6M **THE VERTICAL SHEAR INDUCED SECONDARY CIRCULATION OF TROPICAL CYCLONES**

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1. Introduction

It is well known that a tropical-cyclone (TC) vortex in a sheared environment has upward motion on its downshear side (Raymond 1992; Jones 1995). Such a vertical motion asymmetry has been confirmed by idealized, 3D numerical simulations of TC-like vortices (e.g., Wang and Holland 1996; Frank and Ritchie 1999), and real-data simulations of hurricanes under the intense sheared flows (see Rogers et al. 2003, and Zhu et al. 2004). However, few studies have been performed to isolate the shear-forced secondary circulation (FSC) and investigate its impact on the TC dynamics, except for sensitivity studies. Thus, in this study, we attempt to separate the FSCs by the dry dynamical, latent heating and PBL processes using a recently developed PV inversion and quasi-balanced ω equations (PV-ω system) developed by Wang and Zhang (2003), hereafter referred to as WZ.

2. Methodology

In the PV-ω system, the streamfunction ψ and geopotential height ϕ are first obtained by inverting the nonlinear balance and PV equations for a given PV field, and then a closed set of quasi-balanced ω equations is solved to yield the FSCs by various physical and dynamical processes. The ω-equation in the pseudo-height z-coordinates is given by

$$\nabla^2\left(\frac{\partial^2\phi}{\partial z^2}\omega\right) + f\eta\frac{\partial}{\partial z}\left\{(z_a - z)^{-\mu}\frac{\partial}{\partial z}\left[(z_a - z)^{\mu}\omega\right]\right\} - f\frac{\partial}{\partial z}\left(\frac{\partial\omega}{\partial x}\frac{\partial^2\psi}{\partial x\partial z} + \frac{\partial\omega}{\partial y}\frac{\partial^2\psi}{\partial y\partial z}\right) - f\frac{\partial}{\partial z}\left(\frac{\partial\omega}{\partial x}\frac{\partial^2\chi}{\partial y\partial z} - \frac{\partial\omega}{\partial y}\frac{\partial^2\chi}{\partial x\partial z}\right)$$
$$-\left(f\frac{\partial\eta}{\partial z}\frac{\mu}{z_a - z} + f\frac{\partial^2\eta}{\partial z^2}\right)\omega = f\frac{\partial}{\partial z}[\mathbf{V}_h \bullet \nabla\eta] - \nabla^2[\mathbf{V}_h \bullet \nabla\frac{\partial\phi}{\partial z}]$$
$$-\beta\frac{\partial^3\psi}{\partial t\partial y\partial z} - 2\frac{\partial^2}{\partial t\partial z}J\left(\frac{\partial\psi}{\partial x}, \frac{\partial\psi}{\partial y}\right) + \frac{g}{\theta_0}\nabla^2\dot{q} + F_{x,y} \qquad (1)$$

where $\mu = C_v/R_d$ and $z_a = C_p\,\theta_0/g$; $\eta = \zeta + f$; χ is the velocity potential; $\mathbf{V}_h$ is the sum of the balanced ($\mathbf{V}_\psi$) and divergent ($\mathbf{V}_\chi$) flows; $\dot{q}$ is the latent heating rate; $F_{x,y}$ denotes the PBL processes; and all the other variables assume their typical meteorological meaning. The vertical motion ω can be inverted from Eq. (1), given its right-hand side (RHS) terms, of which the first four are the dry-dynamics processes.

3. Results

Fig. 1 show the west-east cross sections of the FSCs by the latent heating, PBL and dry dynamics processes. The latent heating FSC exhibits a typical vertical circulation of TCs with the bottom-inward, midlevel slantwise and upper-level outward flows. Of relevance to this study is that the latent heat release in the eyewall induces weak compensating subsidence from the tropopause to the surface in the eye, with stronger subsidence occurring aloft (Fig. 1a).

The PBL processes produce radial inflows in the bottom layers that begin to ascend in the eyewall and reach a peak value as large as 0.3 m s^{-1} near the top of the PBL at the circulation center in the eye (Fig. 1b). It is similar to that by the Ekman pumping leading to the spin-down of a cyclonic vortex (Holton 2004).

Fig.. 1c shows that the FSC by the dry dynamics processes is a deep anticlockwise circulation across the storm with a rising (descending) motion in the eastern (western) portion of the eyewall, and an easterly (westerly) flow across the eye aloft (below). Such wave-number-1 vertical motion couplet appears to be similar to the typical impact of a westerly shear on the asymmetry of cloud production in TCs.

To help show the above point, a westerly shear of 10^{-3} s^{-1} with a null surface flow is superimposed to an axisymmetric balanced vortex. The result is given in Fig. 2, which shows that the shear-FSC in this "idealized" case is similar in structure and intensity to that shown in Fig. 1c, except that it is more limited within the RMW. It follows that *it is the interaction of the hurricane vortex with the environmental vertical shear that accounts for the above-mentioned deep anticlockwise FSC*.

Of importance is that *the horizontal component* *of the FSC, which is a consequence of the mass continuity, acts to reduce the vertical shear in the core region*, and *the FSC could reduce 30 – 40% of the destruction by vertical shear*.

