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Does strong vertical wind shear certainly lead to the weakening of a tropical cyclone?

Kelvin T F Chan ©, Donghai Wang, Yu Zhang, Worachat Wanawong, Min He and Xing Yu
Guangdong Province Key Laboratory for Climate Change and Natural Disaster Studies, School of Atmospheric Sciences, Sun Yat-sen University, Guangzhou 510275, People’s Republic of China
E-mail: chenth25@mail.sysu.edu.cn

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Abstract
This is a preliminary pilot study giving an important insight into the feasible improvement of existing prediction of tropical cyclone (TC) intensity change by revisiting the relevant impact of vertical wind shear (VWS), where VWS is commonly defined as the environmental horizontal wind difference between the top and bottom of the shear layer. Macroscopically, strong VWS has been concluded to be detrimental to TC intensification. However, this study, from the microscopic point of view, shows that given the same thermal forcing, strong VWS does not certainly lead to TC weakening. Considering the magnitude, direction or orientation of VWS alone is no longer comprehensively physical enough for predicting the change in TC intensity. Instead, the whole profile of VWS (VWSP), that is the environmental horizontal winds at all levels within the shear layer, determines. The ventilation of dry and low-entropy air that are directly or indirectly driven by the environmental flows in the upper-, mid- and lower-troposphere could modify TC intensity in various extent. The VWSP is proposed to be a new potential proxy or update of the current TC intensity change prediction.

1. Introduction

Environmental vertical wind shear (VWS) is one of the determining factors controls both tropical cyclogenesis and tropical cyclone (TC) intensity. It is typically defined as the magnitude of the environmental horizontal wind between 200- and 850-hPa pressure levels within a certain area from the TC center. Strong VWS has been observed and examined to be detrimental to tropical cyclogenesis and TC intensification (Gray 1968, McBride and Zehr 1981, Merrill 1988, Zehr 1992, DeMaria 1996, Wang and Wu 2004, Paterson et al 2005, Zeng et al 2007, 2008, 2010, Wang et al 2015). VWS may hinder genesis and intensification by ventilating the dry and low-entropy air into the incipient disturbance or vortex, disrupting the formation of a moist column and removing the condensation heat from it, hence, preventing it from deepening (Gray 1968, Emanuel 1989, Bister and Emanuel 1997, Nolan 2007). Therefore, VWS was one of the important predictors for TC genesis and intensity change in many statistical forecasting models (DeMaria and Kaplan 1999, Emanuel et al 2004, DeMaria et al 2005, Knaff et al 2005, DeMaria 2009, Kaplan et al 2015).

Another ventilation mechanism is further hypothesized that VWS decreases the efficiency of the TC heat engine by ventilating the TC with low-entropy air at mid and low levels (Cram et al 2007, Marin et al 2009, Tang and Emanuel 2010, Riemer et al 2010). Convective downdrafts due to evaporation of rain flush the inflow boundary layer with low-entropy air (Powell 1990, Riemer et al 2010, Riemer and Montgomery 2011) which counteracts the generation of available potential energy by surface entropy fluxes and weakens the TC. Other hypotheses like stabilization caused by midlevel warming that increases static stability and reduces convective activity (DeMaria 1996), outward eddy fluxes of entropy and potential vorticity that erode the TC from the top down (Frank and Ritchie 2001), entrainment of cool/dry air in the upper troposphere (Wong and Chan 2004), and eddy momentum fluxes that weaken the mean tangential winds (Wu and Braun 2004) have also been suggested.
Apart from looking at the magnitude of VWS, the direction of VWS has also found to be important for TC genesis and intensity. Some studies show that easterly shear is more favorable to TC intensification than westerly shear (Ritchie and Frank 2007, Zeng et al 2010, Shu et al 2014). The beta-induced northwesterly shear within the inner core of the TC could partly offset the easterly shear and thereby results in weaker VWS and favors TC intensification. In addition, the easterly shear induced asymmetric inflow can help bring warm moist air from the south and southeast quadrants of the TC and be favorable for TC intensification over the western North Pacific. On the other hand, Wei et al (2018) recently found that the westerly VWS has a much higher correlation with change in TC intensity than the easterly VWS over the western North Pacific. Besides, Rappin and Nolan (2012) found that the orientation of VWS can influence the TC genesis time and TC development. He et al (2015) also showed that unidirectional and non-unidirectional VWS could result in different TC evolution, however, without explanation. Finocchio et al (2016) suggested that the height and depth of VWS could be important for improving the TC intensity forecast, but their experiments were conducted by non-unidirectional VWS only. Nevertheless, Finocchio and Majumdar (2017) later found that the shear height and depth parameters do not appear to be viable predictors for statistical intensity prediction.

