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Impact of cloud microphysics on hurricane track forecasts

Robert G. Fovell[1] and Hui Su[2]

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[1] Simulations of Hurricane Rita (2005) at operational resolutions (30 and 12 km) reveal significant track sensitivity to cloud microphysical details, rivaling variation seen in the National Hurricane Center's multi-model consensus forecast. Microphysics appears to directly or indirectly modulate vortex characteristics including size and winds at large radius and possibly other factors involved in hurricane motion. Idealized simulations made at higher (3 km) resolution help isolate the microphysical influence. **Citation:** Fovell, R. G., and H. Su (2007), Impact of cloud microphysics on hurricane track forecasts, *Geophys. Res. Lett.*, *34*, L24810, doi:10.1029/2007GL031723.

1. Introduction

[2] Official National Hurricane Center (NHC) statistics show that Atlantic hurricane position forecasts have improved markedly in recent decades. Yet, the 2005 season demonstrated that much progress remains to be made. On September 24, 2005, Hurricane Rita made landfall near the Texas/Louisiana border as a Saffir-Simpson Category 3 storm with $\sim$54 m s^{-1} maximum winds. This location was correctly identified in the NHC forecast issued 36 h prior to landfall but their 54 h forecast had the highest probability landfall located west of Houston, a >130 km shift that prompted a hurried and ultimately unnecessary evacuation. This position discrepancy was about average when compared to recent years, but looms very large indeed when weighted by population.

[3] Weather forecasts in general have made great use of ensemble forecasting, in which different models, model physics options and/or initializations are applied to the same event, yielding an objective measure of forecast uncertainty. Previous work involving both real-data and idealized modeling has shown that the choice of cumulus parameterizations, boundary layer and/or cloud microphysics schemes can dramatically influence hurricane simulations, especially with respect to intensity and intensification rate, rainfall production and inner core structure [e.g., *Willoughby et al.*, 1984; *Lord et al.*, 1984; *Braun and Tao*, 2000; *Wang*, 2002; *McFarquhar et al.*, 2006; *Zhu and Zhang*, 2006]. Regarding microphysics, *Lord et al.* [1984] found including ice processes resulted in a significantly stronger storm, while *Wang* [2002] and *Zhu and Zhang* [2006] showed that disallowing melting and evaporation permitted substantially more rapid intensification and lower central pressures. However, sensitivity of hurricane track or propagation speed to cloud microphysics has either not been found in these studies or has gone unreported.

[4] Herein, we demonstrate that microphysical assumptions can dramatically impact forecasted track in Weather Research and Forecasting (WRF) [*Skamarock et al.*, 2007] model simulations of Hurricane Rita at horizontal resolutions of 30 km and 12 km, as typically used for operational (real-time) forecasts. A more idealized model at finer resolution is used to examine the generality of the results.

2. Operational Ensembles (30 and 12 km Horizontal Resolution)

[5] Most of these simulations employed WRF version 2.1.2 and a spatially extensive domain centered on the northern Caribbean. Four microphysical parameterizations (MP) were explored: the Kessler ("warm rain"), the Lin et al. (LFO), and the three and five class WRF single moment (WSM3 and WSM5) options. All but the Kessler scheme incorporate frozen water in some fashion. The Kain-Fritsch (KF), Grell-Devenyi and (from WRF 2.0.3.1) Betts-Miller-Janjic (BMJ) convective parameterizations (CPs) were tested. Runs were also made with MP and/or CP schemes deactivated. The influence of subgrid-scale turbulent mixing was also explored, and found to affect intensity more than track in this experiment. Other physics schemes were held fixed.

[6] The operational simulations employed 31 vertical levels with a 50 mb model top. Usage of additional levels or a higher model top were not found to materially affect hurricane motion. Initial and boundary data were provided by National Centers for Environmental Prediction Global Forecast System forecasts at one degree resolution, commencing either 06 UTC or 18 UTC Sept. 22nd. In the 30 km ensemble, an LFO/KF simulation started at 18 UTC, about 39 hours prior to landfall, yielded accurate predictions (not shown) of landfall location, storm width, timing and intensity (936 mb), in good agreement with the contemporaneous NHC forecast.

