

Microphysical influences on hurricane track and intensity in idealized simulations

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1. Introduction

Hurricane Rita's Sept. 24, 2005, landfall at the Texas-Louisiana was correctly identified in the National Hurricane Center (NHC) forecast issued 36 h earlier, but their 54 h forecast targeted Houston, prompting a frantic evacuation. The position error in the latter forecast was not large when compared to recent history, which has seen steady and remarkable improvement in forecast accuracy. Indeed, the actual landfall position fell within the NHC's multi-model consensus spread, albeit at its eastern edge. However, the population-weighted error was substantial.

The NHC ensemble consists of over a dozen different models of various types and levels of complexity. Fovell (2006) and Fovell and Su (2007; "FS") demonstrated that a similar ensemble spread for the Rita landfall could be obtained from a single model, the WRF-ARW, via manipulation of microphysical and cumulus schemes. Their simulations employed "operational resolutions" of 30 and 12 km initialized using NCEP GFS gridded forecast fields. In the Rita ensemble, model runs employing the Kessler "warm rain" scheme tended to track more westward relative to schemes that considered the ice phase, such as LFO and WSM3. The latter vortex propagated the most northward which, at least in the case of Rita, yielded the most accurate landfall forecast.

FS's analysis suggested that microphysical assumptions affected track by influencing vortex size. The Kessler scheme tended to maintain relatively wider and weaker storms that were likely more susceptible to the "beta drift" that causes vortex self-propagation towards the northwest (Holland 1983). WSM3's storms were the narrowest, though not the most intense. Vortex asymmetries owing to convection were also potential factors. FS showed that the WSM3 storm possessed enhanced ascent (and thus convective heating) on its northeast side, rotated clockwise from the Kessler vortex's maximum ascent location. The influence of asymmetric heating on storm motion was demonstrated by Willoughby (1992).

FS also documented other microphysical sensitivities – to hydrometeor fallspeeds and the latent heat of fusion, for example – that varied with resolution and thus are probably also case dependent. Further, Hurricane Rita progressed through a complex and dynamic environment, complicating analysis of the microphysical influences. Thus, we found it prudent to explore the impact of microphysics on storm track, as well as intensity, in a more idealized framework, but one that kept some of the characteristics and advantages of the real-data WRF.

2. The real-ideal WRF hybrid

The simulations described below employed a modified real-data version of WRF version 2.1.2 and 2.2 dubbed "Waterworld" (WW) which retains Earth's rotation and (optionally) curvature, but has no land, a uniform SST set at 29°C and a calm, horizontally homogeneous base state based on Jordan's (1958) hurricane season composite. WW utilizes an ingenious technique developed by Gary Lackmann and Kevin Hill of North Carolina State University employing GEMPAK to fashion a fully 3D GRIB formatted data set from a single, specified sounding. This data set is then ingested by the WRF preprocessor as if it came from one of the supported models. Thus, this is truly a "real-ideal" hybrid.

Our WW employs three telescoping domains, the outer spanning 3240 km by 3240 km with 27 km resolution and the innermost being 669 km on a side with 3 km grid spacing. The outer domain is intended to capture the entire environmental response to the hurricane; its boundary conditions are fixed, and thus effectively closed. (There is no actual parent model, and thus no boundary tendencies.) Our choices were dictated by computing resource limitations, but there is no evidence that these domains were too small for the problem at hand.

In most idealized hurricane studies, an initial vortex is supplied. We elected to let the model spin up its own vortex from an initial bubble, as in so-called cloud models. Such a disturbance of desired size and placement can be incorporated in the WW initialization, again thanks to Lackmann and Hill.

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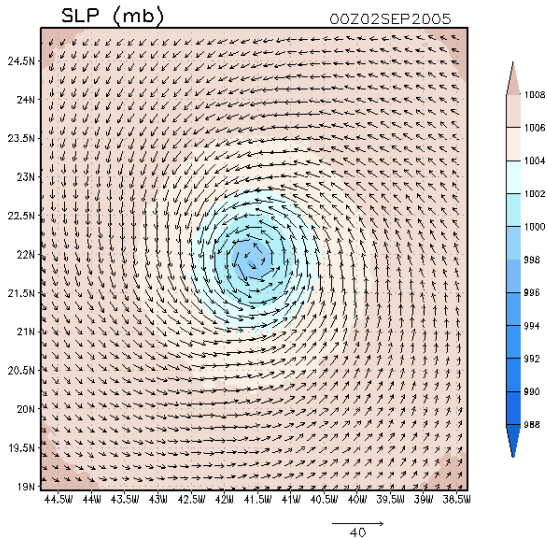


Fig. 1: CP-spinup storm on f -plane showing sea-level pressure (colored) and 10 m wind vectors at 24 hours after initialization. The 3 km domain is shown.

