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SENSITIVITY OF DEVELOPING TROPICAL CYCLONES TO INITIAL VORTEX DEPTH AND THE HEIGHT OF ENVIRONMENTAL DRY AIR

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1. INTRODUCTION

Understanding the ways in which a developing tropical cyclone (TC) interacts with its environment is fundamental to diagnosing predictability. A useful approach to assessing how these interactions affect the predictability of TC structure and intensity evolution is to examine the sensitivity to perturbing the TC environment. However, aspects of the TC vortex itself may also influence the evolution of structure and intensity. This study uses a series of idealized, convection-resolving simulations to investigate how both the depth of an initial TC-like vortex and the height of dry air in the adjacent environment alter the structure and intensity evolution of a developing TC. Addressing such sensitivity questions is a necessary step toward improving our ability to anticipate critical yet poorly-understood aspects of TC evolution, such as rapid intensification and variations in the extent of damaging winds.

2. MODEL AND METHODS

The WRF-ARW model v3.4.1 (Skamarock et al., 2008) is used in a two-way triply-nested grid configuration. The three grids have square dimensions of 4500km, 1200km, and 300km with respective horizontal resolutions of 18km, 6km and 2km. The two innermost grids follow the vortex at 750hPa, and have sufficiently high resolution to obviate a cumulus parameterization in all three grids. First we initialize the outer grid, a doubly-periodic *f*-plane at 20N, with a uniform moist tropical sounding and constant SST of 29C. Then, a modified Rankine vortex in hydrostatic and gradient-wind balance is placed in the center of this outer grid. The vortex represents a mature tropical storm with 30 ms^{-1} maximum tangential winds at a radius of 90km.

3. RESULTS AND DISCUSSION

3.1 Vortex Depth Simulations

The first set of simulations examines the sensitivity to the prescribed vertical decay of the tangential winds. Smoothly varying axisymmetric wind fields for each vortex are prescribed by adjusting parameters in equations 3 and 4 of Nolan (2007). All vortices have the same radial structure, with the cutoff radius in eq. 3, R = 600km. Winds are maximized at the top of the boundary layer by setting z_{max} in eq. 4 to 1.5km for all vortices, and L_z is set to 3km, 5km, and 6.5km for the shallow, mid, and deep vortices respectively. For the shallow vortex, α=2.0, and for the mid and deep vortices, α=2.5. In each simulation, the model is integrated for 192 hours.

TC intensity is evaluated using the average sea level pressure in a 20km square box centered within the 2km grid, and TC structure is evaluated using a simple inner-core size metric corresponding to the maximum radius of azimuthally-averaged tangential hurricane-force (33 ms^{-1}) winds at 10 meters. The evolution of both of these metrics is depicted in Figure 1.

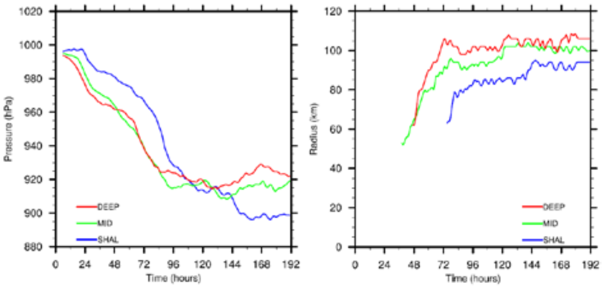

Figure 1: Minimum sea-level pressure (left) and maximum radius of hurricane force (33 ms^{-1}) 10-m winds (right) for the deep (red), mid (green) and shallow (blue) vortices. The first 6 hours are omitted due to a model adjustment period.

The deep and mid vortices follow similar intensity trajectories, while the shallow vortex remains considerably (>10 hPa) weaker until 96 hours. The deep and mid vortices also have similar structural evolutions, while the shallow vortex remains more spatially compact. It is interesting to note that despite similar intensities of the three vortices between 96 and 144

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hours, their size metrics differ considerably, illustrating the tendency for simple intensity metrics like minimum sea level pressure to mask important aspects of TC development. An additional simulation of a deeper vortex (not shown) exhibits a very similar structure and intensity evolution to the mid and deep vortices in Figure 1, suggesting the initial depth of the vortex may only influence the TC evolution if it is shallower than a certain threshold.

We further examine this apparent threshold using vertical cross-sections of vertical relative vorticity (ζ). Figure 4 depicts ζ along east-west oriented slices through the center of each vortex at 0, 12, 24 and 30 hours for the shallow and deep vortices from Figure 1.

