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THE USE OF SHEAR GRADIENT VORTICITY IN TROPICAL CYCLONE HEAVY PRECIPITATION PREDICTION: A HIGH-RESOLUTION NUMERICAL CASE STUDY

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Abstract: This study introduces a new dynamical quantity, shear gradient vorticity (SGV), which is defined as vertical wind shear multiplying the horizontal component of vorticity gradient, aiming to diagnose heavy precipitation induced by some strong convective weather systems. The vorticity gradient component can be used to study the collision or merging process between different vortexes or the deformation of a vortex with a sharp vorticity gradient. Vertical wind shear, another contributed component of SGV, always represents the environmental dynamical factor in meteorology. By the combined effect of the two components, overall, SGV can represent the interaction between the environmental wind shear and the evolution of vortexes with a large vorticity gradient. Other traditional vorticity-like dynamical quantities (such as helicity) have the limitation in the diagnosis of the convection, since they do not consider the vorticity gradient. From this perspective, SGV has the potential to diagnose some strong convective weather processes, such as Extratropical Transition (ET) of tropical cyclones and the evolution of multicell storms. The forecast performance of SGV for the numerical ET case of Typhoon Toraji (0108) has been evaluated. Compared with helicity, SGV has shown a greater advantage to forecast the distribution of heavy precipitation more accurately, especially in the frontal zone.

Key words: Shear Gradient Vorticity; extratropical transition; heavy precipitation

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1 INTRODUCTION

Heavy precipitation always causes severe flood hazards almost everywhere in the world. Forecasting the burst and distribution of the extremely high rainfall precisely is a crucial but difficult task for weather operation and meteorological research. Among those flood and precipitation events, precipitation cases associated with an Extratropical Transition (ET) process of Tropical Cyclones (TCs) dominates a significant proportion[1]. In weather record, Chinese mainland and other coastal regions including Japan, Korean Peninsula or even North American and Australasia islands are under the threat of extremely torrential rainfall induced by ET events almost every year, with floods, landslides and other secondary disasters posing more threat than violent gusts (e.g., Typhoon Winnie in 1997, Hurricane Floyd in 1999), and Hurricane Fabian in 2003)[2-5]. Many ET events were associated with the interaction of a decaying tropical cyclone and a baroclinic cyclone (always a midlatitude trough), resulting in sudden torrential rainfall with accumulated amount of several hundred millimeters in a very short time. The heavy

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precipitation induced by ET has been a challenging topic to the operation or the research community of Quantitative Precipitation Forecasting (QPF)[1]. The variation and distribution of precipitation is very sensitive to different physical factors that control or dominate the ET processes (e.g. cold trough, frontogenesis, topography and so on)[1]. Successful QPF operation of this kind of high-impact weather events requires more accurate but simple dynamical diagnosis tools.

QPF, which is to make quantitative forecast of the distribution and variation of accumulated precipitation over a specified time period over a specified area, has been advocated for decades[6, 7], becoming a hot topic nowadays[8, 9]. Studies associated with QPF are usually based on models or observations[10]. To provide a physical framework to diagnose strong convection and heavy precipitation, Doswell[9] developed an ingredients-based method to forecast the potential of flood produced by storms. For various types of severe weather systems, the process of precipitation is quite different. And many papers discussed the precipitation mechanism with different points of view[11]. To investigate the mechanism of torrential rainfall, some suggested that the conditional symmetric instability (CSI) is an important factor[12] and the interaction between CSI and frontogenesis would be favorable for the burst of heavy precipitation events related to the ET processes[13-15]. In the heavy precipitation cases related to ET, Harr and Elsberry[16] identified that heavy precipitation always occurs in a warm frontogenesis region which always lies in the north and east quadrant of the tropical cyclone circulation. This implies that the understanding of frontogenesis is quite important to high quality QPF on the ET events.

