	-3.08	-2.43	-1.16	-0.78
14～15	-0.87	-2.09	-2.85	-3.75	-3.48	-3.06	-4.33	-3.93	-3.83	-3.13
>15	-1.96	-3.89	-5.69	-7.11	-6.24	-6.22	-6.43	-5.33	-4.88	-3.50

The correlation coefficients between GVWS2 and TC intensity change for different intensity groups (TD, TS, and TY) during different time periods are calculated (Fig.3). The coefficients of the TS groups are significantly larger than those of the TD and TY groups, indicating that VWS has higher effects on the TC intensity change when the TC intensity is at TS grade. TCs would resist relatively quite strong VWS when they intensify to TY. The largest coefficient for the TD groups appears at 24 h, which is 6 h later than that of the TS and TY groups.

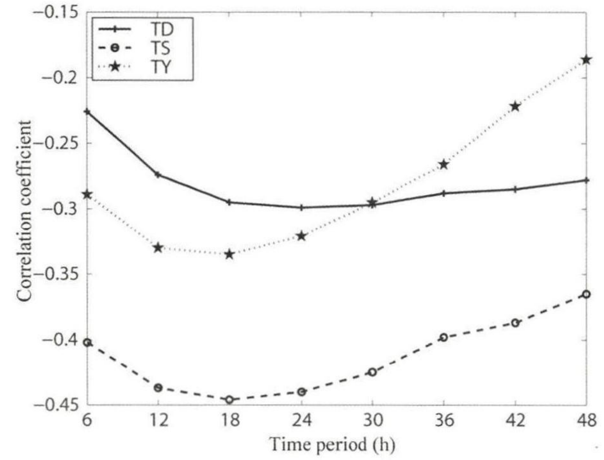
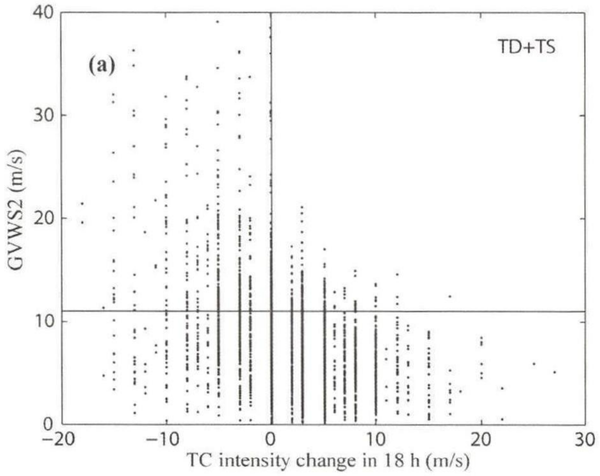


Figure 3. Correlation coefficients between GVWS2 and the TC intensity change for the different intensity groups (TD, TS, and TY) during the different time periods.

Figure 4 shows a scatter diagram of the TC intensity change during the future 18 h against the generalized wind shear (GVWS2) for the TD + TS group and the TY group. The average GVWS2 is 7.2 m/s of the TY group, which is 0.9 m/s less than that of the TD + TS group. For the TD + TS group, 50% (380) tends to weaken and 20% (153) tends to intensify when GVWS2 is larger than 11 m/s. For the TY group, 64% (407) tends to weaken and 15% (94) tends to intensify when GVWS2 is larger than 8 m/s. GVWS2 is not the only factor that affects the TC intensity change. TC would weaken with small VWS when the other factors (e.g., thermodynamic factors) are detrimental to the TC intensification. The critical VWS values above which TCs on average would be weakened are different for the TD + TS group and the TY group.



