Advanced Research WRF Developments for Hurricane Prediction

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1. Introduction

The present paper represents a proof-of-concept study on the skill of explicit forecasts of tropical cyclones. The term 'explicit' refers to a lack of (implicit) treatment of clouds and precipitation as provided by a cumulus parameterization. Recent papers have suggested that models with horizontal grid increments between 2 and 4 km may forego parameterized convection, and by treating precipitation processes explicitly, more realistically simulate organized convection (Fowle and Roebber 2003, Done et al. 2004). The Advanced Research WRF (ARW, Skamarock et al. 2005) was first developed to simulate continental, deep, moist convection using grid increments less than 10 km. Whether a model of this design can realistically and accurately predict hurricanes is an open question.

The merits of explicit simulation for hurricanes have been shown only for case studies (e.g. Liu et al. 1997, Braun et al. 2006), not for large samples of cases. By examining several tens of cases in a quasi-operational setting, we will demonstrate the clear potential of the ARW for predicting hurricane intensity and structure not previously demonstrated in a significant sample.

2. Model Setup and Methodology

The configurations of the real-time ARW model in 2004 and 2005 were similar, with grid spacing and physics options being constant. A nested configuration, featuring a 12-km outer domain with a nest on a 4-km mesh was integrated, as was a single-domain 12-km forecast. During 2004, the interactive nest was fixed in space and contained 450x500 points in the north-south and east-west directions respectively. The location of the 4-km domain was dependent on the initial and forecast location of the hurricane, chosen to contain the storm throughout the 48 h forecast period. In 2005, the nest was allowed to move following the geopotential height minimum at 500 hPa, thus allowing use of a smaller nested domain (308x316 points).

On the 12-km domain we used the Kain-Fritsch cumulus parameterization, but the inner domain had no parameterization. Both domains used the WSM3 microphysics scheme that predicted only one cloud variable (water for T > 0ºC and ice for T < 0ºC) and one hydrometeor variable, either rain water or snow (again thresholded on 0ºC). Both domains also used the Yonsei University (YSU) scheme for the planetary boundary layer (Noh et al. 2001). This is a first-order closure scheme that is similar in concept to the scheme of Hong and Pan (1996), but, in comparison tests, appears less biased toward excessive vertical mixing.

The forecasts were integrated beginning at 00 UTC during the time when a hurricane threatened landfall within either 48 h (2004) or 72 h (2005). During 2004, both domains were initialized directly from the National Centers for Environmental Prediction Global Forecast System (GFS) model with no additional data assimilation or balancing. In 2005, forecasts were initialized using the Geophysical Fluid Dynamics Laboratory (GFDL) model, with the GFS used when the GFDL was unavailable. Occasionally, forecasts were begun at 12 UTC in addition to the 00 UTC forecasts.

Several systematic errors in ARW were found during the initial integrations. The most severe of these was an under-estimate of the surface fluxes over water, effectively resulting in reduced drag and a larger radius of maximum wind because near-surface parcels were unable to flow across angular momentum surfaces. These have been corrected and a new version of the ARW tailored for hurricane prediction developed, herein termed the Advanced Hurricane WRF (AHW). AHW is distinct from the NCEP HWRF, based on the Nonhydrostatic Mesoscale Model (NMM) core (Janjic 2004) in the use of (a) an automated moving nest; (b) a mixed-layer ocean model; (c) surface heat exchange tuned for hurricane intensity and (d) an advanced data assimilation technique specific to hurricanes based on the Ensemble Kalman filter (EnKF).

