18A.2

PREDICTION OF ATLANTIC TROPICAL CYCLONES WITH THE ADVANCED HURRICANE WRF (AHW) MODEL

Jimy Dudhia*, James Done, Wei Wang, Yongsheng Chen, Qingnong Xiao, Christopher Davis, Greg Holland, Richard Rotunno, and Ryan Torn

National Center for Atmospheric Research
Boulder, Colorado

1. INTRODUCTION

*The Advanced Hurricane WRF (AHW) is a relatively new derivative of the Advanced Research WRF (ARW) model that was initially developed from the community release of the WRF model after the 2005 season (Davis et al. 2008). The use of a moving, 2-way nested grid system allows local resolution of roughly 1 km, making it ideal for the prediction of the multiple length scales present in hurricanes ranging from the scale of outflow (1000 km or more) to the sharp gradients inside the eye wall (5-10 km). During the past four Atlantic hurricane seasons, the nested model was run in real time and in retrospective mode to produce forecasts of hurricane track, intensity and structure out to several days lead time. During the 2004 and 2005 hurricane seasons, the model performed comparably to operational models using an innermost nest of 4 km grid spacing, with evidence of improved intensity forecasts beyond 1.5 days during the 2005 season as shown by Davis et al.. During 2006, a second nest of 1.33 km grid spacing was added to resolve the eye wall of storms. In 2007, a mixed-layer ocean model was added to provide a feedback of mixing-induced sea-surface cooling to the atmosphere and forecasts were extended to five days.

The 2007 season featured 15 named storms, including five hurricanes, of which two (Dean and Felix) made landfall in the Caribbean as category 5 storms. None of the other hurricanes exceeded category 1, but all made landfall in the Gulf or Caribbean.

* *Corresponding author address:* Jimy Dudhia, MMM Division, NCAR, P.O. Box 3000, Boulder, CO 80307-3000; e-mail: dudhia@ucar.edu

Figure 1 shows an example of the reflectivity field from a forecast of Hurricane Dean as it approached landfall on the Yucatan Peninsula, both on the 4 km domain, and on the 1.33 km nest. Both these domains track the hurricane using a vortex-following algorithm.

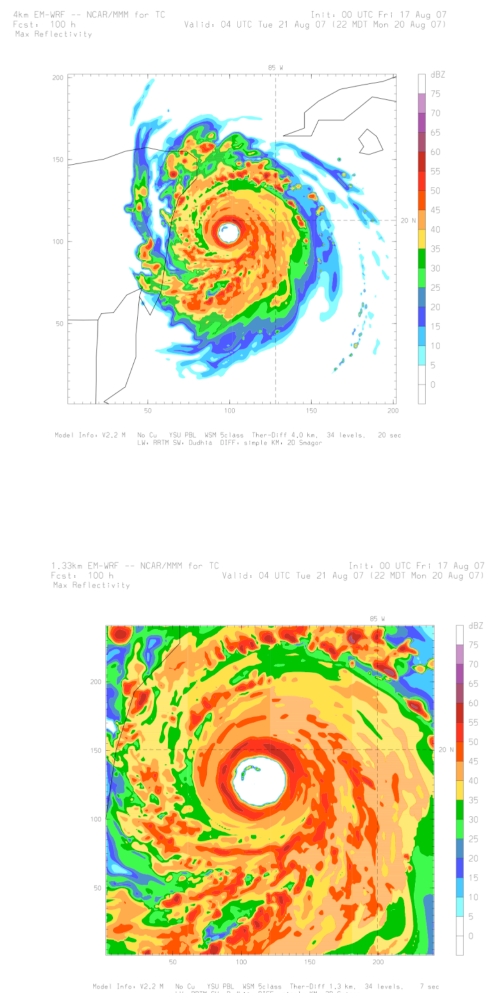

Figure 1. Reflectivity forecast at 100 hours (04 Z 21 August 2007) from the AHW 4 km domain (top), and 1.33 km domain (bottom).