From the literature review of above, it is therefore suggested that looking at magnitude, direction or orientation of VWS alone is no longer comprehensive and informative enough to predict tropical cyclogenesis and TC intensity. The whole profile of VWS (VWSP; i.e. the environmental horizontal winds at all levels within the shear layer) should be considered which forms the main objective of the present study. Section 2 describes the model configurations and experimental designs of this study. Section 3 presents how different VWSPs lead to different TC development (both track and intensity) and a case study is followed by. Section 4 proposes VWSP is a new proxy or update of the current TC intensity change prediction. Finally, the conclusion and discussion are given in section 5.

2. Model and experimental design

The Advanced Hurricane Weather Research and Forecasting Model (WRF, known also as AHW) version 3.9.1 is employed. A large rectangular domain (11 000 × 5000 km²; figure 1) with 40 vertical levels and 5 km horizontal grid resolution is configured. For the model physics, the 5-layer thermal diffusion, MM5 similarity surface layer physics (Jiménez et al 2012) and Yonsei University planetary boundary layer scheme (Hong et al 2006) are used. The Newtonian radiative cooling (Rotunno and Emanuel 1987) is employed to model the longwave radiation physics. No shortwave radiation is used. The modified surface bulk drag (Donelan et al 2004) and enthalpy coefficients (Brutsaert 1975) are applied.

The initial vortex is designed as the analytic axisymmetric cyclone which is in hydrostatic and gradient-wind balance (Rotunno and Emanuel 1987). The maximum wind, radius of maximum wind, radius of vanishing wind, and depth of the vortex are set to be 20 m s⁻¹, 100 km, 800 km and 20 km respectively. The vortex is initialized at the center of the domain and be spun up in a quiescent environment with the Jordan (1958) mean hurricane sounding, over the open water at 28 °C time-invariant sea surface temperature, and on an f plane at 20°N for 42 h such that the symmetric spunup vortex reaches maximum wind ~24 m s⁻¹ and central minimum sea-level pressure ~998 hPa, which is at the level of tropical storm. The spunup vortex possessing tropical storm...
intensity rather than typhoon/hurricane intensity is initiated in this study because tropical storm is the necessary stage for every TC. As a preliminary study, such initialization should be generic enough to cover most of the cases in the reality.

The spunup vortex is then superimposed by different environmental VWS (VWS\textsubscript{env}) profiles (VWSPs; figure 2). Apart from the control experiment (i.e. the no shear experiment), three different magnitudes of VWS\textsubscript{env}: weak shear (|VWS\textsubscript{env}| = 4 m s\textsuperscript{-1}), moderate shear (|VWS\textsubscript{env}| = 8 m s\textsuperscript{-1}) and strong shear (|VWS\textsubscript{env}| = 12 m s\textsuperscript{-1}) are designed. In each type of VWS\textsubscript{env}, five VWSPs are further configured. Therefore, there are totally 16 experiments. Although the change of environmental horizontal winds with height is non-linear and complex in reality, as a preliminary pilot study (and like many other idealized studies, e.g. Ge \textit{et al} 2013, Rappin and Nolan 2012, Li \textit{et al} 2015), a simple linear profile is adopted in this study (figure 2). The details of various experiments are tabulated in table 1. All experiments are simulated for four days and the lateral boundary conditions are doubly periodic. It is noted that environmental flows are maintained throughout the simulation, so do the VWS\textsubscript{env}. Because simulations are conducted on an f-plane, there is no beta effect and the direction of VWS\textsubscript{env} does not matter the conclusions. Notes also that because Wang \textit{et al} (2015) recently found that the conventional 200–850 hPa VWS is less representative of the attenuating deep-layer shear effect than 300–1000 hPa VWS found over the western North Pacific, similar layer (i.e. 9 km–surface) is defined as the shear layer in this study.