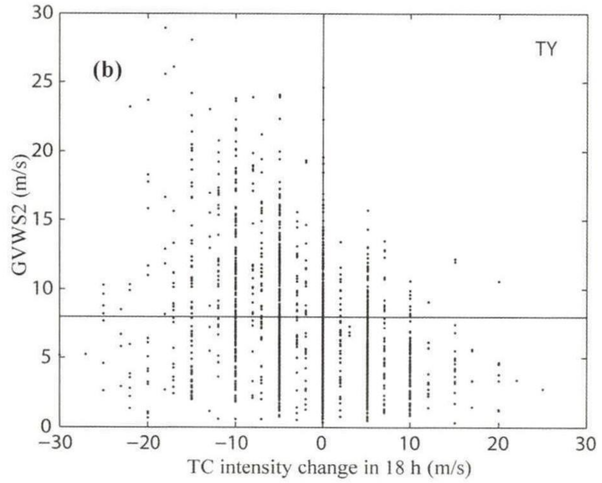


Figure 4. Scatter diagram of the TC intensity change during the future 18 h (m/s) vs. the generalized wind shear averaged within an annulus of 200-800 km from the TC center (GVWS2; m/s) for (a) the TD + TS groups and (b) the TY groups. The horizontal line indicates GVWS2 of 11 m/s in (a) and 8 m/s in (b); the vertical line indicates the intensity change equal to 0 m/s.

The total samples are stratified into three latitude groups (>23°N, 16°–23°N, and <16°N), and the correlation coefficients between GVWS2 and the TC intensity change for the different latitude groups are calculated (Fig.5). The latitude intervals were chosen such that the samples in the three groups were approximately equal in size. Fig.5 shows that the coefficients decrease

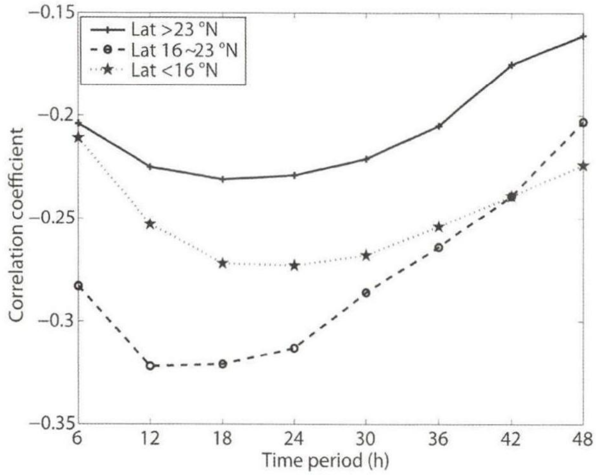


Figure 5. Correlation coefficients between GVWS2 and the TC intensity change for the different latitude groups (>23°N, 16°–23°N, and <16°N) during the different time periods. The test indicated that all the coefficients were significant at the 99% level.

in magnitude with latitude at nearly all of the time intervals, which indicates that the intensity of high-latitude TCs is less sensitive to VWS than that of the low-latitude TCs.

4 STATISTICAL PREDICTION MODEL FOR INTENSITY CHANGE

4.1 *Model experiment*

Operational TC intensity prediction models include the subjective prediction methodology based on statistical-dynamical models (Knaff et al.[26]), pure numerical models (Bender et al.[27]), and statistical models (Chu[28]), and based on multiple linear regression method. For these models, the dependent variable is the TC intensity change; the predictors used include the potential factors that may affect the TC intensity change. The forecast models are developed based on a multiple regression that is used to select predictors based on their ability to predict the dependent variable.

CMA has three operational statistical models, which include a climatology and persistence model (STI-CLIPER for short, see Yu et al.[29]), as well as a statistical prediction scheme involved in climatology persistence, synoptic predictors, infrared satellite data (Hu et al.[30]), and the method based on the combination of the genetic algorithm and artificial neural network (Yao et al. [31]). The potential predictors used in STI-CLIPER include the current TC intensity, latitude, and longitude; 12-h change in intensity, latitude, and longitude; and 24-h change in intensity, latitude, and longitude.

The traditional regression method based on the ordinary least-squares (OLS) is not able to provide an exact estimation and distinct analytic results when a high degree of collinearity exists among the impact variables; this method can hardly select the right independent variables objectively (Word[32]). To overcome the limitation, Song et al.[33] developed a new statistical intensity model based on the partial least squares (PLS) regression called PLS-CLIPER. These results indicate that PLS-CLIPER produces skillful intensity forecast, with a smaller error and a larger tendency accordance ratio relative to STI-CLIPER. Therefore, PLS is employed in the present study.