2.1. The 30 km Ensemble Results

[7] The physics-based ensemble experiment was conducted for the earlier initialization time. Figure 1 presents a sea-level pressure (SLP) track plot for the LFO/KF (control) run. At each point depicted, the lowest SLP recorded during the final 27 hours of the 54 hour simulation, based on hourly data, is plotted. Similar to the contemporaneous NHC forecast, the control run's hurricane made landfall near Houston. It deepened to 924 mb before weakening prior to reaching land; this minimum pressure was slightly lower than actually measured at or subsequent to this time (931 mb). The track followed by the model hurricane's eye is traced by the open circles, representing three-hourly positions ending at 12 UTC Sept. 24th, about three hours after the actual storm reached the coast.

[1]Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, California, USA.

[2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.

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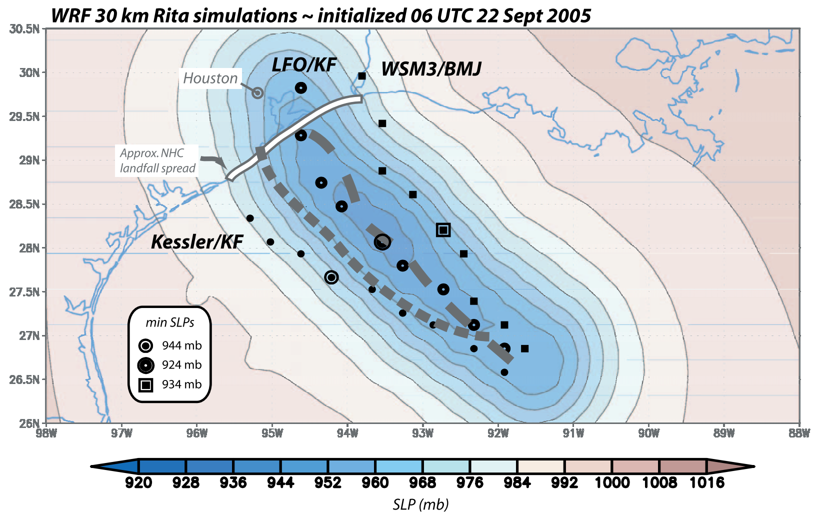

Figure 1. Sea level pressure track plot for the 30 km control (LFO/KF) run commencing 06 UTC Sept. 22nd, covering the simulation's final 27 h; contour interval 8 mb. For selected ensemble members, markers denote eye positions every 3 h ending 12 UTC Sept. 24th. Dashed tracks represent sensitivity runs described in section 2.2. Only part of the domain is shown. Landfall area encompassed by NHC ensemble members reaching the coast by 12 UTC Sept. 24th is highlighted.

[8] Superposed are the best and worst results from this ensemble, as determined by position error. The WSM3/BMJ combination (solid squares) correctly simulated both landfall location and timing. In contrast, the Kessler/KF member (solid circles) produced a weaker (minimum SLP 944 mb), more westward moving storm. Tracks from remaining members (not shown) generally fell between these two extremes. Taken together, this physics-based ensemble possessed a similar spread with respect to landfall as the NHC's multi-model ensemble did at this same time (also indicated on Figure 1). The NHC ensemble consists of over a dozen models of various types and levels of complexity.

2.2. The 30 km Ensemble Sensitivity Tests

[9] Many microphysical parameterizations treat hydrometeors in bulk, based on presumed particle size distributions, types and densities. Even the simplest schemes contain numerous assumptions and "knobs" that might lack observational or theoretical justification, and thus can be a source of uncertainty. To be useful uncertainty, each scheme has to have a reasonable chance of producing the most skillful result in any given situation, something a more extensive experiment might reveal. Since model physics can interact in complex and potentially unpredictable ways, the performance of various MP schemes and the impact of their inherent assumptions are likely case- and even resolution-dependent.