Muramatsu[17] suggested that the evolution of the low-Level frontal patterns associated with the ET events varied from case to case and the evolution of the low-level thermal pattern sometimes appeared to be inconsistent with satellite imagery. In TC operation, Japan Meteorological Agency (JMA) classified the ET events as three types referring to the difference between TC circulation and midlatitude cyclones[18]. Other studies also divide these ET events to several groups with the names of “complex”, “compound” and “dissipated”[19-20]. Whatever classification criterion of the ET events, the relative roles of the frontogenesis process and the interaction between different cyclones are highly concerned in the ET studies[1, 18-20]. From the fluid mechanical perspective, ET can be viewed as a collision or merging process[38] taking place between two highly rotating vortexes (one vortex is the TC and the other is the baroclinic midlatitude cyclone) in the entire vorticity field in the Eulerian viewpoint, or a deformation process that evolves from a barotropic axisymmetric cyclone to a baroclinic non-axisymmetric cyclone in the TC circulation in the Lagrangian viewpoint. During the dramatic changing process of the vortex, a low-level front in the cyclonic circulation generates and develops quickly as an important feature of ET[1]. And rotational frontogenesis was found to be related to the evolution of vortical cyclone[1, 21]. To study heavy precipitation induced by the frontogenesis process during ET, careful investigation on the vorticity field is deserved.

In dynamics, vorticity, defined as the curl of the velocity, is one of the most important and basic physical variables that describe the features of the vortical fluid. As the differentiation variable of the velocity, vorticity represents the degree of the rotation in the fluid field. Starting from vorticity, researchers introduced many physical variables related to vorticity, including potential vorticity[22-23], entropy[24], helicity (here is the density of helicity)[25-27], and a new concept named convective vorticity vector[28] as shown in Eq. (1) to diagnose fluid mechanics. These variables can be referred to as vorticity-like quantities since they are related and originated from vorticity.

$$\begin{cases} \vec{\omega} & \text{vorticity} \\ \dfrac{\vec{\omega}}{\rho}\cdot\nabla\theta & \text{potential vorticity} \\ \vec{\omega}\cdot\vec{\omega} & \text{enstrophy} \\ \vec{\omega}\cdot\vec{V} & \text{helicity} \\ \dfrac{\vec{\omega}}{\rho}\wedge\nabla\theta & \text{convective vorticity vector} \end{cases} \tag{1}$$

Potential vorticity, associated with dynamics and thermodynamics, can express the conservation and release of vorticity in atmospheric processes. Because of the conservation in the adiabatic and frictionless atmosphere and invertibility under certain balance condition, potential vorticity plays an important role in weather diagnosis[23]. Enstrophy also can describe how the fluid evolves to dissipate energy in terms of kinetic energy[24]. Helicity can represent the rotation degree within the moving direction of the fluid parcel, which is proved to be highly associated with the stability of the fluid[29] and conserved in the isentropic fluid[25]. Since helicity can describe the development and tendency of fluid structure accurately, Lilly[30] introduced helicity in the research of convective storm. Helicity is then deduced to be Storm Relative Environment Helicity (SREH) and used to diagnose severe storms[31].

Although widely applied in the atmosphere studies and operations, these vorticity-related quantities mentioned above cannot represent the influence of the vorticity gradient directly. Large vorticity gradients are prevalent in some severe weather systems, such as supercell[32], roll vortexes in the boundary layer of tropical cyclones[33], and the eyewall region of tropical cyclones[34]. In the case of ET, especially in the frontal zone, large gradients and transient variation of vorticity also can be found easily (e.g. the numerical result by Davies[35]).

Previous studies have shown that almost all of the appreciable precipitation associated with ET occurs over a warm frontal zone. Thus, the frontal zone is important to the organization of heavy precipitation in the ET processes[1]. Frontogenesis process is always accompanied with a complex vorticity structure or even a sharp vorticity gradient[35]. Previous studies found some convective cells evolved in the frontogenesis region of the extratropical cyclones[36, 37]. In the classic concept model of cell-splitting[32], a positive-negative vorticity couplet (cyclonic-anticyclonic vortex couplet) is a distinct feature in the central region of the thunderstorm. In the developing stage of the multicell storm in the frontal zone, torrential precipitation generally occurs in the center of vortex couplets. In this region, the value of vorticity is quite small or even zero. In such storms with sharp vorticity gradient, vorticity-like quantities will be "focused on" to describe the dramatic variation of severe convective storms and precise distribution of the heavy precipitation induced by these storms. This dilemma brought difficulty to precise understanding of the fine structure of some convective storms and the evolution of heavy precipitation including the frontal zone in the ET processes.