\begin{table}[h]
\centering
\begin{tabular}{ccc}
\hline
\textbf{U\textsubscript{fc}} & \textbf{U\textsubscript{100}} & \textbf{Experiment} \\
\hline
\textbf{Control (No shear)} & 0 & 0 & CTRL \\
\hline
\textbf{Weak shear} & 0 & 4 & S4wL0oU4w \\
(|VWS\textsubscript{env}| = 4 m s\textsuperscript{-1}) & -2 & 2 & S4wL2eU2w \\
& -4 & 0 & S4wL4eU0o \\
& -7 & -3 & S4wL7eU3e \\
& 3 & 7 & S4wL3wU7w \\
\hline
\textbf{Moderate shear} & 0 & 8 & S8wL0oU8w \\
(|VWS\textsubscript{env}| = 8 m s\textsuperscript{-1}) & -4 & 4 & S8wL4eU4w \\
& -8 & 0 & S8wL8eU0o \\
& -11 & -3 & S8wL11eU3e \\
& 3 & 11 & S8wL3wU11w \\
\hline
\textbf{Strong shear} & 0 & 12 & S12wL0oU12w \\
(|VWS\textsubscript{env}| = 12 m s\textsuperscript{-1}) & -6 & 6 & S12wL6eU6w \\
& -12 & 0 & S12wL12eU0o \\
& -15 & -3 & S12wL15eU3e \\
& 3 & 15 & S12wL3wL15w \\
\hline
\end{tabular}
\caption{Experimental designs of different experiments. U\textsubscript{fc} and U\textsubscript{100} are the environmental horizontal winds (unit: m s\textsuperscript{-1}) at surface and 300-hPa pressure levels respectively.}
\end{table}
3. Results

3.1. Track

Vortices in shear experiments have different tracks (figure 1), where track is tracked by locating the minimum sea-level pressure (MSLP) of the vortex. Vortices are generally steered by the lower-to-mid tropospheric environmental flows, that are, easterly or westerly in these cases. Vortex experiencing higher lower-to-mid tropospheric environmental flow moves faster. In addition, vortex has northward deviation in general which basically results from the asymmetric convection caused by the VWS. Stronger convective activity is generally found in the northern flank of the vortex (figure 3). Referring to previous TC track studies (Wu and Wang 2000, Chan and Chan 2016), such vortex movement are largely driven by the horizontal advection and diabatic heating components of the potential vorticity tendency equation respectively. On the other hand, vortex in no shear experiment (CTRL) is symmetric and remains at rest (not shown) because the environmental flow is absent and it is on an f plane.

Due to the vortex symmetry on an f plane, the vortices experience the easterly shear have southward deviation in general (not shown). It is therefore suggested that the vortex in the westerly shear would likely have higher northward movement component than that in the easterly shear in spherical earth, where f is not constant. A beta-plane or spherical earth experiment is needed to confirm this which is left for the future work.

3.2. Intensity

Figure 4 shows the time series of the vortex intensity in weak, moderate and strong shear experiments, where vortex intensity is denoted by the MSLP. All vortices in the shear experiments are weaker than that in the no shear (CTRL) experiment. Generally, vortex experiences stronger VWSenv has slower vortex development and attains weaker vortex intensity, which agrees well with previous studies. The vortices deepen from 998 hPa to around 960 hPa and 980 hPa in the weak shear and moderate shear experiments in 48 h respectively, while the vortices in the strong shear experiments do not deepen but weaken in general.

Most importantly, it is noted that even the vortex experiences the same magnitude of VWSenv, the intensity evolutions of the vortex could vary with different VWSPs. In weak and moderate VWSenv, vortex which experiences the same VWSenv but weaker lower-tropospheric environmental flow can develop faster and attain higher intensity (figures 4(a), (b)). Based on the time-averaging intensity measure, the vortices experiencing the weakest lower-tropospheric environmental flow (S4wL0oU4w and S8wL0oU8w) are strongest, while those experiencing the strongest lower-tropospheric environmental flow (S4wL7eU3e and S8wL11eU3e) are weakest. It is primarily because the weaker (stronger) lower-tropospheric environmental flow possesses less (more) penetration effect (figure 3) so that it ventilates less (more) low entropy air into the vortex (figure 5), which is less (more) detrimental to the vortex intensification, in which the low entropy air is from the environment and/or convective downdrafts due to evaporation of rain (see figure 8). Yet, though the cool (figure 5) and dry (figure 6) air intrusion associated with flows in the upper troposphere in weak and moderate VWSenv do not vary such conclusion substantially, this is not the case in strong VWSenv. The upper-tropospheric flow is shown to be the secondary factor which could modify the vortex intensity (figures 5(c), (f), (i), (l), (o) and 6(c), (f), (i), (l), (o)). Notes that although the cross sections shown in figures 5 and 6 do not align exactly with the directions of resultant VWS interacting with the vortices (not shown; westerly to southwesterly in general; defined as the direction of mean wind difference between 300 hPa pressure level and surface within 600 km radius from the vortex centers), the average over ±200 km meridional belt from the zonal axis across the vortices centers could largely capture the characteristics (especially those outside the eye region).