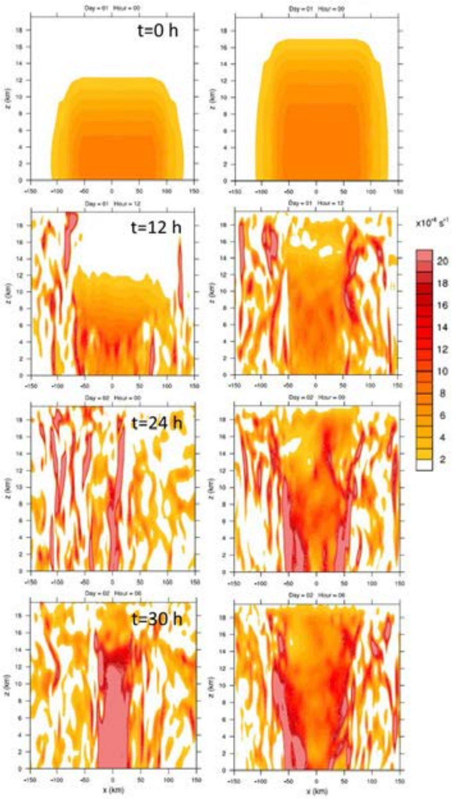

Figure 2: East-west cross sections of vertical relative vorticity (ζ) through the center of the shallow vortex (left) and the deep vortex (right). Each row corresponds to t = 0, 12, 24, and 30 hours from top to bottom.

After 24 hours, the prescribed shallow vortex disintegrates into filaments of residual vorticity associated with deep convection. By 30 hours, these filaments have axisymmetrized into a deep column of vorticity, at which point rapid intensification commences. However, the vortex at this stage bears little resemblance to the prescribed vortex. The tendency for the model to replace the prescribed shallow vortex with a deeper vortex could be due to an initial TC intensity that is too strong to sustain such a shallow wind field. A 30 ms^{-1} vortex quickly produces deep convection that transforms the prescribed shallow vortex into a deeper column of vorticity. Therefore, initializing a strong tropical storm may significantly limit the possible vertical structures that will be sustained by the model, and future work should involve varying the depths of weaker initial vortices.

3.2 Dry Air Simulations

Given the potential limitations of perturbing the kinematic structure of a mature TC, the remainder of this study focuses on the sensitivity to dry environmental air. This sensitivity has been examined using both real TCs (e.g. Dunion and Velden, 2004; Sippel et al., 2011) and idealized simulations (e.g. Kimball, 2006; Hill and Lackmann, 2009, Braun et al., 2012). In particular, much attention has been given to the impact of dry mid-level air on TC evolution, primarily due to the prevalence of mid-level drying in the Tropical Atlantic associated with the Saharan Air Layer (SAL). Braun et al. (2012) found that, without vertical wind shear, mid-level dry air had to be initialized very close to the center of the TC in order to delay intensification. In addition, there is a growing consensus that stronger vortices are less sensitive to dry air in the mid-levels (Sippel et al, 2011) and perhaps in other vertical levels as well (Riemer and Montgomery, 2011). However, it has not yet been shown how this sensitivity may change for ambient dry air at different heights. The intent of this part of the study is, thus, to better understand how a TC responds to variability in the height of environmental dry air.

Within the same idealized framework used for studying sensitivity to prescribed vortex structures in section 3.1, we subject an axisymmetric TC to dry air confined to three tropospheric layers. The control vortex has similar structural parameters as the mid vortex in section 3.1, except with α=2.0 in eq. 4 of Nolan (2007). For the three perturbed simulations, relative humidity is reduced by a factor of 80% at three specified pressure levels, where the level of maximum drying is 900, 700 or 500 hPa. The initial drying decays as a Gaussian vertically away from these levels, and radially toward the vortex center (top row of Figure 4). Each dry air simulation is integrated for 120 hours.

Figure 3 depicts the intensity and structural evolution of the control TC (no dry air) and the three TCs in different dry environments using the same sea level pressure and inner-core size metrics as in Figure 1. The intensity evolution of TCs in environments with dry air at 500 and 700 hPa is very similar. However, for dry air at 900-hPa, the intensification of the TC is delayed by 24 hours, and is followed by a period of rapid intensification. This suggests that the initial intensification of a TC may be most sensitive to drying within the boundary layer. Physically, this seems reasonable considering dry air in the boundary layer has a more direct pathway into the core of the TC as inflow associated with the TC secondary circulation develops. Nevertheless, the intensity of the control case without any dry air is similar to that of the dry cases throughout the simulation, and is actually among the weakest cases by 120 hours, indicating fairly limited overall intensity sensitivity to any of the dry air configurations.