With a favorable sounding and warm ocean surface, the atmosphere responds by creating a closed cyclonic circulation over a pendulum day, after which a storm dealt only with the environmental heterogeneity that it itself created.

Our desire was to generate a well-resolved vortex providing an identical starting point to each microphysical scheme, congruent with the operational ensembles' cold start initializations. This was accomplished by employing the Kain-Fritsch convective parameterization (CP) scheme alone for a spin-up period of 24 or 36 hours, and no microphysics. Having microphysics active from the outset permitted more rapid development, but also had a first-order effect on how the storm organized. In particular, the WSM3 scheme resulted in extremely slow development and very tiny (and thus poorly resolved) vortices. Figure 1 presents the sea-level pressure (SLP) and 10 m wind field at 24 hours resulting from a CP spinup run on an f -plane located at 22°N .

3. Microphysical track sensitivity in WW

Figure 2 presents time series of domain minimum SLP for microphysical experiments conducted with variable f with the initial bubble placed at 20°N latitude. The simulations employed 31 vertical levels with a model top at 50 mb. After a 24 hour spin-up with the Kain-Fritsch CP, simulations continued with either the CP scheme or one of three MP schemes (Kessler, LFO or WSM3) active. The storms quickly diverged with respect to intensity, the LFO scheme resulting in the strongest storm as in the real-data Rita runs. Previous studies have identified graupel as being instrumental in enhanc-

ing storm development (e.g., Lord et al. 1984; Zhu and Zhang 2006).

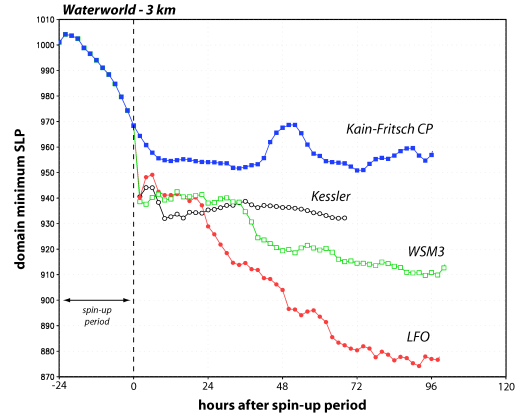


Fig. 2: Time series of domain minimum SLP for simulations employing the Kain-Fritsch CP alone or with Kessler, WSM3 or LFO microphysics. The shared 24 hour spin-up period is also displayed.

A substantial difference in track and propagation speed also ensued (Fig. 3). As in the real-data runs, the Kessler vortex tracked farthest to the west, the WSM3 storm moved most northward, and the LFO simulation fell in between. At 54 h after the end of the spin-up period, the Kessler vortex's forward motion was 9 km h^{-1} and increasing. At that time, the LFO and WSM3 storms were 43% and 52% slower, respectively. Since there was no initial environmental flow, this is entirely self-propagation. When combined with track variations, physical separations soon became extremely large among the storms.

Figure 3's inset shows radial profiles of the 10 m wind speed outward from the eye at the 54 h mark. The LFO storm was still intensifying at this time, and spent over 2 days at or very near Category 5 intensity, while the warm rain vortex fluctuated between Categories 2 and 3. The Kessler storm also had the most radially expansive circulation, and was thus again the most influenced by beta drift. The translation speed differences may reflect the variation in wind speeds seen at large radius, as suggested by Fiorino and Elsberry (1989). The rapid propagation speed seen in the Kessler case represents the most significant difference with respect to the real-data Rita runs; in the latter, the Kessler vortices were among the slowest movers.

