13C.4 A PRELIMINARY STUDY OF HURRICANE WIND STRUCTURE EVOLUTION USING HWRF

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1. INTRODUCTION

Tropical cyclone (TC) wind structure evolution is currently neither well understood nor well forecasted. TCs with similar intensity can have greatly different radius of maximum wind, radius of hurricane-force winds, and inner-core kinetic energy (for example, as measured by 0-200 km area integrated kinetic energy from aircraft flight level data). The structural variability is influenced by various mechanisms both within the storm and its surrounding environment. These variations can have substantial repercussions with respect to storm impact. Therefore, it is important to correctly model the wind structure evolution as well as the mechanism influencing these changes.

A comparison of the inner-core kinetic energy (KE) versus intensity (maximum wind) for the HWRF (Hurricane Weather Research and Forecast model) forecasts to that from the aircraft analyses for six storms (Charley, Emily, Ivan, Katrina, Rita, and Wilma) will serve as a first look at assessing the accuracy of the HWRF model. This work may lead not only to improvements to the HWRF model, but also to a better understanding of the important factors contributing to TC wind structure evolution.

2. DATA

A. Storms

Hurricanes Charley ‘04, Emily ‘05, Ivan ’04, Katrina ‘05, Rita ‘05 and Wilma ‘05 were selected for this study because they represent storms of varying structural evolution and intensity. In addition, each of these storms has a reasonably large amount of aircraft reconnaissance data making them desirable candidates for studying the accuracy of the available HWRF model forecasts.

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B. Aircraft Reconnaissance Data

For this study the objectively analyzed aircraft reconnaissance flight-level data is used to calculate KE, as described in Maclay et al (2008). The aircraft reconnaissance reanalysis data is used as the ground truth against which the HWRF forecasts are compared. In this way an estimation of the accuracy of the model’s handling of storm structural evolution is determined.

The 0-200 km wind-fields of the storms on a cylindrical grid (Δr = 4 km, $\Delta\theta$ = 22.5º) are determined from an objective analysis of the aircraft reconnaissance data as described by Mueller et al (2006). The 0-200 km radial domain is chosen to match the standard length of the flight legs for the aircraft reconnaissance flights. In order to best capture the time evolution of the KE, the objective analysis was run using data composited over 6-hr intervals instead of the 12-hr intervals used by Mueller et al. Examples of the measured flight-level winds and a corresponding analyzed wind-field from Hurricane Wilma 2005 are shown in Fig. 1.

C. NCEP’s Hurricane Weather Research and Forecast (HWRF) Model Data

The NCEP Hurricane Weather Research and Forecast (HWRF) 2007 model uses a movable, 2-way nested grid. The inner grid has 9-km grid spacing and the outer has 27-km grid spacing. It uses advanced physics schemes from the GFS (Global Forecast System) and GFDL (Geophysical Fluid Dynamics Laboratory), and advanced vortex initialization which uses a prototype GSI (Gridpoint Statistical Interpolation). For the ocean coupling it uses the Princeton Ocean Model (POM) with the loop current initialized in the same manner as with the GFDL model. HWRF became operational in 2007, but retrospective runs from the 2004 and 2005 seasons are also available, which are used in this study. (Surgi, 2008)

For the calculations used here (winds within 200-km of the center of the storm), only data from the inner grid is needed. The HWRF output files include information on variables such as the winds, relative humidity, pressure, geopotential height, temperature, and convective heating in 50 hPa pressure increments from the surface up to 50 hPa. The zonal (*u*) and meridional (*v*) winds at the 700 hPa level are used to calculate the KE for all of the forecasts for each of the six storms. The 700 hPa pressure level is chosen because it is the standard flight level for the reconnaissance flights. Each forecast goes out to 126 hours at 6 hour increments, and for each forecast time of each forecast for each storm the total inner-core kinetic energy is calculated.

3. INNER-CORE KINETIC ENERGY (KE)

The low-level inner-core kinetic energy (KE) of a storm has been shown by Maclay et al (2008) to be a useful measure of storm size. Furthermore, changes in the KE provide information about the structural changes occurring within the storm. To estimate KE from a single level some assumptions are necessary. First, consider the storm to be a thin disk within a constant radius and depth interval (Fig. 2). For the aircraft reconnaissance data the total KE is calculated by integrating the kinetic energy for a single air parcel over the volume of the disk:

$$KE = \int_{z_1}^{z_2}\int_0^{2\pi}\int_0^R \frac{1}{2}\rho(U^2+V^2)rdrd\theta dz \,, \qquad (1)$$

where *U* is radial wind, *V* is tangential wind, *ρ* is air density, *r* is radius, *θ* is azimuth, and *z* is height. The flight-level winds are assumed to be representative of the storm structure over a 1 km depth and are usually available out to a 200 km radial distance from storm-center. The variation in the air density, *ρ*, is assumed to be small, thus a constant of 0.9 kg/m^3 (a typical air density at 700 hPa) is used.