Because of the limitation of traditional vorticity-like quantities, more precise diagnosis tool is needed in storms with a complex distribution and a dramatic variation of vorticity. Therefore, this paper aims to propose more precise quantities that can represent and diagnose heavy precipitation induced by the aforementioned storms. In the second section, shear gradient vorticity (SGV) and its dynamical property are introduced and discussed. And then, SGV is used to forecast the heavy precipitation distributed in a frontal zone related to ET in a high-resolution numerical case, compared with helicity. A brief summary is given in the last section.

2 THE PROPOSED CONCEPTION OF SHEAR GRADIENT VORTICITY

As aforementioned, the fluid structure with a large vorticity gradient is prevalent in some severe weather systems including the frontal zone. To some extent, the frontal zone in the extratropical cyclone is the region with most violent variation of the vorticity field during the ET process that is usually companied with a vortex collision process associated with a TC and a midlatitude cyclone. Under this consideration, the frontal zone can be thought as a region where the ET cyclone experiences vorticity intensification.

In dynamics, the mechanism of the large-scale, extratropical, planetary fluid motions can be interpreted by the coexistence and mutual interaction of three mechanisms: isolated coherent vortices, geostrophic or two-dimensional turbulence and dispersive Rossby waves[39]. Although the vorticity intensification by way of stretching neither takes effect in geostrophic nor two-dimensional hydrodynamics, the vorticity gradient, denoted as $\vec{G} = \nabla\zeta$, can experience similar intensification and reduction process as vorticity does in three dimensions, favoring the formation of isolated vortices[39, 40]. Vorticity gradient is increased through the mutual interaction among neighboring vorticity parcels[39].

If an approximation is made that both strain and vorticity are slowly varying compared with the vorticity gradient in the Lagrangian frame, the magnitude of the vorticity gradient will grow (decrease) in time with a positive (negative) Q as shown in Eq. (2) (also see Eq. (12) of Mcwilliams[39]).

$$\vec{G} = \nabla\zeta \propto \exp(\pm Q^{\frac{1}{2}t}) \tag{2}$$

And Q is defined as in Eq. (3) and Eq. (4)

$$Q = S_1^2 + S_2^2 - \zeta^2 \tag{3}$$

$$S_1 = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y},\ S_2 = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \tag{4}$$

S_1 is the stretching deformation and S_2 is the shear deformation.

Under this situation, the vorticity gradient can express the developing degree of high-rotating vortexes with a complex vorticity structure. Thus, the vorticity gradient can be utilized to represent the collision or merging process of vortexes[39, 40] or the strengthening process of a vortex, which happens in ET or multicell storms.

The Vortical Gradient Vorticity (VGV) is defined in Eq. (5), where $\vec{\omega}_h$ expresses the environmental vorticity tube and $\nabla\zeta$ represents the development degree of vortical weather systems with a sharp vorticity gradient as discussed earlier.

$$\mathrm{VGV} = \vec{\omega}_h \cdot \nabla\zeta \tag{5}$$

In many convective systems, the vertical shear of horizontal wind is more significant and the environmental vorticity can be simplified as the vertical wind shear in a reasonable approximation[41].

$$\vec{\omega} \approx \vec{k} \wedge \frac{\partial \vec{V}_h}{\partial z} \tag{6}$$

Thus, VGV is reduced to be Shear Gradient Vorticity (SGV) defined as follows:

$$\mathrm{SGV} \approx \vec{k} \wedge \frac{\partial \vec{V}_h}{\partial z} \cdot \nabla_h\zeta \tag{7}$$

From Eq. (7), SGV links the vertical shear of environmental wind and the evolution of convective systems with a large vorticity gradient (e.g. frontal zone) as shown in the concept model (Figure 1). The interaction of environmental dynamical factor and the evolution of vortical system would induce strong convection and heavy precipitation[31].

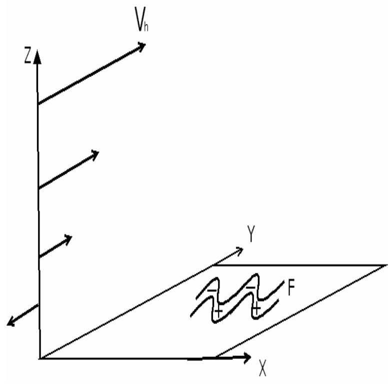


Figure 1. Conceptual figure of SGV. F denotes the front region with positive-negative vorticity couplets and V in different heights denotes the vertical shear of horizontal wind.

