4A.7 HOW MUCH VERTICAL SHEAR CAN A WELL-DEVELOPED TROPICAL CYCLONE RESIST?

Yuqing Wang*[1], Michael T. Montgomery[2], and Bin Wang[1]
[1]International Pacific Research Center and Department of Meteorology, School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu, HI 96822
[2]Department of Atmospheric Science, Colorado State University, Ft Collins, CO 80523

1. Introduction

Among the many factors believed to limit the intensity of a tropical cyclone (TC) vortex, vertical shear-induced asymmetries in the inner-core region of the storm are generally considered a major impediment to a TC attaining its maximum potential intensity (MPI). The vertical shear effect varies with the stage of development of the cyclone. Imposition of moderate vertical shears to a weak vortex tends to produce a long-lasting reduction in development, a result that is now well known (Gray 1968). The vertical shear effect on well-developed TCs, however, is controversial. Observations from the western North Pacific and other TC basins suggest that in most circumstances strong TCs can resist vertical shears as strong as 15–20 m s^{-1} over 12 km depth.

Recent theoretical studies demonstrate that even dry TC-like vortices can survive modest vertical shear (Reasor et al. 2004). The full physics numerical study by Frank and Ritchie (2001), however, suggests a different picture in which steady unidirectional weak vertical shear with magnitude of 5 m s^{-1} over 12 km substantially weakens a category 5 TC in approximately two days. Frank and Ritchie attributed the weakening of the simulated storm to the outward transport of high equivalent potential temperature at upper levels due to the vertical shear-induced eddies. The following questions then arise: (1) How much vertical shear can a well-developed TC resist in an otherwise favorable tropical oceanic environment? (2) What are the key processes that maintain a TC in a vertically sheared environment? (3) What role (positive or negative) do moist processes play in TC/shear interactions?

In this study we examine these questions using the triply nested, moveable mesh, hydrostatic primitive equation TC model—TCM3. We will demonstrate that strong well-developed TCs can resist unidirectional vertical shear as strong as 15 m s^{-1} over 12 km, consistent with observations. A resolution of the apparent contradiction of these results and those of Frank and Ritchie (2001) is presented and the physical mechanisms responsible for the resistance of the model TC to vertical shear will be explained.

2. Experimental design

We first spin up a model TC on an f-plane centered at 18^{o}N for 96 h without any shear, following the experimental design of Wang (2001). Vertical shear is then introduced when the model TC reaches a quasi-steady equilibrium. The profile of zonal wind is sketched in Fig. 1. This flow is constructed to be in hydrostatic and geostrophic balance across the model domain. After inserting the shear flow the total flow field (quasi-steady TC + zonal shear) evolves consistent with the TCM3 model equations. Although this procedure does not exactly mimic the manner in which a TC typically moves into a sheared environment, it serves as a useful expedient for examining the effects of vertical shear with different strengths.

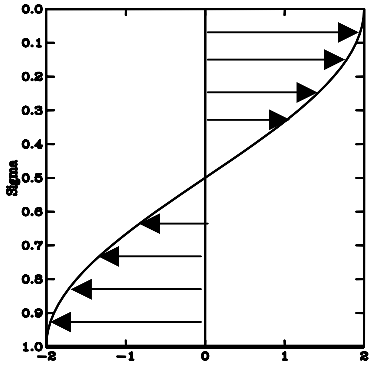

Fig. 1. The vertical profile of the horizontal wind used in our model experiments.

The profile of zonal mean wind in Fig. 1 gives a vertical shear of 3.4 m s^{-1} corresponding to the wind difference between approximately 200 and 850 hPa–a definition commonly used by TC forecasters. We hereafter adopt this definition of unidirectional vertical shear. At any given height the vortex center is defined using the potential vorticity (PV) centroid, which is an invariant for the dry adiabatic equations on an f-plane:

$$\overline{X} = \frac{\int PVxdxdy}{\int PVdxdy}; \qquad \overline{Y} = \frac{\int PVydxdy}{\int PVdxdy}$$

The domain of integration is a circular area whose radius is approximately 500 km from the surface vortex center.