[10] We have attempted to identify MP scheme "knobs" that excite the sensitivity seen above. The most significant difference between the Kessler scheme and any MP that considers ice is that the average particle fall speed is likely different when frozen condensate is included. Fall speed assumptions directly and indirectly influence particle growth rates, the horizontal spread of condensate and vertical heating profiles, potentially interacting strongly with how and where CP-based adjustments are triggered. To explore the role of hydrometeor fall speed on the ensemble spread, we took the most accurate member (WSM3/BMJ) and forced ice to share the terminal velocity of raindrops having equivalent mass. This resulted in a simulated hurricane landfall to the west of Houston, shown on Figure 1 as the short-dashed line, a considerable increase in position error.

[11] The long-dashed line on Figure 1 shows what transpired when the rainwater terminal velocity was set to zero in the Kessler scheme, effectively removing precipitation. This run's position error was no worse than that of the control run. Without precipitation, there is little to no evaporation cooling in the boundary layer. However, another modified Kessler run lacking only evaporation of rainwater possessed the same track as the original Kessler/KF storm. These results suggest that, at least for this particular situation, considerable sensitivity can be excited via manipulating hydrometeor fall speeds.

2.3. The 12 km Ensemble Results and Sensitivity Tests

[12] To ascertain whether the microphysical influences found in the 30 km runs persist when the resolution is altered, a full physics-based ensemble was conducted using 12 km grid spacing. Model hurricanes with realistic intensity without CP schemes were obtained at this resolution, so only those members are considered herein. Figure 2 shows SLP track plots for the 12 km Kessler, LFO and WSM3 runs. As in the 30 km ensemble, the Kessler scheme produced the weakest and most westward propagating hurricane, still making landfall well west of Houston. This was also clearly the widest vortex of the three. The WSM3 simulation again yielded the most accurate landfall while LFO microphysics maintained the deepest storm (929 mb). All of the 12 km runs made without CP schemes tended to make landfall a few hours late.

[13] While the basic MP dependencies are similar at this higher operational resolution, some of the specific sensitivities differ from their 30 km counterparts. For example, at 12 km and without active CP, altering the rainwater terminal velocity in the Kessler scheme had less impact on the landfall location (not shown). At 30 km, that alteration was perhaps exaggerated owing to interaction with the cumulus parameterization, which is more critical to vortex