Doswell et al.[11] suggested that vertical motion, static stability, moisture supply, and topographic effect are key factors to forecasting heavy precipitation. The variation and distribution of precipitation can be related to the large-scale forcing of middle-latitude troughs or baroclinic systems due to the tropical cyclones[12]. From the dynamical view, SGV combines the vertical shear of horizontal wind with the vorticity gradient. The wind shear usually represents the environmental dynamical effect and is also related to vertical ascent. The vorticity gradient can express the development of the severe convective storms including frontogenesis process in ET or the collision among different high-rotating cyclones, fronts or convective cells. In other words, the SGV is to physically represent the interaction of environmental dynamical factors with the intensification degree of convective systems by a sharp vorticity gradient.

In this consideration, SGV has the potential to diagnose heavy precipitation induced by the frontogenesis during the ET process.

3 PRECIPITATION FORECAST PERFORMANCE IN THE CASE OF TYPHOON TORAJI

To quantitatively evaluate the potential capability of SGV, a numerical experiment is employed to examine its performance in a severe storm with heavy precipitation. In 2001, the landfall typhoon Toraji (0108) induced several flooding hazards during its reintensification stage of ET while moving poleward[42]. From the discussion in section 2, SGV seems to have the potential to diagnose the development of convective systems and the distribution of heavy precipitation induced by convective systems with a complex structure.

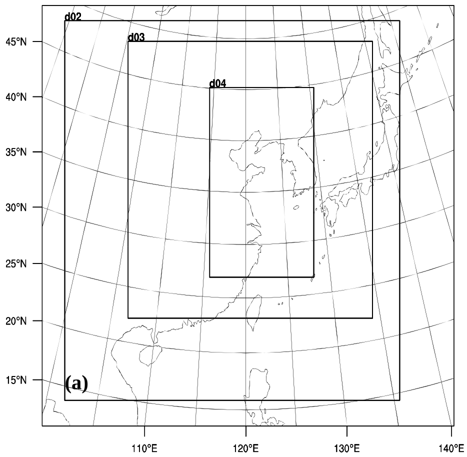
In this paper, Toraji is simulated to evaluate the forecast performance of SGV by a numerical test through an advanced research version of WRF model (ARW)[43] developed by the National Center for Atmospheric Research (NCAR). The WRF model is based on an Eulerian solver for the fully compressible non-hydrostatic equations, cast in flux conservation form, using a mass (hydrostatic pressure) vertical coordinate. WRF uses a third-order Runge-Kutta time integration scheme coupled with a split-explicit 2nd-order time integration scheme for the acoustic and gravity-wave modes. The 5th-order upwind-biased advection operations are used in the fully conservative flux divergence integration, and the 2nd-6th order schemes are run-time selectable. The ARW carries multiple physical options for cumulus, microphysics, planetary boundary layer (PBL) and radioactive physical processes.

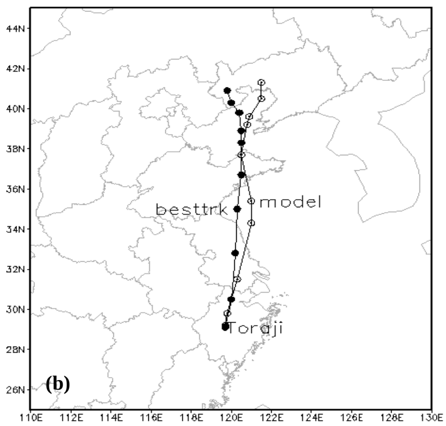
The model was initialized directly by the FNL data with 1-degree resolution, which is provided by National Centers for Environmental Prediction (NCEP)/NCAR Reanalysis Project (NNRP). The numerical simulation uses four nested domains (Figure 2a) with two-way nesting and 47 vertical levels. Total simulation time is 12 hours, starting at 1800 Coordinated Universal Time (UTC) 31 July and ending at 0200 UTC 1 August 2001. The detail configuration of numerical experiment is shown in Table 1. In this study, only the numerical result in the inner domain of d04 is discussed.