In strong VWSenv, although the time-averaging intensity of vortex experiencing the strongest lower-tropospheric environmental flow (S12wL15eU3e) is weakest, the vortex experiencing the weakest lower-tropospheric environmental flow (S12wL00U12w) is not strongest, which is inconsistent with what has concluded from the weak and moderate VWSenv experiments. Even the lower-tropospheric environmental flow is zero, vortex cannot develop and intensify (figure 4(c)). It is because the inertial stability of the vortex at the upper-tropospheric outflow region cannot resist such a strong environmental flow, so that the outflow region interacts readily with the environmental flow (figure 3(l)). The vortex with stronger intrusion of cool and/or dry air in the upper troposphere is more detrimental to TC development (figures 5(l) and 6(l) or see figures 8(d), (e)).

Interestingly, among all the strong VWSenv experiments, only the vortex in S12wL6eU6w experiment can maintain and intensify gradually from 998 hPa to 980 hPa after 96 simulation hours (figure 4(c)). It is probably because vortex is embedded in the non-unidirectional shear (i.e. environmental flow in the upper troposphere is in opposite direction to that in the lower troposphere) such that the vortex experiences calm-to-moderate environmental flows (ranged between 0–6 m s−1) in the whole shear layer. The inertial stability of the vortex could barely resist part of such environmental flows (figures 3(c) and 8(c)), and hence, the vortex could develop
and intensify slowly. TC Danny (1997) is one of the good and supportive examples of this circumstance (see next section).

3.3. Case study
TC Danny (1997) first formed from a non-tropical system in the North Atlantic. It developed into a tropical depression south of the Louisiana coast on July 16, 1997. The system strengthened into tropical storm on July 17 as it tracked northeast toward the southeast Louisiana coast. Danny continued to intensify and became a Category 1 hurricane at midnight on July 18. It then made landfall near Buras on July 18 and moved back over the Gulf waters. It is noted that even Danny was in strong $VWS_{env}$ ($|VWS_{env}| \approx 10 \text{ m s}^{-1}$; figure 7), it could still intensify from a tropical storm to a hurricane at midnight on July 18. Molinari et al. (2004) attributed this to the development of axisymmetrization of lower-tropospheric vorticity and vertical mixing of moist entropy by

Figure 3. Reflectivity at 700-hPa (shading, unit: dBZ) and streamlines at 850-hPa (gray) and 300-hPa (red) pressure levels in different experiments. X and Y axes denote the displacement from the vortex center (0, 0) in zonal and meridional directions respectively.
convection. However, they did not explain further why there were the development of axisymmetrization of lower-tropospheric vorticity and vertical mixing of moist entropy. Here, we show the non-unidirectional $VWS_{env}$ (figure 7) is the main reason leading to these. Although TC Danny was experiencing strong $VWS_{env}$ at 06
UTC on July 18, 1997, the lower-tropospheric and upper-tropospheric environmental flows were non-unidirectional (southeasterly in the lower troposphere and northwesterly in the upper troposphere). The environmental flows within the shear layer were indeed calm-to-moderate (ranged between 0.7–7.0 m s\(^{-1}\); figure 7) such that the inertial stability was strong enough to resist (or partially resist) them and allow the development of axisymmetrization of lower-tropospheric vorticity and vertical mixing of moist entropy and led to intensification of Danny eventually. Such case study agrees well with and validates what has been found in the numerical simulations.

Figure 5. Zonal–height cross sections of the equivalent potential temperature (shading; unit: K) and winds (vector; vertical velocity is multiplied by a factor of 50) averaged over ±200 km meridional belt from the zonal axis across the vortices’ centers (from west to east) in (left) weak, (middle) moderate and (right) strong shear experiments at 24 simulation hour. Vortex center locates at \(X = 0\).
4. New proxy