3. Microphysical intensity sensitivity in WW

Results presented above demonstrate that, consistent with previous work, microphysical schemes that incorporate ice can encourage more intense storms. Wang (2002) and Zhu and Zhang (2006) also investigated the influence of neglecting evaporation and melting of hydrometeors on storm strength. In par-

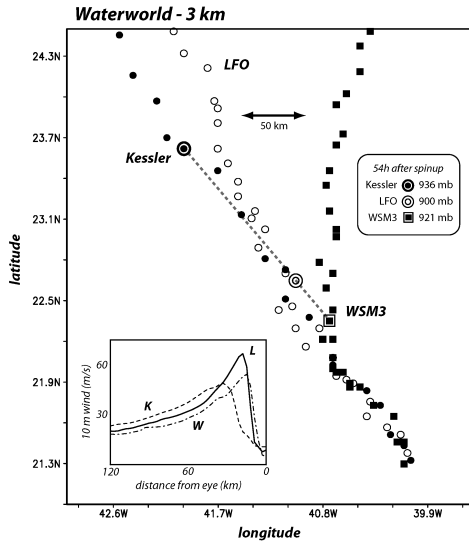


Fig. 3: Three-hourly positions for Waterworld storms employing Kessler (K), LFO (L) and WSM3 (W) microphysics, commencing 12 hours after end of spin-up period. Positions and central pressures after 54 h are highlighted. Inset shows radial profiles of 10 m wind speed vs. distance from eye at 54 hours after spin-up.

ticular, Wang (2002) found that deactivating rain evaporation and snow and graupel melting resulted in very rapid intensification rates and the attainment of very low central pressures (down to 860 mb in one case). This was an idealized modeling study in which the initial storm vortex was supplied.

Figure 4 presents minimum SLP time series for WW simulations made on an f -plane located at 22°N . These runs also used 31 model levels, but the model top was placed at 10 mb, resulting in lower vertical resolution than in the track experiment. The initial environment was still calm and the simulations shared a 36 h Kain-Fritsch CP spin-up period. As expected, none of the model storms translated significant distances, owing to the absence of imposed steering currents and the beta effect. In addition to the Kessler and LFO schemes, a run was made using the “no-cloud cloud model” (NCCM) strategy (Fovell 2004); this involves removing condensation from the domain as it is generated in the Kessler scheme. The NCCM necessarily neglects water loading and hydrometeor sedimentation and cannot possess saturated downdrafts.

Among these runs, the NCCM assumption resulted in the most intense storm by far, reaching an incredible 780 mb by 36 hours after the end of the spin-up period. This experiment is more similar to the “NEVP” case in Zhu and Zhang (2002) than in Wang (2002) as the latter did not deactivate cloud water evaporation. However, Zhu and Zhang’s (real-data) simulation did not deepen beyond ≈ 900 mb.

The 780 mb figure far exceeds any reasonable maximum potential intensity (e.g., Emanuel 1988), and it seems fairly certain that the final intensity is exacerbated by upper boundary problems as the storm eventually produced significant disturbances near the model’s 10 mb top. Therefore, it is the extremely rapid intensification that is of interest.

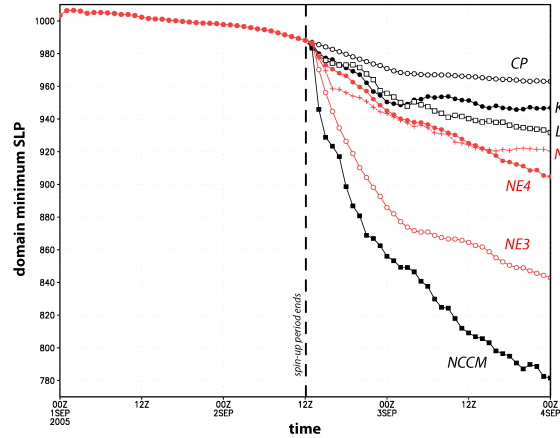


Fig. 4: Time series of domain minimum SLP for various f -plane simulations. See text.

Also shown (in red) are time series from three no-evaporation Kessler-based simulations (NE1-NE3). None of these runs had cloud water evaporation, but condensate was *not* removed, meaning that water loading was present. In NE2, rainwater production was not permitted. After a brief period of relatively swift intensification, this storm’s strengthening rate decreased and its final central pressure was an unspectacular 920 mb. For NE3, rainwater production and sedimentation were allowed, which could help shift condensate loading to the lower troposphere. This storm intensified almost as rapidly as the NCCM run, which argues against water loading necessarily being a brake on hurricane development. For NE4, we neglected cloud and rainwater evaporation only above the 3.5 km level. Its smaller intensification rate suggests that lower to middle tropospheric cooling is a major controlling factor.