Figure 2b compares the model-simulated track of Toraji with the JMA best-track estimates. In general, this WRF-based experiment simulates Toraji's track very well, especially its rapid intensification stage of the ET process moving from Shandong province to Liaoning province from 2000 UTC 31 July to 0200 UTC 1 August, 2001. Figure 2c shows the simulated storm intensity, indicated by the minimum sea level pressure of 996.7 hPa at 0000 UTC 1 August, 2001, while the intensity of JMA's best track is 995 hPa. Generally, this numerical test is similar to the observation. The result of WRF is successful in repeating the ET process of Toraji, especially at early stage.

Table 1. Parameter list of the numerical simulation.

Region	d01	d02	d03	d04
Grid number	82×73	193×193	421×421	601×991
Resolution(km)	54	18	6	2
Height level	47	47	47	47
Time	073112UTC–080212 UTC	073112UTC –080212 UTC	073118UTC –080212 UTC	073118UTC –080112 UTC
mp_physics	WRF Single-Moment 3-class scheme	WRF Single-Moment 5-class scheme	WRF Single-Moment 6-class scheme	Morrison double-moment scheme
bl_pbl_physics	Mellor-Yamada-Janjic scheme	Mellor-Yamada-Janjic scheme	Mellor-Yamada-Janji c scheme	Mellor-Yamada-Janjic scheme
cu_physics	Kain-Fritsch scheme	Kain-Fritsch scheme	0	0
sf_sfclay_ph ysics	MM5 similarity	MM5 similarity	MM5 similarity	MM5 similarity





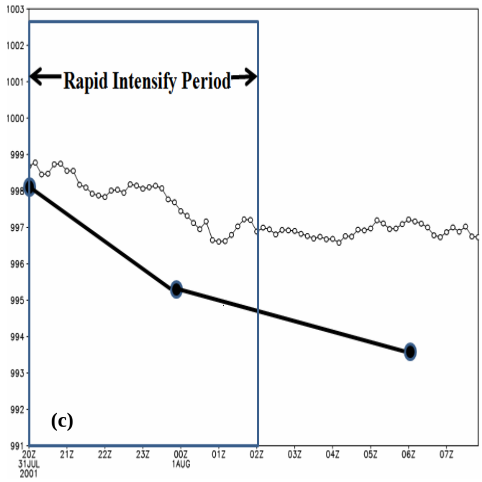


Figure 2. (a) Numerical domain from Day 1 to Day 4 (Only the result of Day 4 is discussed in this study); (b) Typhoon track of numerical simulation (Hollow circle) and JMA best track (Solid circle); (c) Intensity variation of numerical simulation (Hollow circle) and JMA best track (Solid circle). The *y*-axis denotes the intensity of Toraji (minimum central sea-level pressure, units: hPa).

During the period from 2000 UTC 31 July to 0200 UTC 1 August, the decayed Toraji intensified again and the lowest central surface pressure dropped 4 hPa within several hours as shown in Figure 2c. In this study, the focused time slot is the “rapid intensification period”. During this period, a quasi-linear frontal zone of hundreds of kilometers in length and dozens of kilemeters in width generated and evolved along the northeast quadrant of Toraji from southwest to northeast during the whole ET process (Figures 3a–3b). Figure 3a shows that the maximum accumulated precipitation was more than 250 mm within several hours and distributed mainly in the quasi-linear frontal zone, indicating that the heavy precipitation band in the frontal zone played a dominant role in the ET process of Toraji.