3. Statistics for 2004 and 2005

Intensity is measured using the traditional metric of maximum sustained wind at 10 m MSL. Observations are based on a 1-minute average. The model output is instantaneous. However, Skamarock (2004) showed that the energy spectrum of the ARW decays around 7 Δx, (28 km for the 4-km grid). With a

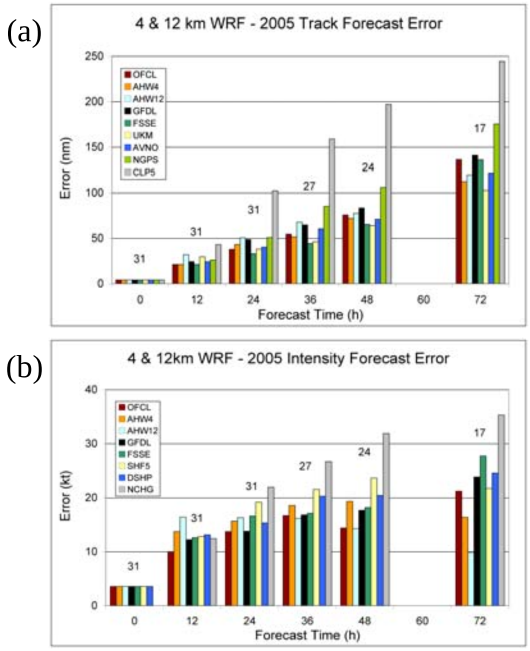

Figure 1. (a) Root-mean-squared track errors for 2005 forecasts (nautical miles), with sample size indicated above each color bar and (b) root-mean-square intensity errors (knots), formatted as in (a).

velocity of 50 m s^{-1}, this length scale corresponds to a time scale of about 10 minutes. Thus, the instantaneous motions in the model are actually representative of time scales longer than the reference 1-minute averaging period assumed for maximum wind estimates. This can also be viewed from the time step of the model, 24 s, and noting that only oscillations with periods of several minutes or more will be well resolved.

Intensity and track forecasts from the ARW are compared with the official forecast of maximum intensity from the National Hurricane Center (NHC). In addition, several other models, initialized and verified at the same times as AHW were verified the same way. Figure 1 presents the results for track and intensity. Overall, the AHW was inferior to the other models at 12 h. By 36 h, there was little discernable skill difference between either the 4-km or 12-km AHW and other models. By 72 h, both 4-km and 12-km AHW were better than even the official forecast. Notably, the 12-km forecast was at no time significantly worse than the 4-km forecast.

4. Structure

The resolution dependence of various structural features in simulations of mature hurricanes are next investigated using a case study of Hurricane Katrina with an additional inner nest of 1.33-km spacing. Recent results (Chen et al. 2006) have

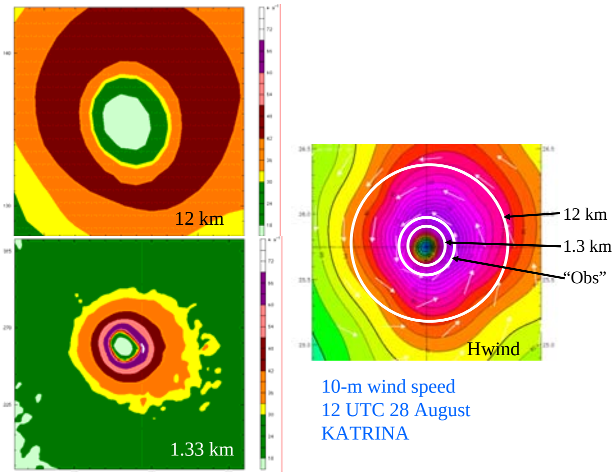

Figure 2. (a) 10-m wind speed (m/s) from 36 h Katrina forecast on the 12-km grid, valid 12 UTC 28 August; (b) as in (a) but from the forecast on the 1.33 km grid; (c) HWind product valid 12 UTC 28 August. White circles in (c) represent radii of maximum winds estimated from (a), (b) and (c). Orange shading represents category 1 intensity.

suggested that proper treatment of the inner core requires a grid spacing less than about 2 km. The 12-km, 4-km and 1.33-km forecasts were all rerun after the hurricane season, using an updated AHW.