The HWRF model data is in Cartesian rather than cylindrical coordinates. Therefore, an equation analogous to Eqn. 1 must be used to calculate the model KE. The integration is done over the area, *A*, containing all grid points within 200 km of the modeled center of the storm at the 700 hPa height:

$$KE = \int_{z_1}^{z_2}\int \frac{1}{2}\rho(u^2+v^2)dAdz \,, \qquad (2)$$

where, in this case, *u* and *v* represent the zonal and meridional winds, respectively. By integrating over all the grid boxes within 200 km from the storm-center, the area, *A*, ends up being nearly cylindrical in shape and nearly equivalent to the area used in the aircraft reconnaissance data.

4. HWRF KE VERSUS ACTUAL KE

Once the total KEs for each of the storm forecasts has been calculated, they can then be compared to the aircraft reconnaissance derived KE values to determine the accuracy of the model forecasts. The accuracy of the model from initialization through the five days (126 hours) of the forecast can be shown by comparing all of the initial times against the corresponding reconnaissance KE data, then 24 hours into each forecast against the matching aircraft KE data, and so on for the 48, 72, 96, and 120 hour forecast times. Figs 3-8 show plots of the 00, 24, 48, 72, 96, and 120 hour forecast KE values versus the corresponding aircraft reconnaissance derived KEs. The axes on these plots have been scaled to represent equivalent magnitudes, thus if the model forecasts were “perfectly” accurate then all of the data points would lie along the diagonal dashed line (y = x). Each of the six storms is represented by a separate color, so that the data points corresponding to each storm can easily be identified. Points to the right of the dashed line indicate that the model is overestimating the storm’s inner-core KE, and those to the left of the dashed line indicate an underestimation of the KE.

These plots show that for the 00 through 72 hour forecast times the HWRF model tends to overestimate the KE, since the majority of the data points are clearly to the right of the dashed line. For the 96 and 120 hour forecast times the bias is not as apparent. A simple way to see how the KE data compares as a mean throughout the forecast period is to consider the mean error (HWRF KE minus the aircraft reconnaissance KE). The mean absolute value of the error is plotted in Fig. 9 along with the bias. The mean actual KE for the storms from the aircraft data is also shown on this plot for reference. Rather surprisingly, the greatest error in the model occurs at the initialization (00 hr). The error then decreases slightly, but remains fairly steady and then decreases slightly more after 72 hrs. This decrease indicates that the model may corrects itself slightly with respect to the KE. The bias curve in Fig. 9 shows that the HWRF forecasts for these six storms generally overestimate the KE for the majority of the forecast. It is not until the 120 hour forecast time that the model has a mean error that is negative, signifying an underestimation of the KE.

The R-squared correlations between the HWRF and the reconnaissance KE are not very high (less than 0.7) for any of these data plots due to the high amount of scatter (Fig. 10). However, they do show that the best correlations occur early in the forecast times and degrade towards the later times as the model data becomes more scattered. Note that the R-squared correlation provides a measure of the strength of the trend within the data and is not affected by the bias. This suggests that at the start the error is mostly a problem of the model initializations of the storm structure. However, as the forecast runs the error remains large, but the R-squared values decrease rapidly indicating a decline in the correlation between the model and the actual data. With the poor correlations in the later forecast times, it is clear that the model is not developing the storm structure properly and a bias correction at this point would not be beneficial.

5. CONCLUSIONS AND FUTURE WORK

The findings presented here make a strong argument for a reassessment of the HWRF model's initialization of the storm structure. The fact that the KE is so greatly different from the actual KE from the aircraft data indicates that the details of the storm structure in the inner-core area are not being well represented. While the model is limited by its 9 km resolution, improvements still could be made. With an improved structural initialization, the task of assessing the model structural forecast will be more feasible, and the model may have a better chance to more accurately evolve the structure of storms through the forecast period. A hurricane is a complex system, so improvements made to the modeling of one portion of the storm evolution will likely also improve other components such as intensity and track forecasting. All of which are of great importance and interest for those living in tropical cyclone prone areas of the world.

The next step in this study is to derive the energy budget equations for the hurricane inner-core volume. These equations will describe the flux of kinetic and available potential energies in both mean and eddy forms into and out of the inner-core volume, as well as the energy conversions contributions to the energy budget. This analysis will provide greater insight into TC structural evolution.