Figure 5 shows vertical cross-sections of relative humidity (RH) spanning the eye for the Kessler and NCCM cases at 12 h after the end of the spin-up period. Particularly striking is the very low RHs in the NCCM storm’s eye (Fig. 5b), reaching down nearly to the ocean surface. Even in subsequent development, RHs in the Kessler eye do not fall below 40% in the lowest 2 km. The NCCM eye has especially large temperature anomalies (not shown), partly owing to substantially stronger updrafts in the eyewall area. Lower RH values are also seen above the lower troposphere beyond the eyewall, a consequence of necessarily subsaturated downdrafts. As the NCCM

scheme cannot transport condensate into the upper troposphere and stratosphere, RHs are very low in those regions as well.

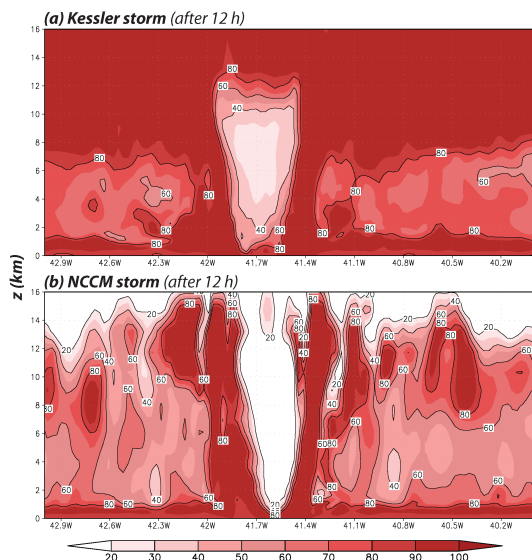


Fig. 5: Vertical cross-sections of relative humidity spanning the eye for f -plane Kessler and NCCM runs. The horizontal dimension is approximately 300 km.

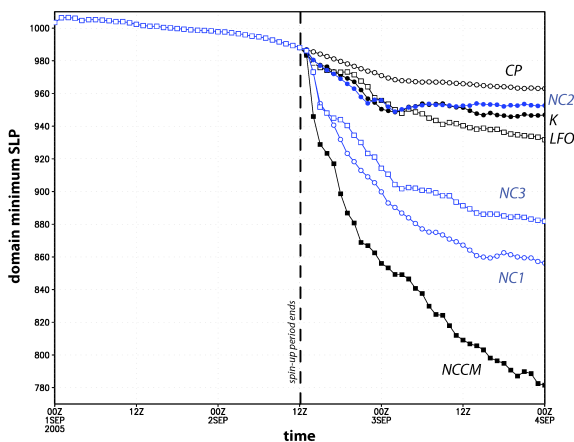


Fig. 6: As in Fig. 4, but including some special NCCM experiments. See text.

Figure 6 shows some SLP time series from Fig. 4 with three new NCCM runs (NC1-NC3) added, while Fig. 7 presents their RH cross-sections. For NC1, condensation was removed and evaporation neglected only in the lowest 3.5 km. This storm's intensification rate was very similar to that of experiment N3 (Fig. 4) over the first 24 hours and the largest fraction of the full NCCM run's development rate was captured. Relative humidities for this run (Fig. 7a) were much higher in and above the middle troposphere compared to the NCCM experiment (Fig. 5b), though they were lower in the boundary layer. This storm's eye still has extremely low RHs penetrating to the sea surface.