Initialization of the more recent simulations was at 00 UTC 27 August using the GFDL initial conditions (the GFDL was not available in real time). The 1.33-km simulation was initialzed identically to the 4-km simulation. As shown in Fig. 2, the circulation (area integral of vorticity) is greatly exaggerated in the 12-km forecast of Katrina (and other storms). In this particular example, the radius of maximum wind in the 12-km forecast is nearly 4 times its value in the 1.33 km forecast, and 3 times that observed. The finest-resolution forecast actually produces an eye that is slightly too small, and contracts the hurricane-force winds too much. This indicates that prediction of the size of a hurricane circulation, while of paramount importance to applications such as storm surge modeling, is a difficult undertaking, and one that is apparently highly sensitive to model resolution.

5. Initialization

As is clear from the statistical results (Sec. 2) initializaton of the hurricane vortex remains a serious issue for obtaining accurate short-range forecasts. It is crucial to have initial condtions with vortex in the correct location and with the correct structure.

There are some key challenges for data assimilation in hurricanes. Observations of vortex structure are limited and do not define vortex structure completely. The background forecast may have the vortex in the wrong location. Unless the vortex is “shifted”, either through bogussing or relocation methods, observations may have unintended effects.

At present, we are exploring various data-assimilation strategies to address initialization of vortex. Presently both 3DVar (Barker et al. 2004) and EnKF are available for WRF and for routine

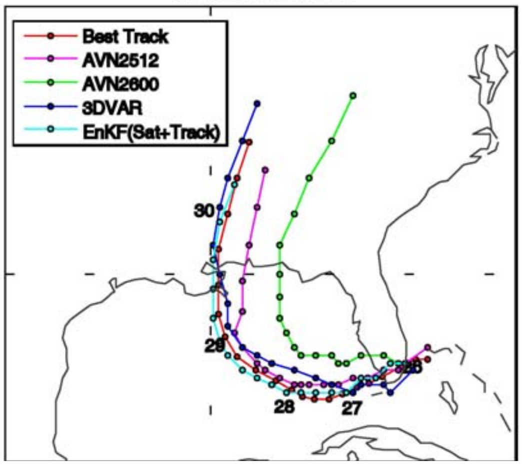

Figure 3. Tracks from data assimilation experiments for Katrina, initialized 00 UTC 26 August, compared with WRF initialized with GFS beginning at 12 UTC 25 August and 00 UTC 26 August. Positions are marked every 6 h.

application to hurricanes. 4DVar is under development.

A novel feature of the EnKF is its ability to assimilate frequent observations of the vortex position, such as can be obtained from geostationary satellite imagery (Chen and Snyder 2006). Figure 3 shows 5-day 36-km simulations of Katrina's track using initial conditions at 00 UTC 26 August 2006 from three sources: the operational GFS analysis, the WRF/3DVar analysis just using the GFS analysis as background, and the WRF/EnKF analysis. The 3DVar analysis is based on conventional radiosondes and surface observations. It also employs a vortex bogussing procedure in which bogus vortex observations are constructed based on the hurricane position, central sea-level pressure and maximum wind and assimilated along with the real observations (Xiao et al. 2006). The EnKF analysis is based on a WRF hourly forecast-analysis cycle over the period 12 UTC 25 July to 00 UTC 26 July. It uses 26 ensemble members and assimilates the vortex position and minimum sea-level pressure from the NHC best-track estimates together with thinned satellite winds.

Although we by no means consider these results to be conclusive, both the 3DVar and EnKF analyses yield noticeably better track simulations than that from the operational analysis. Intensity, as measured by either minimum sea-level pressure or maximum wind, is systematically underestimated in all three simulations (not shown), as expected given the coarse 36-km resolution. It is also clear that the track is very sensitive to initial conditions---a 5-day simulation beginning from the GFS analysis 12 h eariler, at 12 UTC 25 July, also shows a markedly better track than that based on the operational analysis of 00 UTC 26 July.