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FIGURES

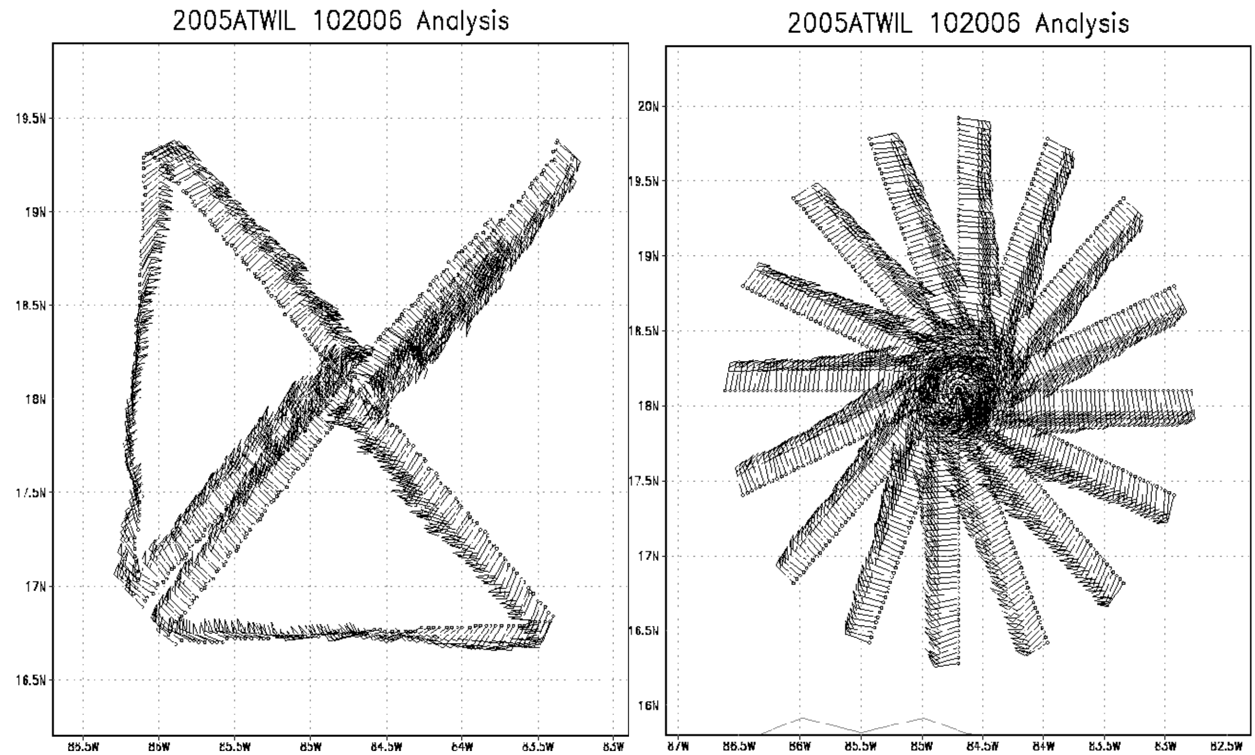

Figure 1: A sample of the aircraft reconnaissance flight-level data for Hurricane Wilma is shown on the *left*, and a corresponding reanalysis of the reconnaissance data in a cylindrical coordinate system is shown on the *right*.