With the complexities involved in the TC intensity change, the statistical-dynamical approach can combine the statistical methodology (e.g., STI-CLIPER and PLS-CLIPER) with the environmental predictors derived from numerical weather models. The Statistical Typhoon Intensity Prediction Scheme (STIPS) has been used operationally at the Joint Typhoon Warning Center (JTWC). A time lag appears to exist between the onset of the increased vertical wind shear and the onset of the TC intensity change; thus, the TC intensity is predictable from the vertical wind shear. In this study, we develop a statistical-dynamical approach called PLS-STIPSV by adding the VWS factors to the potential predictors in PLS-CLIPER. Therefore, the potential predictors used in the PLS-STIPSV development can be divided into two categories (Table 3): (1) those related to climatology, persistence, and trends of intensity-CLIPER factors; and (2) those related to the environmental VWS factors. The predictands are the intensity change from the initial forecast time at 6 h intervals for the future 6–72 h. The cross-validation was produced after the regression equations were developed (Wold[32]; Song et al.[33]).

4.2 *Model evaluation*

PLS-STIPSV was developed based on the TC samples from 2000 to 2005. PLS-CLIPER was produced based on the data from 1976 to 2005. Forecast comparisons between PLS-STIPSV and PLS-CLIPER were made using independent data in 2006. The potential forecast capabilities of these models in terms of mean absolute errors (MAE) are shown in Fig.6. The MAE values are shown to increase from 1.87 m/s at 6 h to 8.77 m/s at 72 h (Fig.6a). PLS-STIPSV MAE is smaller than that of PLS-CLIPER through the 72 h forecast pe-

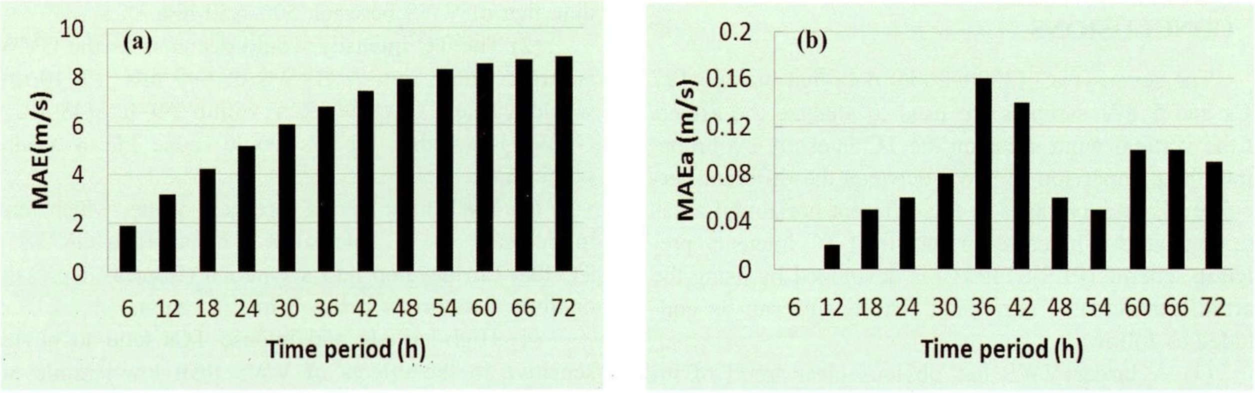


Figure 6. (a) Mean absolute errors of PLS-STIPSV, and (b) Difference of mean absolute errors between PLS-STIPSV and PLS-CLIPER for the independent data in 2006.

riod except that in 6 h, suggesting the superiority of the forecast skill of PLS-STIPS with vertical wind shear factors in the predictors. The difference in MAE between these two models is small, suggesting that we should consider other predictors related to environmental thermodynamical and dynamical conditions and those related to the TC internal dynamics.