The AHW forecasts were verified against the official track and intensity. The focus of this paper will be on the prediction of the intensity for Dean, Felix, Karen, Noel and other storms from the 2007 hurricane season. The sensitivity of maximum wind forecasts will be investigated for changes in air-sea exchange coefficients and upper-ocean feedback.

2. 2007 MODEL CHANGES

In 2007, a simple one-dimensional ocean mixed-layer model was added. The formulations of the surface drag coefficient and enthalpy exchange coefficient were modified from 2006. The latter was modified again after Hurricane Dean 2007 because, as will be shown, this significantly improved the intensity forecast for Hurricane Dean.

2.1 Ocean Mixed-Layer Model

The ocean mixed-layer model is based on that of Pollard, Rhines and Thompson (1973). Each column is independently coupled to the local atmospheric column, so the model is one-dimensional. The ocean part consists of a time-varying layer, representing the variable-depth mixed layer over a fixed layer acting as a reservoir of cooler water with a specified thermal lapse rate. In the mixed layer, the prognostic variables are its depth, vector horizontal current, and mean temperature taken to be the sea-surface temperature (SST). The hurricane winds drive the current, which in turn leads to mixing at the base of the mixed layer when the Richardson number becomes low enough. This mixing deepens and cools the mixed layer, and hence the cooler sea-surface temperature impacts the heat and moisture fluxes at the surface, and has a negative feedback on hurricane intensity. The model includes Coriolis effects on the current, which are important in determining the location of maximum cooling on the right side of the hurricane track. It also includes a mixed-layer heat budget, but the surface fluxes and radiation have much less impact than the hurricane-induced deep mixing on the thermal balance at the time scales considered during a forecast. The ocean mixed-layer model is initialized using the observed SST for the mixed layer, and with a depth representative of known conditions in the hurricane's vicinity. The initial current is set to zero, which is a reasonable assumption given that the hurricane-induced current is larger than pre-existing ones.

2.2 Surface Exchange Coefficients

The non-dimensional drag coefficient, C_d, and enthalpy exchange coefficient, C_k, are known to be factors to which hurricane development is sensitive, and, in particular their ratio C_k/C_d is a determining factor in a hurricane's maximum intensity (Emanuel 1995). However, due to a lack of observations in the hurricane boundary layer, and the growth of complexity of the air-sea interface as hurricane-force winds increase, there is little guidance as to how these coefficients behave near the centers of the most intense hurricanes where they are important in determining the intensity. For C_d, the traditional approaches use formulations in which the roughness length, z_{0m}, increases with wind speed to simply represent wave height effects, but more recently studies such as that of Donelan et al. (2004) indicate that the roughness reaches an upper limit near hurricane-force and either remains flat or reduces beyond that.

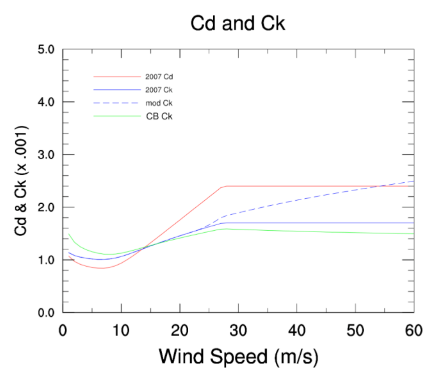

Figure 2. Exchange coefficients as a function of wind speed. Cd formulation used in 2007 (red), Carlson-Boland Ck (green), constant z_{0q} Ck (blue solid), and ramped Ck (blue dashed).

In AHW, we follow this guidance in setting an upper limit for the momentum roughness length, which results in C_d also flattening with high wind speeds in neutral conditions (Figure 2). C_k on the other hand has been parameterized by a wide range of methods, either directly as a constant based on observations such as Large and Pond (1982), or through a separate thermal roughness length, z_{0q}, which is constant or more slowly varying than the momentum roughness length leading to a C_k that increases more slowly than C_d with wind speed, or through an assumption that $C_k = C_d$.