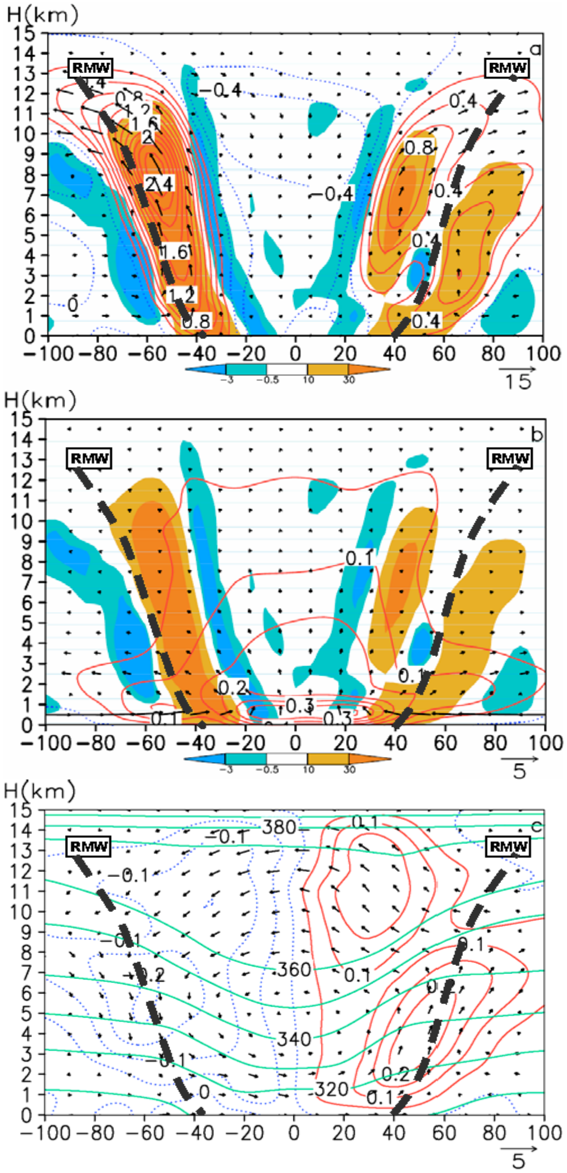

Fig. 1 W-E vertical cross sections through the storm center of (storm-relative) in-plane flow vectors and the vertical motion forced by (a) latent heating (every 0.2 m s^{-1}); (b) the PBL (every 0.05 m s^{-1}); and (c) the dry dynamics processes (every 0.05 m s^{-1}), which are obtained from the 56 – 57 h simulation ending 2100 UTC 23 August 1992. Shadings denote the latent heating (orange) or cooling (blue) rates in K h^{-1}. Green lines in (c) are isentropes.

4. Concluding remarks

The shear-FSC presented above appears to offer some new understanding of the impact of vertical shear on the dynamics of TCs and other types of mesovortices. First, *while vertical shear is inimical to the TC development, the shear-FSC acts to reduce the destructive effects of the shear and resist the downshear tilt of a TC vortex,* as also indicated by Jones (1995) and Wang and Holland (1996). This explains why some intense TCs can resist vertical shear as large as 1.5 x 10^{-3} s^{-1} (Rogers et al. 2003; Zhu et al. 2004; Wang et al. 2004), and why the inner core of a dry vortex could remain upright while its outer portion is markedly tilted (Jones 1995, 2004). Second, the shear-FSC tends to reduce the low-level inflow and upper-level outflow on the downshear side but enhance them on the upshear side, with little impact in the midtroposphere. This reduces the downshear advection of warm air from the eye region. The vortex-restoring effects also explain why some environmental air is forced to flow around a TC, making it more like an "obstacle." Third, for any moist, warm-cored vortex in a sheared environment, i*t should be the total FSC that follows isentropic surfaces in dry stratification*.

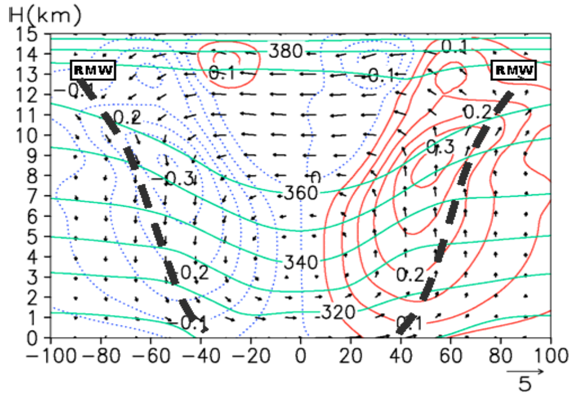

Fig. 2 As in Fig. 1c, but for the FSC by a westerly shear of 10^{-3} s^{-1} associated with an axisymmetric balanced vortex.

Finally, it should be mentioned that Andrew does not exhibit significant downshear tilt. This is partly because its environmental shear is relatively weak, and partly because intense latent heating in the eyewall tends to oppose the forced tilting by the vertical shear by coupling the lower to upper-level vortex flows. In addition, the shear-FSC must have also played a role in resisting the downshear tilt of the storm.

References are not given due to the limited space.