4.3 *Analysis of regression coefficients*

The importance and correlation of each predictor in its explanation of the dependent system can be determined by examining and analyzing the standard regression coefficients. The positive value of the coefficient indicates that the predictor favors the TC intensification. The larger absolute value of the coefficient indicates that the predictor is more important.

Table 4 shows the regression coefficients of each predictor in PLS-STIPSV. All the vertical wind shear factors have a negative correction with the TC intensity change, further confirming that the shear is detrimental to TC intensification. Moreover, the absolute values of these coefficients indicate that the GVWS factors are more important than the UVWS in this regression equation. The effect of the wind shear between 200 and 500 hPa on the TC intensity change is larger than that of the wind shear between 500 and 850 hPa. The coefficients are larger within 18–48 h, which is consistent with the results presented in Section 3.

Table 3. Potential predictors available for inclusion into PLS-STIPSV.

Category	Predictor	Description
CLIPER factors	LAT, ΔLAT-12, ΔLAT-24	Current TC latitude, past 12 h and 24 h changes in latitude
	LON, ΔLON-12, ΔLON-24	Current TC longitude, past 12 h and 24 h changes in longitude
	VMAX, ΔVMX-12, ΔVMX-24	Current TC intensity, past 12 h and 24 h changes in intensity
Vertical wind shear factors	GVWS2, UVWS2	Generalized and zonal 200–850 hPa wind shear within the 200–800 km annulus
	GVWS2_L, UVWS2_L	Generalized and zonal 500–850 hPa wind shear within the 200–800 km annulus
	GVWS2_H, UVWS2_H	Generalized and zonal 200–500 hPa wind shear within the 200–800 km annulus

Table 4. Standard regression coefficients of the VWS predictors in PLS-STIPS.

GVWS2/(m/s)	TC intensity change during different time periods (m/s)							
	6 h	12 h	18 h	24 h	36 h	48 h	60 h	72 h
GVWS	–0.06	–0.08	–0.09	–0.09	–0.09	–0.09	–0.05	–0.05
UVWS	–0.02	–0.02	–0.01	–0.01	–0.00	–0.00	0.01	–0.01
GVWS_H	–0.05	–0.06	–0.06	–0.06	–0.05	–0.04	–0.03	–0.03
UVWS_H	–0.01	–0.01	–0.02	–0.02	–0.03	–0.04	–0.03	–0.00
GVWS_L	–0.02	–0.03	–0.04	–0.03	–0.03	–0.04	–0.04	–0.04
UVWS_L	–0.01	–0.01	–0.00	–0.01	–0.03	–0.04	–0.06	–0.05

5 CONCLUSIONS

The seven-year (2000–2006) data that include 197 TCs and 5 871 samples are used to analyze the effects of the vertical wind shear on the TC intensity evolution. First, the comparison of VWS between the different vertical levels and averages in the different horizontal areas are compared. Thereafter, a statistical TC intensity prediction scheme (PLS-STIPSV) is developed by using the partial least squares regression. The results can be concluded as follows.

(1) A larger VWS has obvious clear trend of inhibiting the TC development. The effect of the general VWS on the TC intensity change is larger than that of the zonal VWS. The negative correlation between 200–500 hPa VWS and the TC intensity change is larger than that of VWS between 500–850 hPa.

(2) The TC intensity would decrease as the GVWS is larger than 8 m/s. A GVWS of 8–9 m/s (9–10 m/s) would cause TC to weaken within 60 h (48 h). A GVWS larger than 10 m/s would cause TC to weaken within 6 h.

(3) VWS may have a threshold value, which tends to decrease as TC intensifies. The average GVWS of TC that can develop into a typhoon (tropical depression or tropical storm) is below 8 m/s (11 m/s).

(4) High-latitude and intense TCs tend to be less sensitive to the effects of VWS than low-latitude and weak TCs.

(5) Finally, a statistical TC intensity prediction scheme (PLS-STIPSV) is developed by using partial least squares regression, which produces skillful intensi-

ty forecasts when the potential predictors include VWS. The difference of MAE between these two models is small, suggesting that we should consider other predictors related to environmental thermodynamical and dynamical conditions and those related to the TC internal dynamics.

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