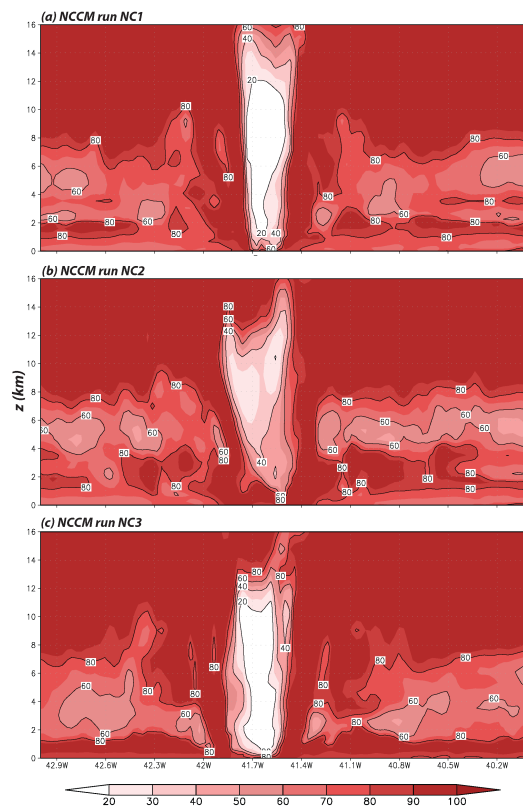


Fig. 7: As in Fig. 5, but for NCCM runs NC1-NC3.

For NC2, the NCCM scheme was further restricted to vertical columns in which the surface pressure exceeded 995 mb, thereby preventing condensation and evaporation removal from the hurricane core including the region of maximum winds. This run evolved similarly to the Kessler storm, and achieved a minimum SLP of only 950 mb (Fig. 6). Beyond the core, RHs for this case were similar to those of NC1 (Figs. 7a, b) suggesting the far-field humidity field had little influence on storm strength or intensification rate. NC2's eye was well defined but RHs in the boundary layer were much higher than in the full NCCM run or case NC1.

Finally, for case NC3, the NCCM scheme was applied only in the lowest 3.5 km of columns in which the surface pressure was lower than 995 mb. This storm also intensified very quickly and developed very low RHs in the lower portion of the eye (Fig. 7c). It is this region that may hold the key to rapid intensification in actual hurricanes, even if the particular mechanism provoked in WRF is lacking in realism.

4. Summary

A real-ideal hybrid of WRF has been used to simulate hurricanes in an initially calm environment with uniform SST, but with real-data model characteris-

tics such as radiation and boundary layer physics and Earth curvature. Sensitivity of track and intensity to microphysical assumptions were studied. Cyclonic vortices were bred in response to an imposed bubble through the use of a convective parameterization for 24 or 36 hours. In curved Earth simulations, microphysics was found to profoundly influence storm track and propagation speed, largely consistent with results from the real-data Hurricane Rita experiments. The influence of microphysics on intensity was examined in an f -plane setting. The reasons why occasionally very strong storms were produced in the model were explored.

5. References

- Emanuel, K. A., 1988: The maximum intensity of hurricanes. *J. Atmos. Sci.*, **45**, 1143-1155.
- Fiorino, M. J., and R. L. Elsberry, 1989: Some aspects of vortex structure related to tropical cyclone motion. *J. Atmos. Sci.*, **46**, 975-990.
- Fovell, R. G., 2004: Adjoint of a parameterized moisture convection model. *Meteor. Atmos. Phys.*, **86**, 173-194.
- Fovell, R. G., 2006: Impact of microphysics on hurricane track and intensity forecasts. Preprints, 7th WRF Users' Workshop, NCAR.
- Fovell, R. G., and H. Su, 2007: Impact of microphysics on hurricane track. Submitted to GRL.
- Holland, G. J., 1983: Tropical cyclone motion: Environmental interaction plus a beta effect. *J. Atmos. Sci.*, **40**, 328-342.
- Jordan, C. L., 1958: Mean soundings for the West Indies area. *J. Meteor.*, **15**, 91-97.
- Lord, S. J., H. E. Willoughby, and J. M. Piotrowicz, 1984: Role of a parameterized ice-phase microphysics in an axisymmetric, nonhydrostatic tropical cyclone model. *J. Atmos. Sci.*, **41**, 2836-2848.
- Wang, Y., 2002: An explicit simulation of tropical cyclones with a triply nested movable mesh primitive equation model: TCM3. Part II: Model refinements and sensitivity to cloud microphysics parameterization. *Mon. Wea. Rev.*, **130**, 3022-3036.
- Willoughby, H. E. 1992: Linear motion of a shallow-water barotropic vortex as an initial-value problem. *J. Atmos. Sci.*, **49**, 2015-2031.
- Zhu, T., and D.-L. Zhang, 2006: Numerical simulation of hurricane Bonnie (1998). Part II: Sensitivity to varying cloud microphysical processes. *J. Atmos. Sci.*, **63**, 109-126.

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