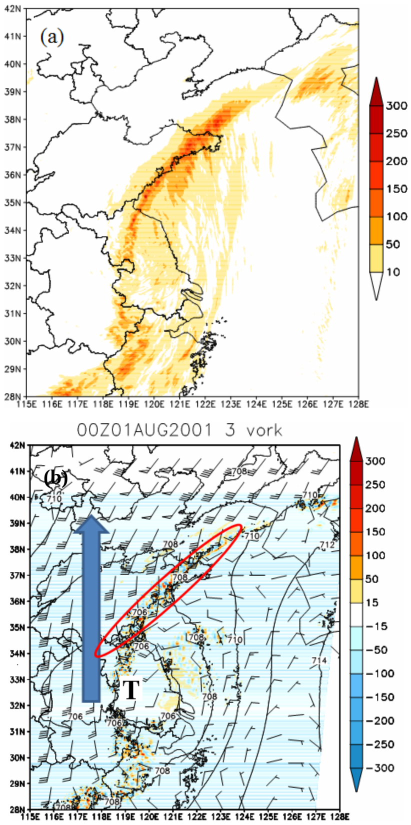
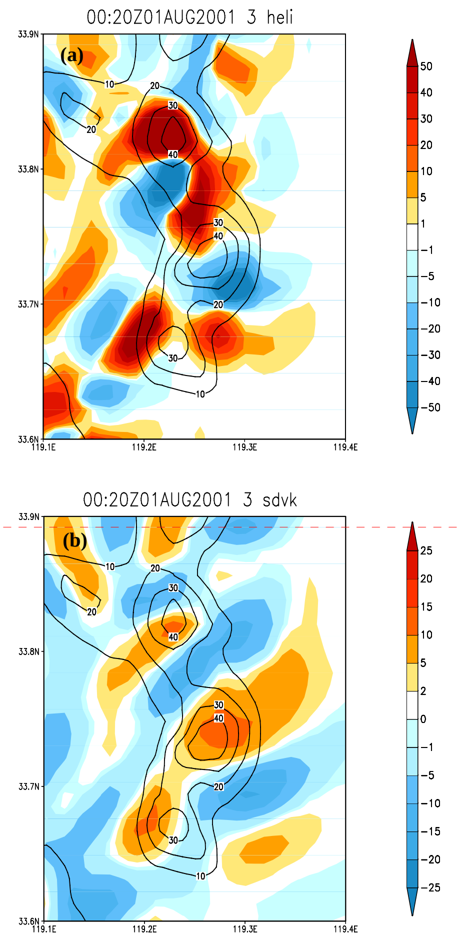


Figure 3. (a) The 6-hour accumulated precipitation from 2000 UTC 31 July to 0200 UTC 1 August, 2001 (Units: mm); (b) The simulated vertical components of vorticity at 3-km height (Shaded, Units: 1×10^{-5} s^{-1}) and vertical shear of horizontal wind at 0000 UTC 1 August during the rapid intensification period. The red circle denotes the frontal zone with positive-negative vorticity parcels alternate permutated, the dark blue arrow presents the direction of wind shear, and the circulation center of Typhoon "Toraji" is denoted by "T".

The vorticity structure in the frontal zone of the ET cyclone is shown in Figure 3b. A linear rain band with some convective parcels embedded in the quasi-linear frontal zone with large wind shear can also be found in Figure 3b. SGV and helicity were applied to diagnose the distribution and evolution of precipitation and convection. Moreover, the vertical component of helicity, which is equal to vertical motion multiplying the vertical component of vorticity, is utilized as a reference for comparison in the evaluation.

Two convective parcels are embedded in the frontal zone (parcel A in Figure 4a and parcel B in Figure 4c) with the maximum rainfall rate about 20 mm in 30 minutes. For these two parcels, the distribution of helicity disagrees with the peak precipitation as a whole (Figures 4a and 4c). In other words, the maximum precipitation in parcel A and parcel B is located around the region where helicity is quite small or even negative. This mismatch implies that helicity could not predict the distribution of heavy rainfall induced by fine vorticity structure in the frontal zone well. On the other hand, SGV is found to perform much better in the parcels A and B (Figures 4b and 4d) than that of helicity (Figures 4a and 4c) with a more similar distribution of rainfall.

The correlation coefficient between the SGV and the simulated convection was further compared in the frontal zone during the ET process. In the simulation, the circulation of Toraji moved northward very quickly and the quasi-linear front also evolved quite transiently. In addition to precipitation, the simulated radar reflectivity (in unit of dBz), a transient variable to avoid time lag during accumulation of rainfall, is further compared with the simulated SGV.