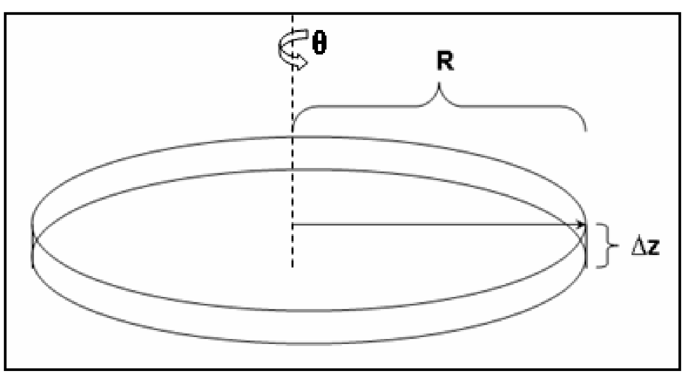

Figure 2: The tropical cyclone inner-core volume

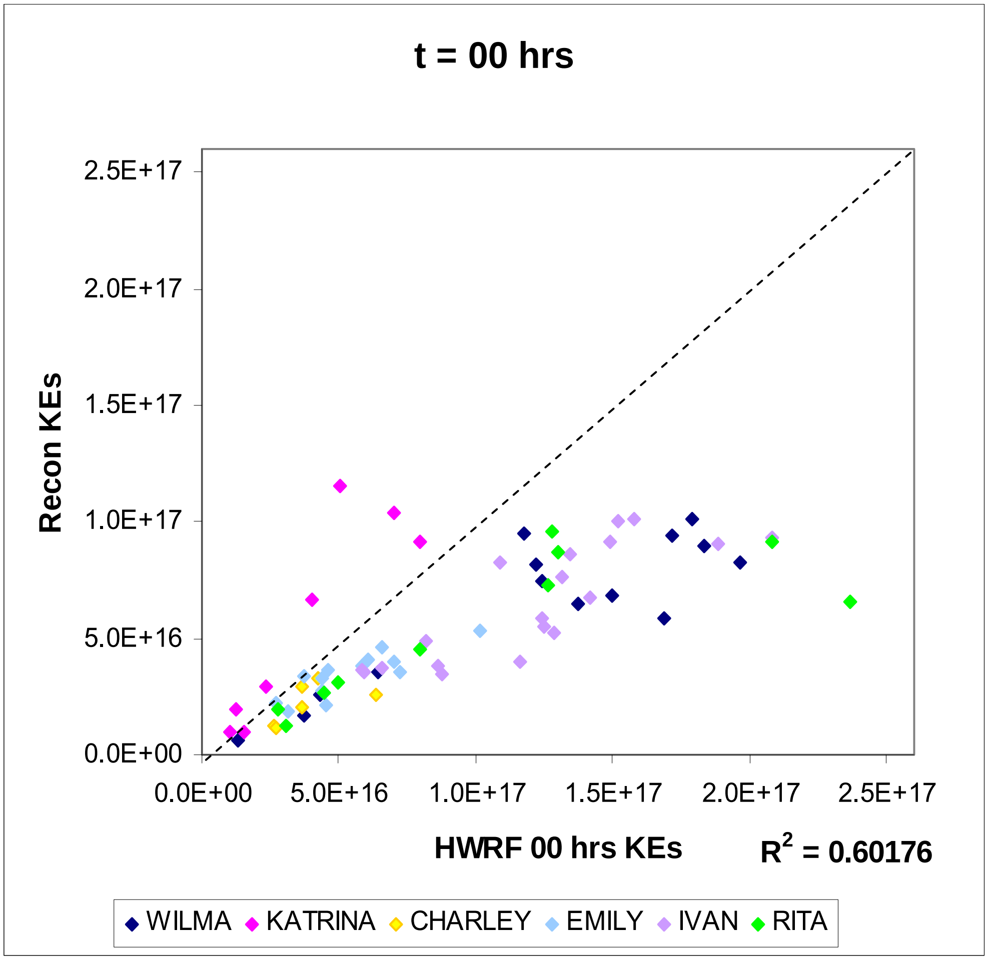

Figure 3: HWRF model 00-hour versus aircraft reconnaissance derived low-level inner-core kinetic energies for Hurricane's Wilma '05, Katrina '05, Charley '04, Emily '05, Ivan '04, and Rita '05.