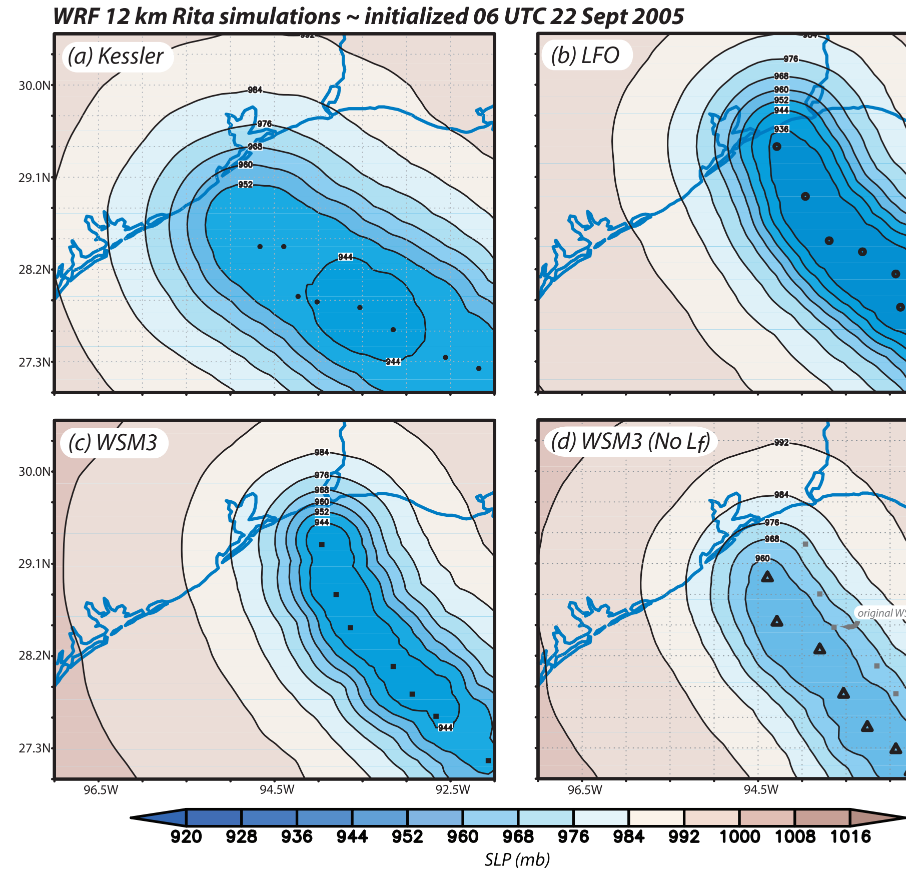

Figure 2. As in Figure 1, but for selected members of the 12 km ensemble. L_f represents latent heat of fusion. Only part of the domain is shown.

development and maintenance at that coarser grid spacing. The substantial influence regarding ice fall speed previously encountered (in the WSM3/BMJ experiment) was also diminished at higher resolution in the absence of a CP. Yet, other sensitivities were discovered. Figure 2d shows what transpired when the WSM3 scheme was modified to neglect the latent heat of fusion (L_f), the extra ∼10% heating that occurs when liquid water freezes. The resulting hurricane was wider, weaker and made landfall at Houston. The same alteration in the 30 km experiment had little effect on track, at least when a CP scheme was active.

2.4. Synthesis

[14] Considering the 30 and 12 km results jointly, we see that microphysical assumptions can exert a significant influence on hurricane track over relatively short (∼54 h) time scales. Microphysics may modulate storm motion by directly or indirectly influencing characteristics such as depth, radial structure and azimuthal asymmetry known to control vortex motion. Among these simulations, vortex depth appeared to vary little but width variations were particularly pronounced, as demonstrated again in Figure 3's vortex-following composites of 850 mb absolute vorticity for the 12 km ensemble's Kessler and WSM3 members. Among these storms, wider vortices tracked relatively more westward, consistent with *Xiao et al.*'s [2000] experience. This may partly reflect "beta drift" [e.g., *Holland*, 1983; *Chan and Williams*, 1987] that is sensitive to winds well beyond the eyewall [*Fiorino and Elsberry*, 1989a, 1989b].

[15] Persistent convective asymmetries can also influence vortex motion by inducing flow across the vortex towards the enhanced diabatic heating [*Willoughby*, 1992; *Wang and Holland*, 1996]. Superposed on Figure 3 is the asymmetric component of tropospheric average ascent, a good proxy for convective heating. The negative values (dashed contours) in this field represent relatively weaker rising motion. For both storms, a dipole pattern is revealed, but the WSM field is rotated clockwise relative to the Kessler pattern, possibly assisting the former's relatively more poleward motion. In any event, among these simulations anything that is done to narrow the vortex, whether it becomes more intense as a result or not, tends to permit the hurricane to propagate more northward. In the case of Rita, at least, that resulted in a more accurate landfall.