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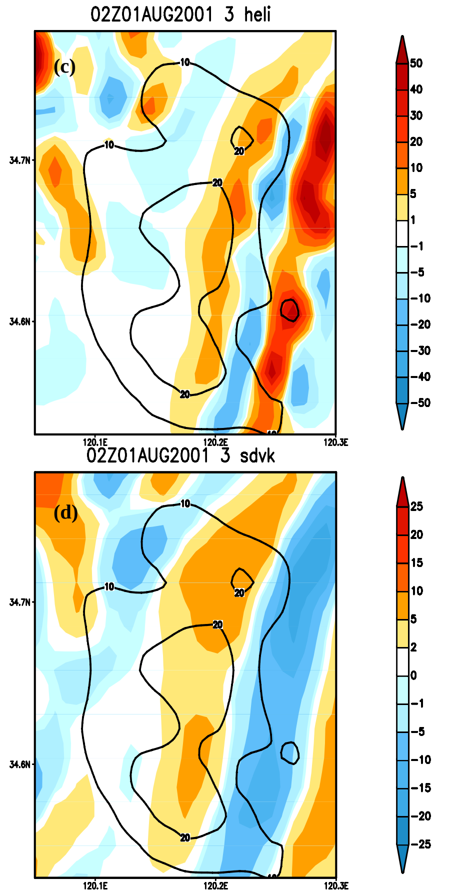
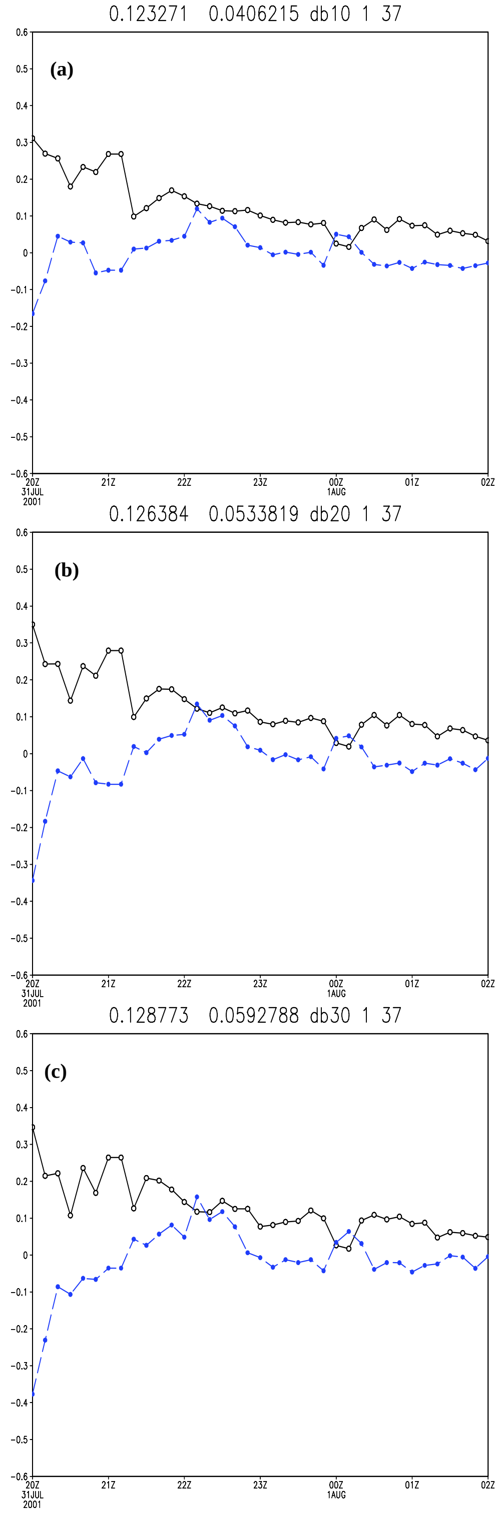


Figure 4. (a) Rainfall parcel A at 0020 UTC 1 August (30-minute accumulated rainfall, contour, Units: mm) and the vertical component of helicity (Shaded, units: 1×10^{-5} m s^{-2}) at 1.5-km height; (b) Rainfall parcel A at 0020 UTC 1 August (30-minute accumulated rainfall, contour, units: mm) and the vertical component of SVG (Shaded, units: 1×10^{-7} s^{-3}) at 1.5-km height; (c) Rainfall parcel B at 0200 UTC 1 August (30 minutes accumulated rainfall, contour, units: mm) and the vertical component of helicity (Shaded, unit: 1×10^{-5} m s^{-2}) at 1.5-km height; (d) Rainfall parcel B at 0200 UTC 1 August (30-minute accumulated rainfall, contour, units: mm) and the vertical component of SGV (Shaded, unit: 1×10^{-7} s^{-3}) at 1.5-km height.