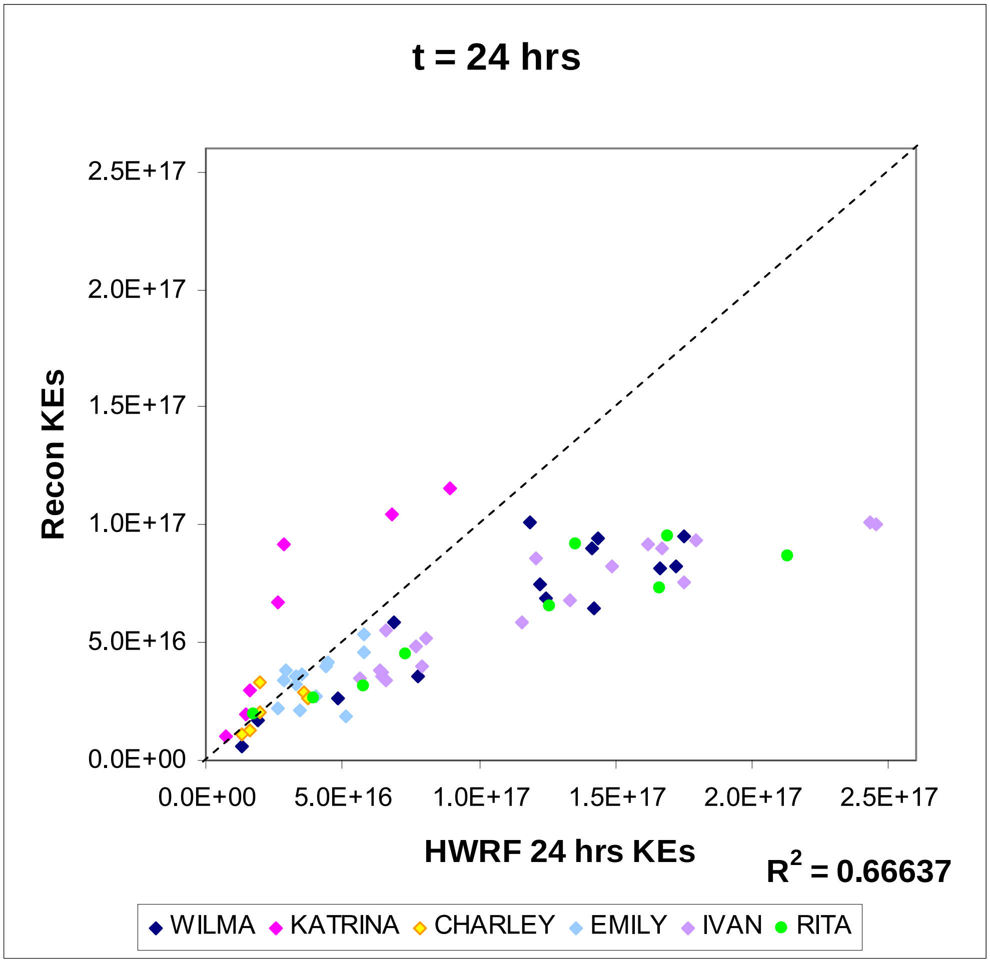

Figure 4: HWRF model 24-hour versus aircraft reconnaissance derived low-level inner-core kinetic energies for Hurricane's Wilma '05, Katrina '05, Charley '04, Emily '05, Ivan '04, and Rita '05.

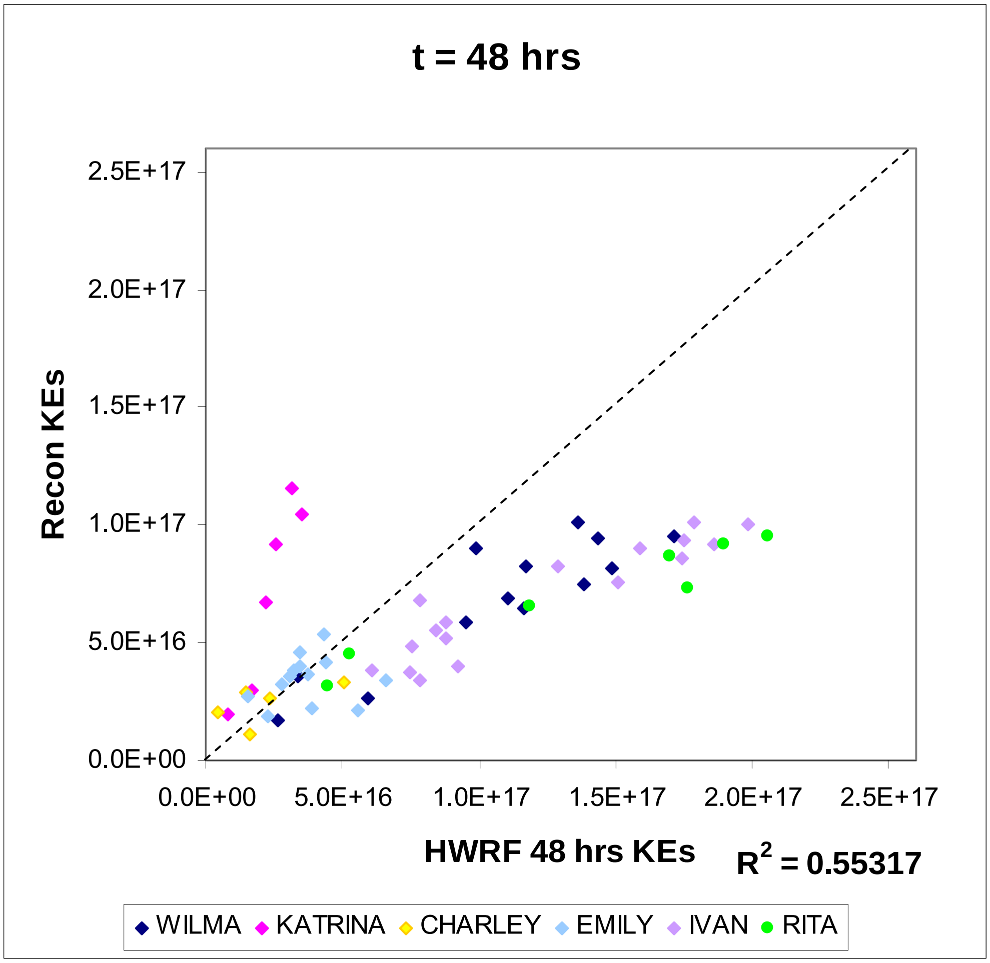

Figure 5: HWRF model 48-hour versus aircraft reconnaissance derived low-level inner-core kinetic energies for Hurricane's Wilma '05, Katrina '05, Charley '04, Emily '05, Ivan '04, and Rita '05.

