

We appreciate Professor John Molinari's perceptive comments and insights that are forward looking. We are very glad our work is so well received by him. We address his questions and comments (highlighted in blue) below.

1) A grid spacing of 5 km means that the smallest resolvable disturbance is at least 10 km. As a result, (i) individual cells, including vortical hot towers, cannot be fully resolved; and (ii) a vortex tilt of 5-10 km between the 1 and 10 km levels is right at the limit of the model (yet such a tilt is frequently present). An open question is what new insights might be gained by higher resolution, or alternatively, what might be missing at the current resolution?

A higher (horizontal) resolution is expected to increase the comparability of the modelled TC structure with real storms. In particular, we would expect a less patchy organization of convection within the stationary band complex, i.e., a better resolution of individual strong convective elements ('VHTs') as Dr. Molinari has mentioned. We would also expect a more complete representation of eyewall updraft lifecycles within the wavenumber-1 envelope associated with the interaction of eyewall mesovortices and the storm relative flow (as found in Braun et al. (2006) for Hurricane Bonnie). In regards to the vortex tilt, we would like to emphasize that the centre positions on the upper (10 km) and lower level (1 km) – from which the tilt is computed– are calculated using the vorticity centroid over a disc of 60 km radius. This measure for the centre location takes into account the vorticity values of ~450 grid points. Thus a tilt magnitude that is on the scale of the grid can still be considered to be meaningful. Further, the tilt evolution is consistent with current vortex Rossby Wave (VRW) theory of Reasor et al. (2004) and also consistent with the higher-resolution simulation (2 km) of Hurricane Bonnie (1998) by Braun et al. A higher-resolution experiment might also better represent the internal structure of the vortex alignment process, e.g. an anticyclonic looping of the upper-level centre (Fig. 11 of Braun et al. 2006).

While we do fully intend to repeat the experiment with higher resolution, we believe that a grid scale of 5 km is nonetheless capable of adequately representing the essential processes of TC – shear interaction. Please recall that the scientific experiment that we were aiming to more fully understand was that of Frank and Ritchie's (2001) pioneering work. Since they used a 5 km horizontal grid spacing, our choice of 5 km horizontal grid spacing was a deliberate one. To improve the experimental design, however, our priority is on formulating a more realistic means of imposing and forcing the vertical shear, and including melting/-freezing effects.

2) The role of ice remains uncertain. Melting is a powerful process that tends to occur entirely within a 500 m layer, producing an intense upward increase of diabatic heating near the melting level. Unlike evaporation, it continues to occur when the air is saturated. In addition, the "central dense overcast" (CDO) of tropical cyclones results in part from advection of ice particles outward from the eyewall.

Growth and fallout of particles in the CDO and subsequent melting and evaporation create broad cooling outside the core. This likely plays a role in preserving the radial temperature gradient in the free atmosphere required to maintain the tropical cyclone, in part by suppressing outer convection. The question: how might the mechanisms introduced by ice physics (on a sufficiently high resolution grid) impact the role of vertical wind shear in tropical cyclones?

We agree with the reviewer that ice microphysics can influence the radial structure of the TC. Due to a less pronounced upper-level temperature gradient, the importance of upper-level mixing processes in a warm rain experiment might be underestimated. VRW theory using dry dynamics has shown that the resiliency of a vortex depends crucially on the radial profile of the wind field outside the peak wind region of the vortex. Although a moist generalization of dry VRW theory suggests that the wind profile outside the peak wind region of the vortex becomes less important for vortex resiliency when cloudiness pervades the vortex (Schecter and Montgomery 2007), we must keep the reviewer's comments in mind when examining our upcoming experiments including ice microphysics. A modification of the 'stationary band complex' and associated downdrafts will presumably lead to further quantitative differences between experiments with 'warm rain' and 'ice' schemes.

In summary, while we believe that our current experimental design captures the essence of the fundamental processes for TC-shear interaction (see 3), we agree that it is an important question how melting/-freezing effects influence the picture presented here.

3) In a broader sense, remarkably little is known in our field about the details of how downdrafts are initiated and how they evolve. The actual process might require knowledge of mixing of updraft and environment air that would have to be parameterized, even with a 1-km grid resolution. I raise the following general questions for future consideration: are downdrafts likely to be stronger when ice processes are included, or weaker as the authors suggest in section 7.2? What is the role of midlevel relative humidity in the initiation and evolution of these downdrafts? In tropical cyclones, at what level are downdrafts initiated, and how often do they reach the surface?

Dr. Molinari described nicely the limited scientific understanding of the details involved in downdraft formation and evolution, and the difficulties of downdraft representation in numerical models.

We of course did not feel satisfied to rely on the model results only for the formation of a vortex scale downdraft pattern. After having found some observational evidence for the occurrence of this pattern in the real atmosphere (Sec. 7.1), we are now more confident that this is not an artifact of our simple microphysics scheme.