6. Ocean Coupling

To forecast the ocean temperature in the ARW hurricane forecasts we have implemented a simple mixed-layer model applied in isolated columns at every grid point. The mixed-layer model is essentially that of Pollard, Rhines and Thompson (1973), except that our implementation allows for nonzero initial mixed-layer depth. The model is based on the assumption of no heat transfer to the individual columns so that temperature changes within a column can occur only through vertical redistribution. The wind field of the hurricane applies a stress at the top of an assumed turbulent mixed layer. This layer deepens it and cools through entrainment of colder water from below. Pressure gradients and advection are neglected, but the Coriolis effect is included. Except for the inclusion of the Coriolis effect, the mixed-layer model is identical to that used by Emanuel et al. (2004) to study the oceanic feedback on an axisymmetric hurricane vortex. As an example of the model's performance we show in Fig. 4 a side-by-side comparison of it with published results (Price 1981) in which a prescribed vortex translates over a full ocean model.

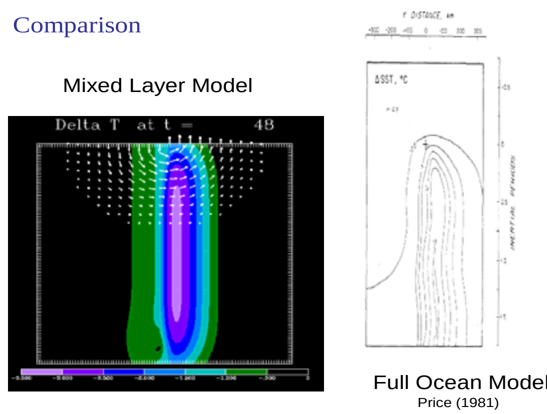

Figure 4. Change in ocean mixed-layer temperature produced by a prescribed vortex translating towards the north at 8.5 m/s over ocean with initial mixed-layer depth of 30m with mixed-layer model on the left and the full ocean model on the right. Both produce a maximum temperature change of approximately 3.1C.

To implement this model with the atmospheric model requires only an initial value of the ocean mixed-layer depth. The initial mixed-layer temperature is taken to be the sea-surface temperature, and the initial current is taken to be zero with the assumption that hurricane-induced currents are much greater than pre-existing ones. There is a prescribed temperature lapse rate of 5 K per 100 meters below the mixed layer, and the temperature dependence of the thermal expansion coefficient is accounted for. The dynamic forcing for the mixed-layer model is the friction velocity from the atmospheric surface layer physics. There is also thermal forcing from the sensible and latent heat fluxes and net surface longwave and shortwave radiative fluxes, but this heating of the ocean mixed layer is generally of secondary importance compared to the ocean thermal mixing. The ocean mixed-layer model is called at every atmospheric model water point at every model time-step, and uses the same time-step. Its updated sea-surface temperature is fed back to the atmospheric surface conditions.

7. Summary

In this article, we have examined the performance of the ARW as applied to forecasts of numerous landfalling Atlantic tropical cyclones in 2004 and 2005. Results point to significant improvements over operational models at time ranges of 48 to 72 hours (and beyond) for both track and intensity prediction. While the ARW forecasts with a 12-km grid performed as well as those using a 4-km grid for track and maximum wind parameters, the vortex structure on the 12-km grid was far too large and rainbands either absent or unrealistic. The 4-km grid produced rainbands with surprisingly good correspondence to observations. The addition of yet another nest of 1.33 km was able to more rapidly intensify hurricane Katrina, as observed, and produced rainbands with realistic structure. However, mesovortices in the eye wall achieved an amplitude too large compared with observations of eye wall reflectivity asymmetries.

Some systematic deficiencies of the ARW were noted, and these are being addressed in a new version of the model, termed the Advanced Hurricane WRF (AHW). This model includes a moving nest with grid spacing below 2 km, improved surface energy flux formulation, coupling to a simple mixed-layer ocean model, and advanced data assimilation in the form of both an ensemble Kalman filter and 3DVAR with a vortex relocation procedure. We anticipate running the AHW for Atlantic hurricanes threatening landfall during the 2006 season and will report on the results of this activity at the next WRF workshop.

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