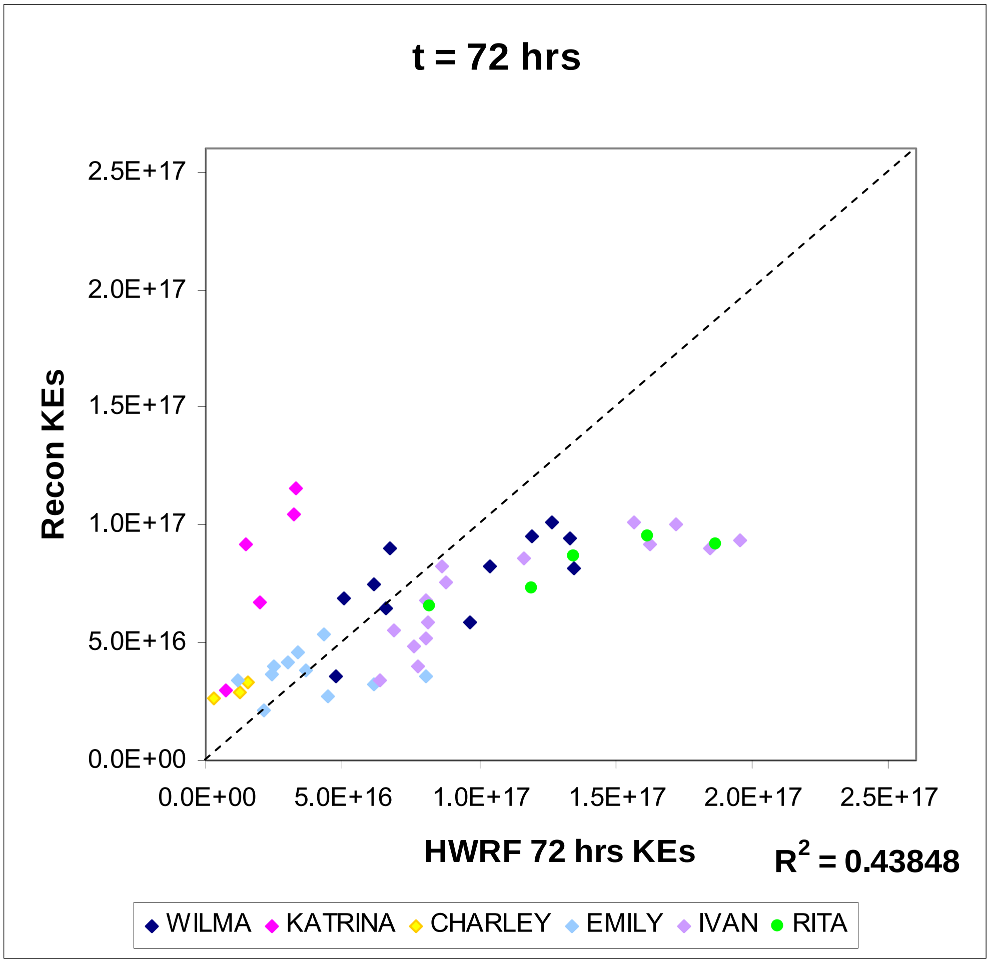

Figure 6: HWRF model 72-hour versus aircraft reconnaissance derived low-level inner-core kinetic energies for Hurricane's Wilma '05, Katrina '05, Charley '04, Emily '05, Ivan '04, and Rita '05.