We would like to emphasise that we propose that the primary formation mechanism for the persistent, vortex-scale downdrafts is the evaporation of precipitation that falls out of sloping(!) convection into unsaturated air below. This vortex-scale process is expected to be much better represented in the model than turbulent mixing of saturated updraft air with unsaturated environmental air. The formation mechanism of these vortex scale downdrafts would then appear to be less complex than processes leading to downdraft formation in predominantly upright convection.

4) [As the authors note, the role of  \$ck/cd\$  not equal to unity must be investigated.](#)

This important issue is one of our priorities for future research.

5) [Storms in these experiments move faster as shear increases. This introduces differing impacts of asymmetric friction that potentially confound comparisons among experiments. One could impose a shear with zero mean flow in the vertical as a way to address this issue.](#)

We agree that there remain important open questions about the role of frictional asymmetries due to storm motion (see also Sec. 7.2). Before embarking on such an experiment using a shear profile with zero mean flow, however, one must be aware of some nontrivial complications of such a configuration. A shear profile with zero mean flow and a wavenumber-1-like vertical structure will exhibit a moderate low-level flow. This low-level flow would contribute to enhancing the surface fluxes in the environment, moistening of the boundary layer (BL) there and modifying the low-level moist entropy. As a result, convection in the environment would likely be more prevalent, and this in turn would contribute to modifying the environmental sounding as compared to the 'reference' experiment presented in the current study. The environmental flow might also exhibit strong vertical shear in the underlying vortex Ekman layer, further complicating the interpretation of the results. While such an experiment might prove helpful, in particular in the first 12-24 h after the shear is imposed, these matters would need to be carefully addressed in the scientific interpretation of the results.

6) [A beta plane introduces asymmetries between easterly and westerly shear. This second-order effect might nevertheless influence the structure and evolution of convective asymmetries and the stationary band complex.](#)

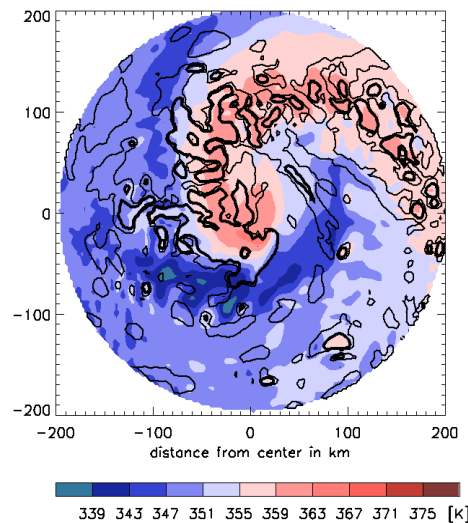
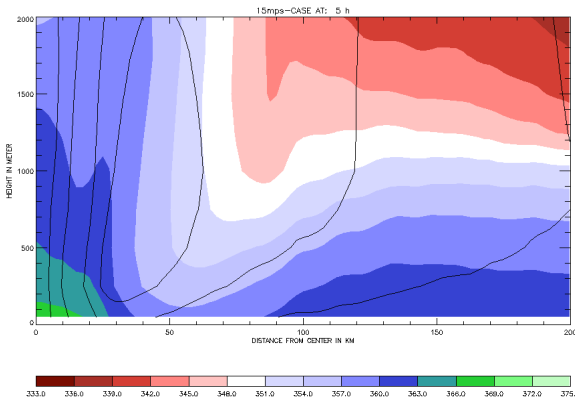
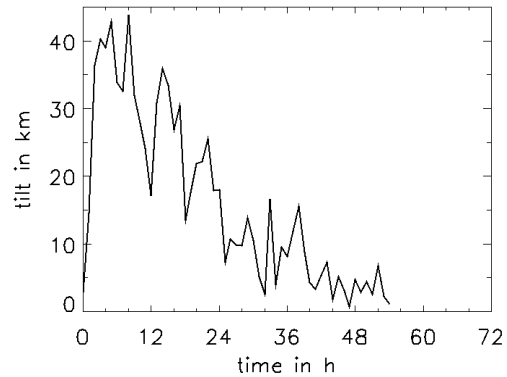
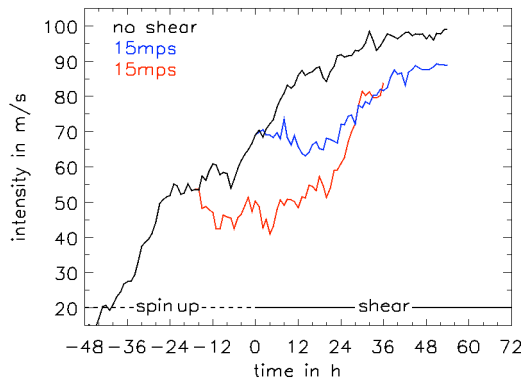
Including the beta-effect in the experiment, of course, breaks the symmetry of the f-plane experiment. The extent to which the beta-effects may introduce 'asymmetries between easterly and westerly shear', however, is not yet clear.