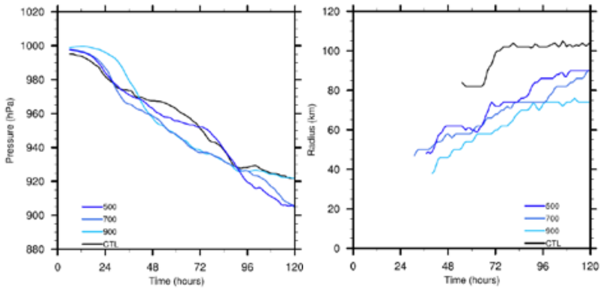

Figure 3: As in Figure 1, except for the moist control vortex (black), and the vortices exposed to dry air at 500-hPa (dark blue), 700-hPa (cerulean), and 900-hPa (cyan)

In contrast, there appears to be greater structural sensitivity to dry air. By 120 hours, the control vortex without dry air is nearly 20% larger than the 500- and 700-hPa dry air cases, and about 40% larger than the 900-hPa dry air case. We further examine this sensitivity using vertical cross sections of azimuthally averaged relative humidity differences between the dry air cases and the control after 24 hours (bottom row of Figure 4). It is apparent from Figure 4 that dry air initialized in the boundary layer reduces moistening outside the eye wall and within the primary stratiform cloud region after 24 hours, indicating suppressed rainband and eyewall convection. For the same forecast time in the 700-hPa and 500-hPa dry environments, reduced moistening in this same region becomes progressively less pronounced. These signatures of reduced moistening are present after 48 hours (not shown), albeit to a lesser extent.

Similar structural sensitivity to environmental dry air was encountered by Kimball (2006) and Hill and Lackmann (2009), who found that dry environments tend to produce smaller TCs through suppressed rainband convection. In addition, the minimal sensitivity of TC intensity to dry air in all dry simulations is consistent with previous studies involving dry air in the absence of vertical wind shear (e.g. Braun et al. 2012).

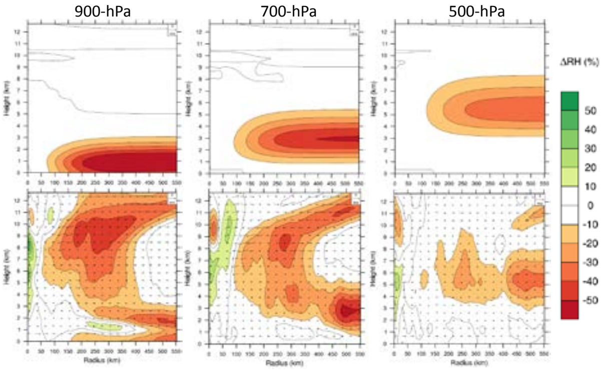

Figure 4: Azimuthally-averaged cross sections of relative humidity differences between the control simulation without dry air, and the three simulations with dry air at 0h (top row) and at 24 hours (bottom row).

Considering nearly all real TCs develop in at least some vertical wind shear, we perform an additional simulation that includes 10 m/s of westerly deep-layer (200-850 hPa) shear throughout the domain with 700-hPa drying. A similarly sheared control simulation without dry air is also conducted for comparison.

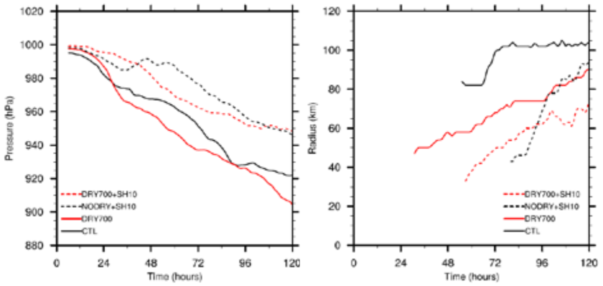

Figure 5: As in Figure 1, except for vortices with dry air at 700-hPa (red) and without dry air (black), with 10 ms^{-1} of westerly vertical wind shear (dotted) and without shear (solid)

Figure 5, which depicts the same intensity and size metrics as in Figures 1 and 3 above, shows that sheared cyclones intensify more slowly. Moreover, by the end of the 120-hour simulation, the sheared TCs are more than 20 hPa weaker than TCs in the quiescent environments with or without dry air. Remarkably, there is still little intensity sensitivity to dry air when wind shear is included. However, shear acts to amplify the structural sensitivity of simulated TCs in dry environments, with a 17% size reduction at 120 hours in the absence of shear, and a 26% size reduction with shear.

To better understand these results, Figure 6 provides three snapshots of the “shear minus no shear” 700-hPa RH difference fields for the simulations without dry air (left column), and the simulations with dry air maximized at 700-hPa (right column)[1].