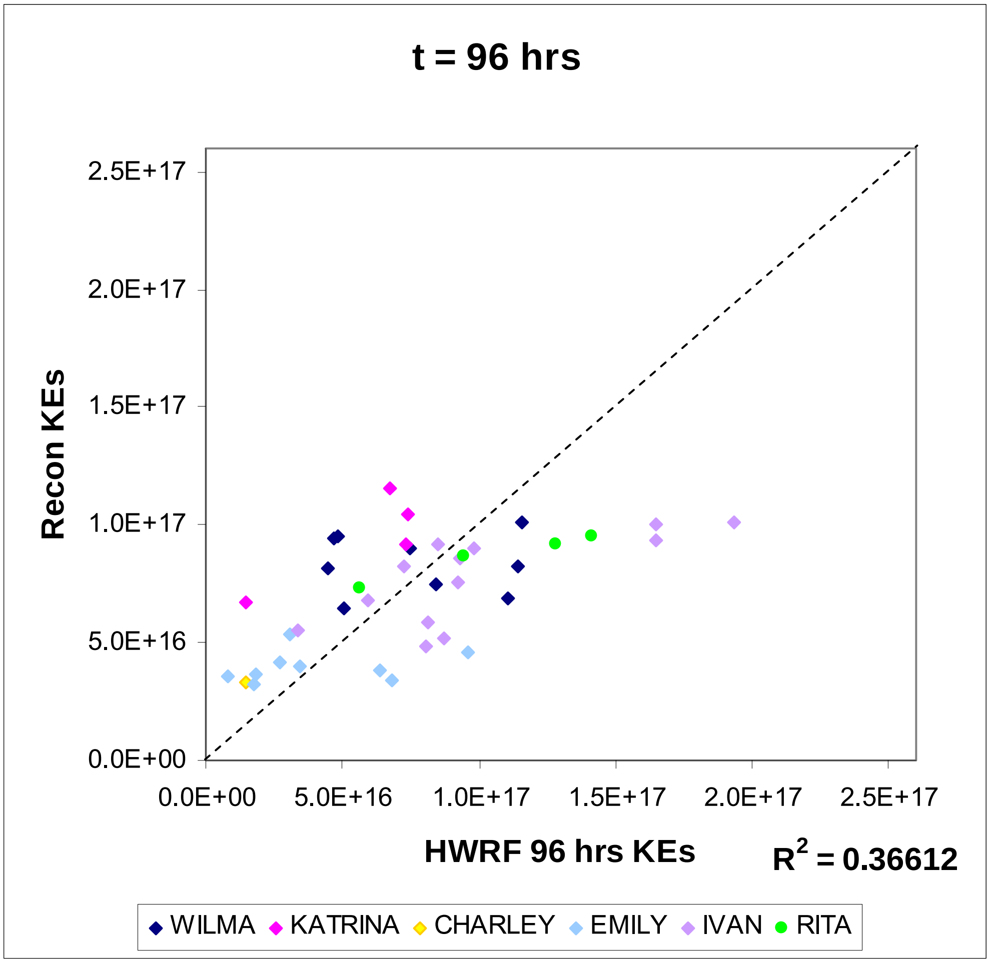

Figure 7: HWRF model 96-hour versus aircraft reconnaissance derived low-level inner-core kinetic energies for Hurricane's Wilma '05, Katrina '05, Charley '04, Emily '05, Ivan '04, and Rita '05.