3. Idealized Experiments

[16] Hurricanes often move through complex and dynamic environments, complicating analysis of the microphysical impacts on simulated track and intensity. To isolate these influences, a modified real-data version of WRF version 2.2 was created which retains Earth's rotation and (optionally) curvature, but has no land, a uniform SST of 29°C and a calm, horizontally homogeneous base state built on *Jordan*'s [1958] hurricane season composite. Three telescoping domains were used, the outer being a 3240 km square with 27 km resolution and the innermost being 669 km on a side with 3 km grid spacing. The outer domain

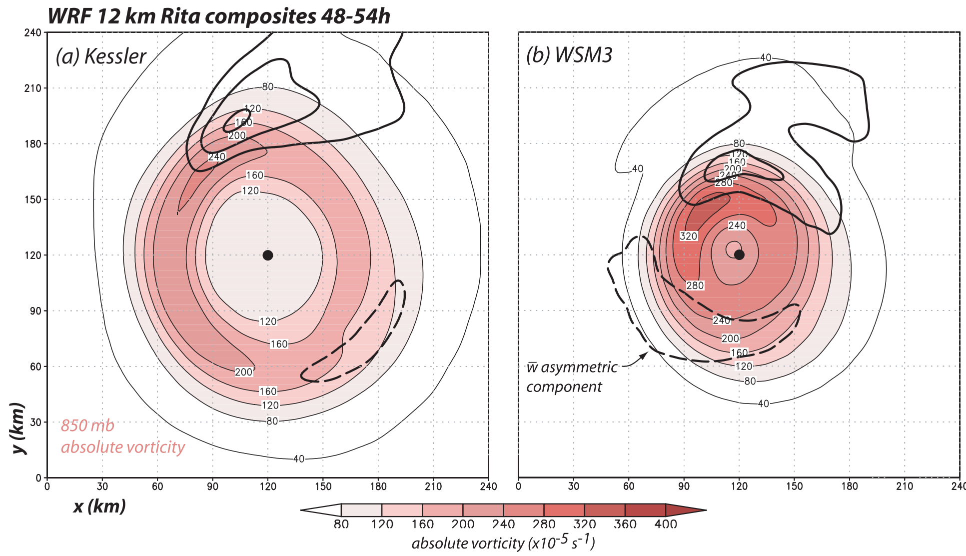

Figure 3. Vortex following composites for the 12 km Kessler and WSM3 members, constructed between forecast hours 48 and 54 h, inclusive. Colored field is 850 mb absolute vorticity (units 10^{-5} s^{-1}); contoured is the asymmetric component of tropospheric average ascent (0.1 m s^{-1} contours, negative values dashed). Black dot marks eye location.

is intended to capture the entire environmental response to the hurricane; its boundary conditions are fixed, and thus effectively closed.

[17] The real-data simulations commenced with a pre-existing vortex and no condensation. Idealized simulations often start off with an artificially imposed circulation. We elected to "breed" a vortex by placing a synoptic-scale warm and moist anomaly centered at 20°N and integrating for a spin-up period (τ_s) of 24 h with the Kain-Fritsch CP scheme active and microphysics switched off. During this period, a coherent and well-resolved cyclone formed, achieving a central SLP of 969 mb by 24 h. At that time, the CP scheme was switched off and one of three MP schemes (Kessler, LFO or WSM3) was activated in all domains.

[18] Figure 4 shows results from an experiment retaining Earth curvature (having variable Coriolis parameter f). Despite sharing a common startup, the storms quickly diverged with respect to track, propagation speed and intensity. Since there was no imposed large-scale flow, vortex motions represent self-propagation clearly modulated by microphysics. As in the real-data runs, the Kessler vortex tracked farthest west and the WSM3 storm moved most northward. A substantial propagation speed difference is also evident: at τ_s + 54 h, the Kessler vortex' forward motion was 9 km h^{-1} and increasing while the LFO and WSM3 storms were moving 43% and 52% slower, respectively. Figure 4a shows the storms at that time were roughly following the 850–200 mb layer average flow they were responsible for creating. When combined with track variations, position differences among the simulated storms eventually became extremely large. The rapid movement of the Kessler vortex relative to the ice MP storms is the most substantial difference with respect to the real-data Rita runs. Quantitatively similar direction and speed disparities were noted in a lower (12 km) resolution version of this experiment (not shown).