In 2007, we initially followed the approach described by Davis et al. (2008), of separately defining a thermal roughness length based on the Carlson-Boland formulation that increases slowly with wind speed. The effect of using a slowly varying or constant z_{0q} with a z_{0m} that is capped is that C_k increases with wind speed, but is also capped at the same speed as C_d, though with typically a lower value leading to a ratio C_k/C_d less than one. However, after verifying the intensity forecasts of category 5 hurricanes, Dean and Felix, our formulation was retrospectively changed as shown in Figure 2. Several new formulations for z_{0q} were investigated, but a successful one, as will be shown in the next section, was one in which z_{0q} was constant with a value typical in other models (10^{-4} m) below 25 m/s (where the friction velocity u^*=~1m/s), but then ramps up with the following function for u* > 1 m/s;

$$z_{0q} = 10^{-4} + 10^{-3}(u^*-1)^2 \quad \text{(meters)}$$

This so-called ramped C_k approach was then used for the 2007 season. While this approach is model-based rather than theoretical or observation-based, there is a justification for such a ramping effect in the enthalpy roughness length. It is beginning to be recognized that sea-spray effects, that may begin to become noticeable in weaker hurricane-force winds, would influence the exchange coefficients (e.g. Andreas and Emanuel 2001, Emanuel 2003). Here we just consider an effect whereby the enthalpy flux exchange coefficient is enhanced possibly due to the increased eddy length scales present in a sea spray layer compared to those over a sharp water boundary. A simple quadratic functional form was chosen to provide a smooth transition in z_{0q}, and the gradient constant is such that C_k ramps almost linearly with wind exceeding the value of C_d beyond about 50 m/s (category 2-3 storms). Hence the ratio C_k/C_d exceeds one by greater amounts as the wind speeds increase much above 50 m/s. As expected, this has the effect of significantly intensifying category 5 storms where wind speeds may exceed 70 m/s.

3. RESULTS

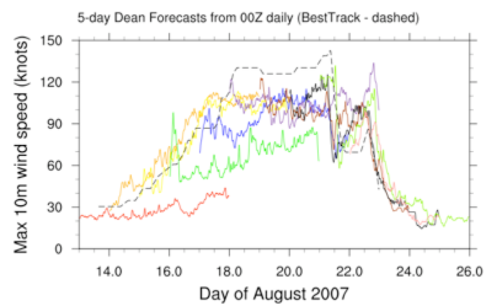

Figure 3. Successive forecasts of 10 m wind speed (colors) and estimated actual value (black dashed) for Hurricane Dean before changing Ck.

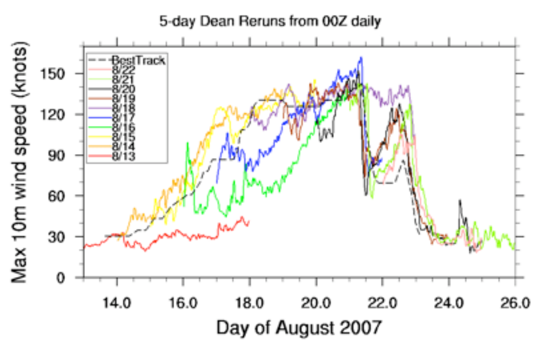

Figure 4. As Figure 3, but after changing Ck.

In the 2007 season, AHW initially used the ocean mixed-layer model and surface exchange coefficients with a slowly varying value of z_{0q} based on the Carlson-Boland formulation. The results for successive forecasts of Hurricane Dean in the Caribbean Sea in August 2007 are shown in Figure 3, where the maximum surface wind speed is shown for these forecasts (colored lines) against the observed estimated maximum (dashed black line). The problem is seen clearly here and also in the minimum central pressure (not shown) that all the forecasts were consistently underestimating the storm intensity despite mostly having very good tracks as indicated by their landfall timing when the wind maximum drops sharply on August 21st. (Also the reintensification over the Gulf of Mexico after crossing the Yucatan Peninsula and second landfall in Mexico can be seen.)