The conventional VWS$_{env}$ metric (i.e. the magnitude of the environmental horizontal wind between 200- and 850-hPa pressure levels within a certain area from the TC center) is widely used to predict the TC intensity change because it is very convenient to calculate and easy to understand. However, the numerical results of this study suggest that considering the magnitude, direction or orientation of conventional VWS$_{env}$ alone is not comprehensively physical enough, whereas VWSP is superior and is proposed to be a new proxy for predicting the change in TC intensity. Therefore, other metrics (together with the conventional one) are tested to quantify the shape and physical meaning of the VWSP. The environmental horizontal winds at the bottom ($U_{sc}$) and top
(U_{300}) levels of the shear layer, and the mean of environmental horizontal winds in the shear layer (SLW) would apparently be the simplest ones. The concept of energy (i.e. the square of winds) would be the advanced ones. Table 2 shows various metrics and vortex intensity changes (ΔMSLP) between 24–72 h of simulations of all numerical experiments and their corresponding correlations to ΔMSLP. It is found that the correlation coefficient between |VWS_{env}| and ΔMSLP is the highest (r = 0.83), U_{sfc}^2, U_{300}^2 and SLW^2 have moderate-to-high correlations with ΔMSLP (r = 0.53, 0.43, and 0.68 respectively), while those of U_{sfc}, U_{300} and SLW are low. When linear multiple regression is applied among |VWS_{env}|, U_{sfc}^2, U_{300}^2 and SLW^2, |VWS_{env}| is found to be marginally insignificant (p value = 0.06 > 0.05), while U_{sfc}^2, U_{300}^2 and SLW^2 are all statistically significant and highly correlate with ΔMSLP (r = 0.92). This suggests |VWS_{env}| is less informative when U_{sfc}^2, U_{300}^2 and SLW^2 are taken into account. Here is the regression equation deduced from the present numerical study:

\[
\Delta \text{MSLP} = -53.24 + 0.66 U_{sfc}^2 + 0.63 U_{300}^2 - 1.09 \text{SLW}^2
\]

Due to the linearity of the VWS_{env} in this study, SLW^2 equates to \((\frac{U_{sfc} + U_{300}}{2})^2\). Thus, the above equation can be derived to:

\[
\Delta \text{MSLP} = -53.24 + 0.39 U_{sfc}^2 + 0.36 U_{300}^2 - 0.55 U_{sfc}U_{300}
\]

Since most of the vortices are at developing stage during 24–72 h of simulations, a negative constant coefficient (i.e. the deepening trend) is present in the equation. Such a constant is therefore not physical to interpret the change in vortex intensity by VWS_{env} at all, but the rest of the terms do. The last three terms clearly suggest that the VWSP (both the magnitude and direction of environmental horizontal flows within the shear layer) could modify the vortex intensity. As these terms are at the same order of magnitude, they are comparably important. Notes also that the form of traditional VWS_{env} (i.e. U_{300} - U_{sfc}) is actually embedded in the last two terms of the equation implicitly. This could be the reason why |VWS_{env}| is not significant in the multiple regression because of such dependence. Most importantly, it is suggested that the conventional proxy (|VWS_{env}|) could be replaced or updated by the new proxy (VWSP) to give a better prediction of TC intensity change.
Table 2. Various metrics and vortex intensity changes between 24–72 h of simulations (ΔMSLP; unit: hPa) of all numerical experiments and their corresponding correlations to ΔMSLP. VWS<sub>env</sub>, (unit: m s <sup>−1</sup>) is the environmental horizontal wind difference between the 300-hPa pressure level and surface. U<sub>sfc</sub> and U<sub>300</sub> are the environmental horizontal winds (unit: m s <sup>−1</sup>) at surface and 300-hPa pressure level respectively. SLW (unit: m s <sup>−1</sup>) is the mean environmental horizontal winds in the shear layer. U<sub>sfc</sub><sup>2</sup>, U<sub>300</sub><sup>2</sup> and SLW<sup>2</sup> are in unit of m<sup>4</sup>s<sup>−2</sup>.