Ritchie and Frank (2007) report south-westerly vertical wind shear with a magnitude of 7 and 12 m/s attributable to the beta effect. The beta-shear thus appears to be comparable with moderate environmental shear values. Ritchie and Frank concluded that the 'resultant' shear relevant for TC evolution can be obtained by vector summation of the 'beta-shear' and the environmental shear; and thus an asymmetry between easterly and westerly shear would be introduced. Following this line of argument, beta would be expected to have a first-order effect on TC evolution in vertical wind shear. Ritchie and Frank (2007), however, did not present respective experiments with beta and vertical shear to support their conclusion.

It is not clear to us that a simple vector summation of the 'beta-shear' and environmental shear is justified. In Frank and Ritchie (2007) TC intensity is hardly affected by the 'beta-shear' of 7 m/s – 12 m/s. This is in stark contrast to the evolution of TC intensity under 5 m/s and 10 m/s shear reported by Frank and Ritchie 2001. In the latter study, the TCs weaken rapidly after an 'incubation' time of approx. 48 h and 36 h, respectively (their Fig. 4). Both studies use the same horizontal grid resolution, environmental sounding, sea surface temperature and initial vortex structure. It should be noted, however, that the experiments differ in the set of physical parameterisations and by an increase of the vertical levels from 20 to 23 in the 2007 study. These differences notwithstanding, based on the fundamentally different evolution of TC intensity in the above-mentioned experiments it is not clear to us that the 'beta-shear' has the same impact on TC evolution as environmental shear has; this would seem to be a basic prerequisite for a vector summation of 'beta-shear' and environmental shear.

In addition, Ritchie and Frank (2007) report changes in the inner-core structure, namely the development of persistent inner-core asymmetries, in their 'beta' experiment. Their result is based on the comparison of two deterministic experiments: one on a constant-f plane, and one on a variable-f plane. This result has been challenged recently by Nguyen et al. (2008). The latter study compares the intensification of a prototype vortex on an f-plane and a beta-plane using the mean structure of the TC from a 10-member ensemble experiments. The ensemble is generated by small-amplitude moisture perturbations in the boundary layer at the initial time. While the beta-gyres are found to be a robust feature in the ensemble mean, Nguyen et al. do not find coherent asymmetries in the ensemble mean for the inner core on the beta-plane. This indicates that the beta-effect, neither by 'beta-shear' nor by induced storm movement, provides a persistent low-wavenumber envelope for the inner-core asymmetries during intensification. Consistent with the findings of Frank and Ritchie (2007), the ensemble mean intensity on the beta-plane is only slightly weaker than the f-plane ensemble mean.

Because it is not clear that the beta-effect induces persistent inner-core asymmetries during the intensification of a TC in quiescent environment it might be assumed that the asymmetries induced by environmental vertical wind shear dominate the beta-effect also. The importance of beta for TCs in vertical wind shear would then appear to be small. To settle this issue it is important, of course, to



Upper left: Comparison of the intensity evolution of the 15mps case (blue), no\_shear (black) and a 15m/s shear experiment in which shear is imposed at 30h (red), upper right: tilt evolution (magnitude) in the 15mps@30h experiment. Lower left: vertical-radial cross section of  $\theta_e$  (color) and tangential wind (contours, every 10 m/s) at 5h, comparable to Fig. 9c. Lower right: average BL  $\theta_e$  (color) and updrafts (contours) at 5h, comparable to Fig. 7c.

perform respective shear experiments with variable  $f$  and interpret them in light of the ‘stationary band complex’ and associated vortex-scale downdrafts. We plan to do so in due course.

7) The shear is introduced in the model at a time of rapid intensification. I am curious whether the impact would be the same if it were introduced at, for instance, hour 30 or hour 66, when the storm intensity was quasi-steady.

We have performed an experiment in which the shear (15m/s) was imposed at 30 h (15mps@30h), a time of consolidation after the initial rapid intensification. All salient features of the reference experiments have been verified in this case also. We provide some figures characterizing the evolution below. Noteworthy, is the fact that the impact of vertical shear on storm intensity was more pronounced here than for

the stronger vortex in the reference experiment: the decrease in intensity is of greater magnitude and persists over a longer time interval.

There are two notable differences between experiments '15mps' and '15mps@30h' that might help to explain the more pronounced weakening in the latter case.. First, the environmental BL  $\theta_e$  is 3-5 K lower than in 15mps. This would help to produce stronger downdrafts and a more efficient flushing of the BL with low  $\theta_e$  air. It should be noted, however, that the core  $\theta_e$  maximum is 3 K lower in the 15mps@30h case also, and thus the core-environment difference is only slightly enhanced. Secondly, the vortex tilt is more than twice as large as compared to 15mps; around 40 km in the first 2 - 8 h after the shear is imposed. There is some indication that precipitation falling out of such a strongly tilted vortex contributes to an efficient depression of the BL  $\theta_e$  early in 15mps@30h. No such signature is found in the reference experiments. Certainly, more research is necessary to examine this hypothesis and it remains to be verified if these features hold true when the vertical shear is imposed in a more realistic manner.

#### References:

Ritchie and Frank, 2007: Interactions between simulated tropical cyclones and an environment with a variable Coriolis parameter. *Monthly Weather Review*, 13: 1889-1905

Please refer to the reference list in the discussion paper for further references.