[19] Figure 4b shows radial profiles of the 10 m wind speed taken at τ_s + 54 h. With regard to intensity, the Kessler (LFO) vortex was weakest (strongest), consistent with the real-data runs. The LFO storm eventually spent over 2 days at or very near Category 5 strength, while the warm rain case fluctuated between Categories 2 and 3. As in the real-data experiment, vortex width rather than depth was

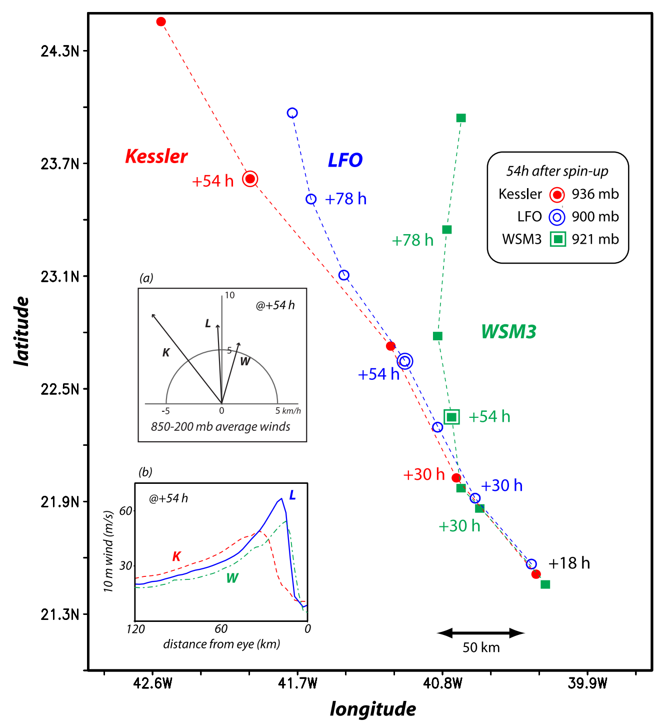

Figure 4. Twelve-hourly positions for the idealized experiments' Kessler (K), LFO (L), and WSM3 (W) storms, starting at τ_s + 18 h. (a) The 850–200 mb layer mean winds averaged in 500 km square storm-centered domains at τ_s + 54 h. Storm circulation is effectively removed. (b) The radial profiles of 10 m wind speed vs. distance from eye at that time.

the obvious discriminating characteristic; Figure 4b reveals the Kessler storm actually developed stronger flow at larger radius, which may explain why it tracked both more quickly and more westward [*Fiorino and Elsberry*, 1989a, 1989b]. In an *f*-plane version of this experiment (not shown), the Kessler vortex was again widest and weakest but, as expected, none of those model storms translated significant distances owing to the absence of beta gyres (and large-scale flow). The important point is that microphysical assumptions can clearly and substantially influence factors responsible for storm motion, especially in situations lacking strong large-scale forcing.

4. Summary and Conclusions

[20] Hurricane track and landfall forecasting is a complex scientific problem with significant societal import. Herein, it was demonstrated that variation of cloud microphysical processes, performed in the context of ensemble forecasting at operational resolutions, can yield an ensemble spread comparable to multi-model experiments, likely by directly and indirectly modulating vortex structure. Indeed, it is possible that the differences among various dynamical models could chiefly reside in their respective handling of microphysics, along with other processes related to convection. The uncovered sensitivities were found to vary somewhat with resolution, possibly owing to a subtle interplay among model physics, and are probably case-dependent. Still, microphysics appears to be one avenue to exciting the inherent propagation sensitivity of hurricane-like vortices and should be considered as a valuable part of physics-based ensemble forecasting.

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R. G. Fovell, Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, Los Angeles, CA 90095–1565, USA. (rfovell@ucla.edu)

H. Su, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA. (hui.su@jpl.nasa.edu)