| VWS<sub>env</sub> | U<sub>sfc</sub> | U<sub>300</sub> | SLW | U<sub>sfc</sub><sup>2</sup> | U<sub>300</sub><sup>2</sup> | SLW<sup>2</sup> | ΔMSLP |
|----------------|--------------|--------------|-----|----------------|----------------|----------|--------|
| CTRL           | 0            | 0            | 0   | 0              | 0              | 0        | −49.5  |
| S4wL0oU4w      | 4            | 0            | 4   | 2              | 0              | 16       | 4      |
| S4wL2eU2w      | 4            | −2           | 2   | 0              | 4              | 4        | −49.4  |
| S4wL4eU0o      | 4            | −4           | 0   | −2             | 16             | 0        | 4      |
| S4wL7eU3e      | 4            | −7           | −3  | −5             | 49             | 9        | 25     |
| S4wL3wU7w      | 4            | 3            | 7   | 5              | 9              | 49       | 25     |
| S8wL0oU8w      | 8            | 0            | 8   | 4              | 0              | 64       | 16     |
| S8wL4eU4w      | 8            | −4           | 4   | 0              | 16             | 16       | 0      |
| S8wL8eU0o      | 8            | −8           | 0   | −4             | 64             | 0        | 16     |
| S8wL11eU3e     | 8            | −11          | −3  | −7             | 121            | 9        | 49     |
| S8wL3wU1w      | 8            | 3            | 11  | 7              | 9              | 121      | 49     |
| S12wL0oU12w    | 12           | 0            | 12  | 6              | 0              | 144      | 36     |
| S12wL6eU6w     | 12           | −6           | 6   | 0              | 36             | 36       | 0      |
| S12wL12eU0o    | 12           | −12          | 0   | −6             | 144            | 0        | 36     |
| S12wL15eU3e    | 12           | −15          | −3  | −9             | 225            | 9        | 81     |
| S12wL3wL15w    | 12           | 3            | 15  | 9              | 9              | 225      | 81     |
| Correlation    | 0.83         | −0.36        | 0.20| −0.39          | 0.53           | 0.43     | 0.68   |

In addition, such a high relationship implies that the change in vortex intensity could be subjected to the distribution of kinetic energy (or wind energy) carried by the environmental dynamics in the shear layer. It is suggested that vigorous energy distribution could disrupt the vortex structure and hence hinder vortex intensification, while mild energy distribution is less destructive and thus less detrimental to vortex intensification.

To summarize, VWSP, which is quantified by (or function of) U<sub>sfc</sub>, U<sub>300</sub> and SLW, is proposed to be a new proxy or update of the current TC intensity change prediction. U<sub>sfc</sub><sup>2</sup>, U<sub>300</sub><sup>2</sup> and SLW<sup>2</sup> are found to be the significant metrics. It is noted that this is an example deduced from the idealized numerical model results. More observational case studies are needed for the cross validation. Other superior options(metrics) are also urged for a better prediction of TC intensity change.

5. Conclusion and discussion

The sensitivity of the change of TC intensity to the profile of VWS<sub>env</sub> (VWS; i.e. the environmental horizontal winds at all levels within the shear layer) is examined using idealized numerical simulations. It is found that given the same thermal forcing, strong VWS<sub>env</sub> does not assuredly lead to TC weakening. Although it is generally true that stronger VWS<sub>env</sub> would results in weaker TC intensity, the VWSP of vortex is more physical to determine the change in TC intensity. Figure 8 shows a schematic diagram of how the VWSP interacts with the vortex and modifies its structure. The ventilation of dry and low-entropy air that are directly or indirectly driven by the environmental flows in the upper-, mid- and lower-troposphere could modify TC intensity in various extent. VWSP is thereby proposed to be a new potential proxy or update of the current TC intensity change prediction. The kinetic energy (or wind energy) carried by the environmental horizontal winds at the bottom (U<sub>sfc</sub>) and top (U<sub>300</sub>) levels of the shear layer, and the mean environmental horizontal wind in the shear layer (SLW) are suggested to be important metrics.

Notes that this preliminary pilot study aims to give an insight into the feasible improvement of existing prediction of TC intensity change and explains why strong VWS<sub>env</sub> does not surely lead to TC weakening by revisiting the relevant impact of VWS<sub>env</sub>, but not target to establish and formulate a complete method, sophisticated matrix or operational index to predict TC intensity change. Before introducing the new proxy to the operation, more observational case studies, statistical analysis and model simulations on the validation and matrix formulation are urged. Besides, the interaction between the vortex possessing typhoon/hurricane intensity and VWSP is also important to look at. These form the next steps of the study.
Figure 8. Schematic diagram of how different VWSPs (left) interact with the vortex and modify the vortex structure (right). The cyclonic inflow in the lower troposphere and anticyclonic outflow in the upper troposphere driven by the vortex itself are indicated by the black arrows. Arrows in green denote the environmental horizontal winds at corresponding levels. The ventilation of cool and dry air in the upper troposphere and cool air in the lower troposphere resulted from VWS_{env} are shown by thick arrows. Convective downdrafts due to evaporation of rain flush the inflow boundary layer with low-entropy air.
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ORCID iDs

 Kelvin T F Chan © https://orcid.org/0000-0001-6150-7612

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