Figure 5 shows the time series of the correlation coefficients for various convection intensities during the period of rapid intensification. The thresholds of radar reflectivity are defined for weak convection (>10 dBz), moderate convection (>20 dBz), strong convection (>30 dBz) and ultra-strong convection (>40 dBz), respectively. From Figures 5a-5d and Figure 6, it is shown that SGV has a closer relationship with convection than helicity in each intensity category during the whole period. Thus, it seems that SGV performs better in the diagnosis of precipitation/convection than helicity (Figures 4-6).



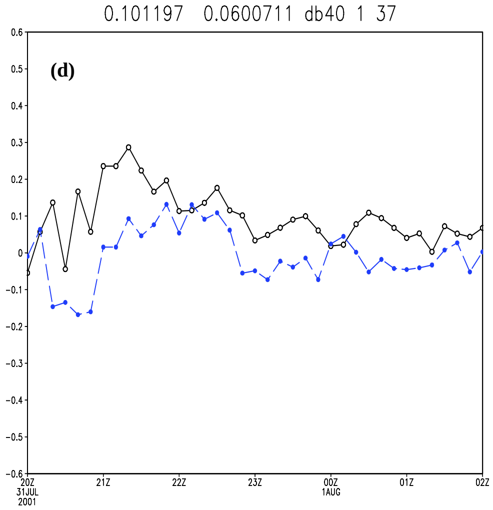


Figure 5. (a) Time series of the correlation coefficient of helicity (blue dashed line), SGV (black solid line) at 1.5-km height with weak convection (>10 dbz) during the rapid intensification stage; (b) Same as (a) but for general convection (>20 dbz); (c) Same as (a) but for strong convection (>30 dbz); (d) Same as (a) but for ultra-strong convection (>40 dbz).

It should be pointed out, however, that the correlation coefficient between dynamical indictors and convection is not quite high, with the highest correlation coefficient less than 0.2. The quick moving extratropical cyclone might bring much difficulty in linking the convection and dynamical structure synchronously.

From the discussions in this section, SGV has shown the potential advantage in diagnosing the distribution and variation of convective precipitation.

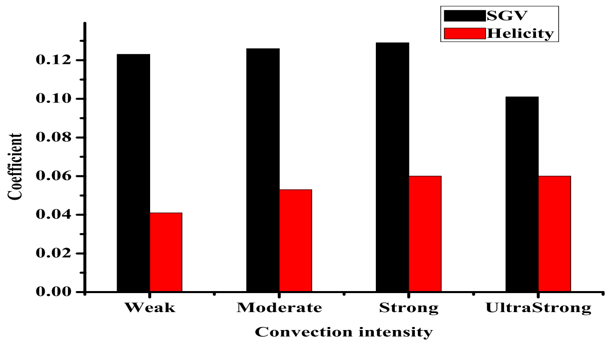


Figure 6. The correlation coefficients between the forecasting quantities (SGV or helicity) and the convection with different intensities of storm (the thresholds of weak, moderate, strong and ultra-strong convection are 10 dBz, 20 dBz, 30 dBz and 40 dBz, respectively).

4 SUMMARY

The fluid structure of some severe convective weather systems, including extratropical cyclones in ET and fronts embedded in cyclones, is quite complex and transient and very difficult to be forecast precisely. A new physical quantity, named SGV, is introduced to diagnose and forecast the distribution and variation of precipitation induced by the combined effect, which is from the environmental wind shear and tropical cyclone with a large vorticity gradient, in this paper.

The SGV links the environmental wind shear and high-rotating storm together with a sharp vorticity gradient. In this regard, SGV is expected to be a powerful utility to diagnose heavy precipitation induced by the interaction between environmental wind shear and strong convective weather systems. Verification of the numerical simulation of Typhoon Toraji has shown that SGV performs better than helicity in depicting the heavy rainfall process.

In this study, SGV just emphasizes the coupling process between environmental wind shear and evolution of cyclones with large vorticity gradient which may occur in rainfall events, e.g. the frontogenesis process of an extratropical cyclone or the evolution of convective cells in a multicell storm. The discussions about the dynamical meaning of SGV are preliminary and further detailed forecast evaluation on SGV is required with more convective cases. Discussions about the dynamical relationship between SGV and precipitation mechanism are necessary in subsequent research.

However, the conception of SGV may offer the QPF researchers a new point of view to understand the evolution of heavy precipitation associated with convective storms, especially those with dramatic changes of vorticity fields such as the ET process.

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