In this region, the ocean mixed layer is very deep, and there is little evidence of cooling in the wake of the storm when the ocean-mixed layer model uses a realistic initial depth, so the under-prediction was not related to the SST feedback. This led us to the change in z_{0q} described in section 2.2, leading to a ramped C_k relation with wind speed at high winds. As can be seen in Figure 4, this alleviated the under-prediction problem in all the rerun forecasts for Dean with similarly improved results for the central pressure, while the track remained good. Later in the season, forecasts of Felix with this new formulation were similarly successful.

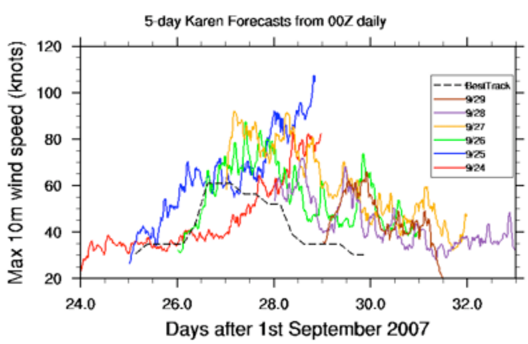

Figure 5. As Figure 4, but for Tropical Storm Karen.

While AHW now seems very capable of simulating intense hurricanes realistically, there remain systematic problems with weak hurricanes and tropical cyclones. As can be seen in Figure 5, the forecasts consistently over-intensify weaker systems such as Tropical Storm Karen producing a category 1 hurricane in this case. This is a problem whether using the newer or older C_k formulation, and it possibly points to issues with low-wind fluxes in the model, but this bias needs further investigation.

4. CONCLUSION

This paper represents a small part of a much larger AHW effort by the co-authors. The research in AHW extends to the areas of providing a well balanced vortex initialization, providing better initial states through data assimilation, ensemble approaches, and cycling, and improving the ocean mixed layer initialization, as well as continuous investigation of the effects of other physics parameterizations including the planetary boundary layer and microphysics schemes. Done et al. (2007) is a companion paper on some other aspects related to this set of forecasts for 2007.

5. ACKNOWLEDGMENTS

The significant computational scale of these simulations, and the capability of running high-resolution hurricane forecasts in real time, were made possible with the help of CISL staff and NCAR computing resources provided by the National Science Foundation.

6. REFERENCES

Andreas, E. L., and K. A. Emanuel, 2001: Effects of sea spray on tropical cyclone intensity. *J. Atmos. Sci.,* **58,** 3741-3751.

Davis, C. A., Wang, W., Chen, S., Chen, Y., Corbosiero, K., DeMaria, M., Dudhia, J., Holland, G., Klemp, J., Michalakes, J., Reeves, H., Rotunno, R., Xiao, Q., 2008: Prediction of landfalling hurricanes with the advanced hurricane WRF model. *Mon. Wea. Rev.* (In Press).

Done, J. M., and coauthors, 2007: Evaluation of real-time hurricane forecasts using the Advanced Hurricane WRF Model. *Eos Trans. AGU,* 88(52), Fall Meet Suppl., Abstract A21C-0643.

Donelan, M. A., B. K. Haus, N. Reul, W. J. Plant, M. Stiassnie, H. C. Graber, O. B. Brown, and E. S. Saltzman, 2004: On the limiting aerodynamic roughness of the ocean in very strong winds. *Geophys. Res. Lett.,* **31,** L18306.

Emanuel, K. A., 1995: Sensitivity of tropical cyclones to surface exchange coefficients and a revised steady-state model incorporating eye dynamics. *J. Atmos. Sci.,* **60,** 3969-3976.

Emanuel, K. A., 2003: A similarity hypothesis for air-sea exchange at extreme wind speeds. *J. Atmos. Sci.,* **60,** 1420-1428.

Large W. G., and S. Pond, 1982: Sensible and latent heat flux measurements over the ocean. *J. Phys. Oceanogr.,* **12,** 464–482.

Pollard, R. T., P. B. Rhines and R. O. R. Y. Thompson, 1973, The deepening of the wind-mixed layer. *Geophys. Fluid Dyn.,* **3,** 381-404.