3. Results

Before showing the results from the full physics model experiments, we first report on several experiments using the dry version of the model. Both vortex and vertical shear were applied at the initial time in a balanced fashion. The initial TC-like vortex has a 3D structure similar to that used in Wang (2001); the maximum low-level tangential velocity is 30 m s^{-1} and the TC is embedded in a weak vertical shear of 3.4 m s^{-1} between 200 and 850 hPa. Fig. 2a shows the centroid trajectories of PV centers at the surface (solid) and z = 6 km (dashed) over 192 h of numerical integration. Clearly evident is the cyclonic precession of the tilted vortex centers. The distance between the upper and lower centers decreases with time, indicating a continuous vertical alignment, consistent with recent theoretical predictions of Reasor et al. (2004), who attribute the

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Corresponding author: Yuqing Wang, IPRC/SOEST, University of Hawaii, Honolulu, HI 96822, email: yuqing@hawaii.edu.

vertical alignment to vortex Rossby wave damping. The final quasi-steady state is a tilt to the left of the shear vector, as found previously by Wang and Holland (1996). To demonstrate the effect of vortex radial structure on the behavior of TC-like vortices in vertical shear, the same vertical shear was applied to the vortex that has a radially confined structure with maximum low-level wind of 30 m s^{-1} as used in Jones (1995). Consistent with the linear prediction of Reasor et al. (2004), because of the more confined radial structure the tilted vortex did not experience a rapid vertical alignment (Fig. 2b). Increasing the shear to 6.8 m s^{-1}, the broad vortex behaved very similar to that shown in Fig. 2a, while the confined vortex becomes sheared off quickly (not shown). These results demonstrate that the broad TC-like vortex can resist moderate vertical shear with dry dynamics alone, as first predicted and explained consistently by Reasor et al. (2004). Mallen et al. (2004) show that most TCs have relatively broad radial structure, favoring the vertical alignment through the vortex Rossby wave damping mechanism.

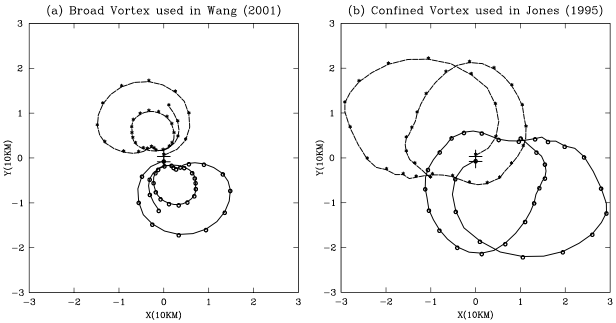

Fig. 2. The centroid trajectories of PV centers at the surface (solid) and z= 6 km (dashed) in a vertical shear of 3.4 m s^{-1} for broad vortex (a) and confined vortex (b).

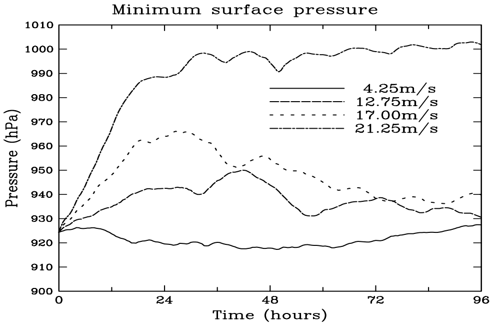

Fig. 3. The evolution of the minimum sea level pressure at the model TC center in different shear experiments.

With the full physics of the model now activated, we considered several different vertical shear magnitudes to determine the critical shear to which the well-developed TC could not resist. Four values of vertical shear 4.25, 12.75, 17.0, and 21.25 m s^{-1} were used. The weak shear had little effect on the intensity of the model storm (Fig. 3). Upon increasing the shear, an immediate weakening of the storm occurs for a day or two, but then the storm reintensifies to an intensity slightly less than that in weak shear. This suggests that the vertical wind shear reduces the maximum intensity that can be reached, but the reduction is less than naïve expectations. When the vertical shear is increased above 20 m s^{-1}, the storm weakens rapidly to a depression and does not re-intensify. Note that the diabatic vortex can resist much larger vertical shear than its dry counterpart. Diabatic heating thus enhances the vertical coherence and increases the TC's capacity to resist vertical shear. The precise mechanisms for this are our current focus.

In summary, our results are quite different from Frank and Ritchie (2001). They found that imposition of a moderate shear of 5 m s^{-1} initially had little effect, but then produced a sharp and sustained weakening 42 h later. A 15 m s^{-1} shear caused an immediate substantial weakening. Since a simple ice phase cloud microphysics was used in Frank and Ritchie, it is believed possibly responsible for the difference from what we show here. Another possible factor is the mesh movement that might cause problems near the leading edge of the moved inner mesh, producing strong outer raindbands that might weaken the storm (E.A. Ritchie, 2003, personal communication). All of these issues require further exploration.

4. Conclusions

We have confirmed that a dry TC-like vortex can resist moderate vertical shear with the development of a quasi-steady tilt to the left of shear vector. Such a resistance depends strongly on the radial structure of the vortex. Confined vortices possessing too rapid a radial decay of tangential wind do not have such capacity and experience destruction even embedded in a moderate vertical shear. A well-developed TC with diabatic heating, however, appears to have a much higher resistance to vertical shear than previously believed. The precise manner in which diabatic processes contribute to the resiliency of the vortex is our current focus.

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