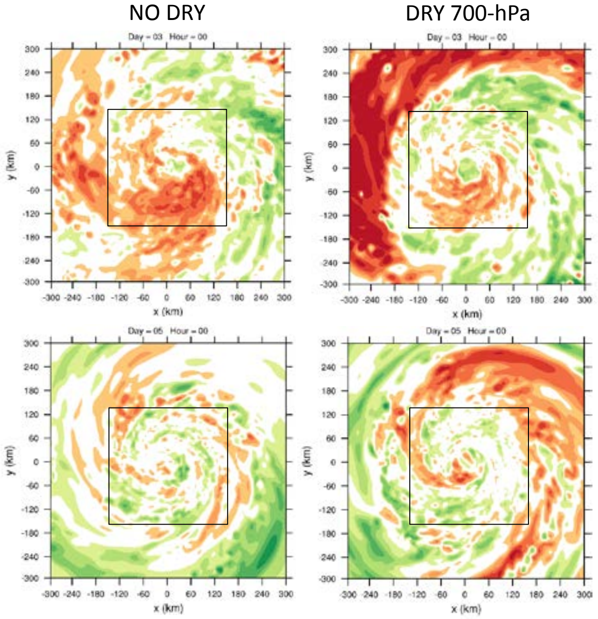

Figure 6: 700-hPa relative humidity (%) differences between simulations with and without 10 ms^{-1} of westerly vertical wind shear (left) without dry air and (right) with dry air at 700-hPa, at 48 hours (top) and at 96 hours (bottom). The colors follow from Figure 4. The square box roughly outlines the innermost 2-km grid.

Even in the absence of dry air (left column of Figure 6), there are substantial moisture reductions near the center of the sheared TC at 48 hours. The position and structure of moisture reductions near the TC center is in qualitative agreement with the shear-induced boundary layer θ_e reductions observed by Riemer et al. (2010), suggesting that reduced moistening may be related to vertical wind shear. The significant band of reduced moistening encircling the TC in the dry simulations remains well separated from the TC core until 96 hours, when it spirals inward (bottom right panel of Figure 6). This is coincident with the time at which the dry sheared case stops intensifying (Figure 5).

Diabatic heating within the inner core is a primary mechanism by which a TC intensifies (e.g. Vigh and Schubert, 2009). Therefore, TC intensity is expected to be weakly sensitive to dry environmental air until such air is able to reach the inner core. This may help explain why the simulated TCs in dry environments are still able to intensify, as there is no clear evidence of the ambient dry air reaching the TC core until late in the simulations. On the other hand, the processes influencing TC size and structure such as outer rainband activity are more exposed to the dry air spiraling around the core region throughout our simulations. Moreover, adding shear appears to facilitate the encroachment of dry ambient air on the outer part of the storm early in the simulation, likely explaining the greater observed structural sensitivity to dry air at all forecast times.

4. CONCLUSIONS

We have performed two sets of idealized simulations with the WRF-ARW model to study the sensitivity of a strong tropical storm to variability in the initial vortex depth and humidity in the adjacent environment. The first set of simulations varies the initial vertical profile of tangential winds for a fairly intense axisymmetric vortex. The primary finding is that deep convection quickly transforms the shallowest TC vortex into a deeper vortex, which is likely due initial maximum winds that are too strong to sustain the prescribed shallow circulation. Therefore, further research on the sensitivity to varying the depth of the initial TC vortex should involve weaker vortices.

The second set of simulations initializes layers of dry air outside the TC core at three different heights. In general, there is minimal intensity sensitivity to all three dry air configurations. However, dry air introduced at lower levels produces smaller TCs by more effectively suppressing rainband convection. This effect diminishes as dry air is initialized at higher levels. Adding vertical wind shear produces weaker TCs, but does not significantly modulate dry air penetrations into the TC core until late in the simulations. It should be noted that this result could be highly sensitive to the selected vertical shear profile, and further research should investigate different shear profiles. Nonetheless, our results suggest that 1) vertical shear has a greater influence on TC intensity, while dry air has a greater influence on TC size; and 2) 10 ms^{-1} of shear may amplify the structural sensitivity to dry air, but does not affect the intensity sensitivity to dry air until late in the simulation.

This study will be extended to further explore the impact of shear and dry air on TCs. Repeating the simulations for weaker TCs could confirm whether stronger tropical cyclones are indeed better able to shield themselves from hostile environments, as suggested in recent studies. Furthermore, it would be useful to determine the minimum vertical wind shear required to weaken a mature TC vortex, with or without dry air. Identifying these types of thresholds in the shear-moisture sensitivity phase space is important for determining scenarios where predictability of TC structure and intensity may be lost.

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[1] To account for vortex tilting with height, relative humidity differences are computed between sub-windows of the 6-km grid that are centered on the 700-hPa geopotential minimum of each simulation.

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