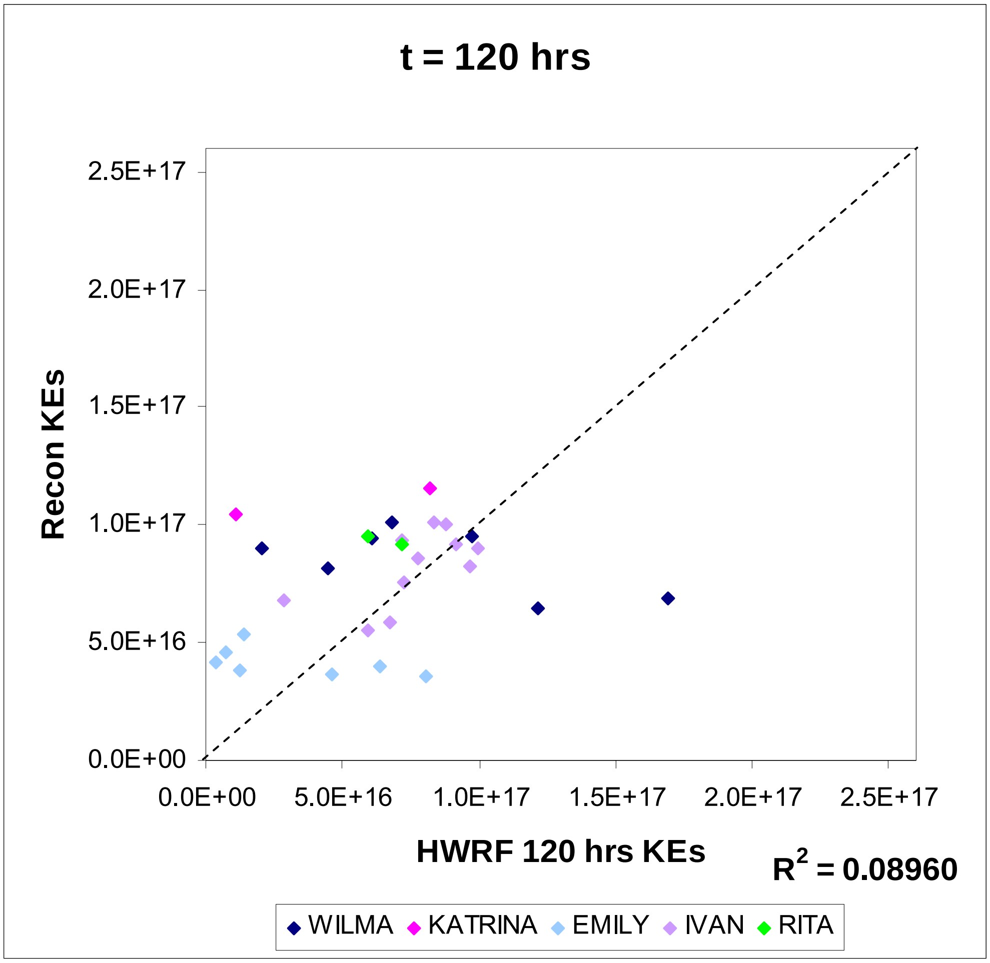

Figure 8: HWRF model 120-hour versus aircraft reconnaissance derived low-level inner-core kinetic energies for Hurricane's Wilma '05, Katrina '05, Charley '04, Emily '05, Ivan '04, and Rita '05.

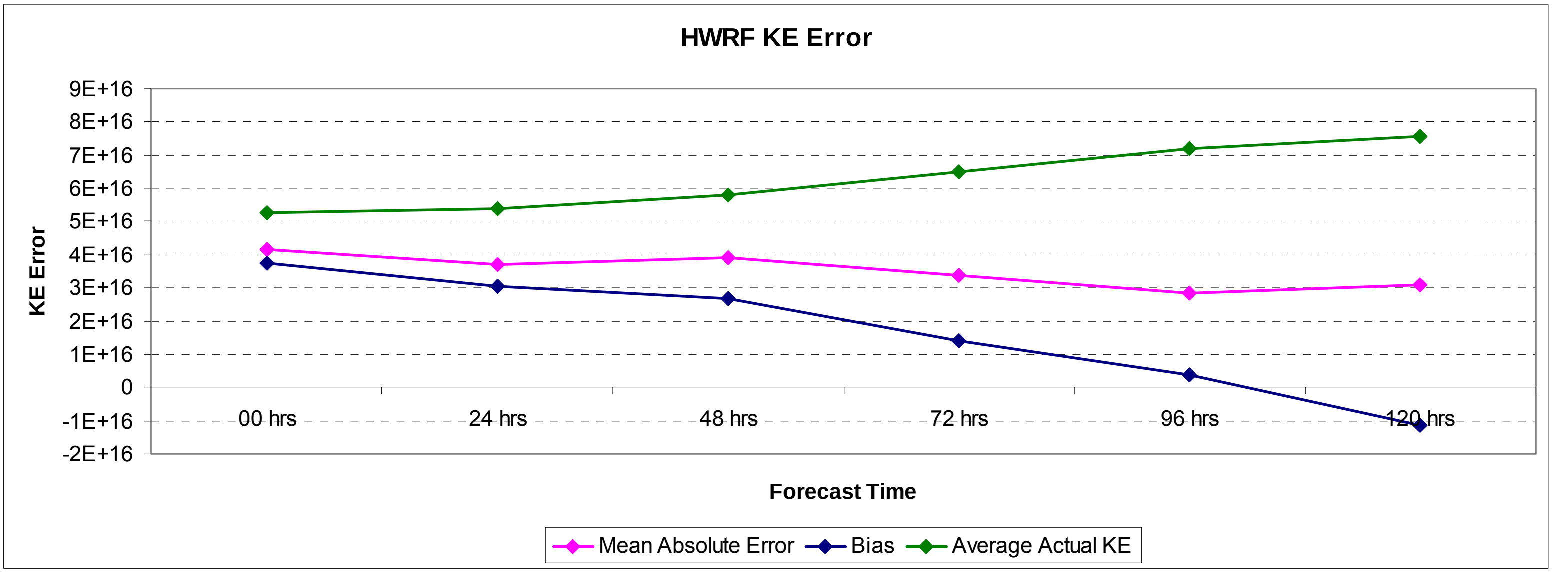

Figure 9: Comparison of the average actual KE from the aircraft reconnaissance data to the mean absolute error and the bias (mean error) of the HWRF model KEs for Hurricane's Wilma '05, Katrina '05, Charley '04, Emily '05, Ivan '04, and Rita '05 for HWRF forecasts at 00, 24, 48, 72, 96, and 120 hours.

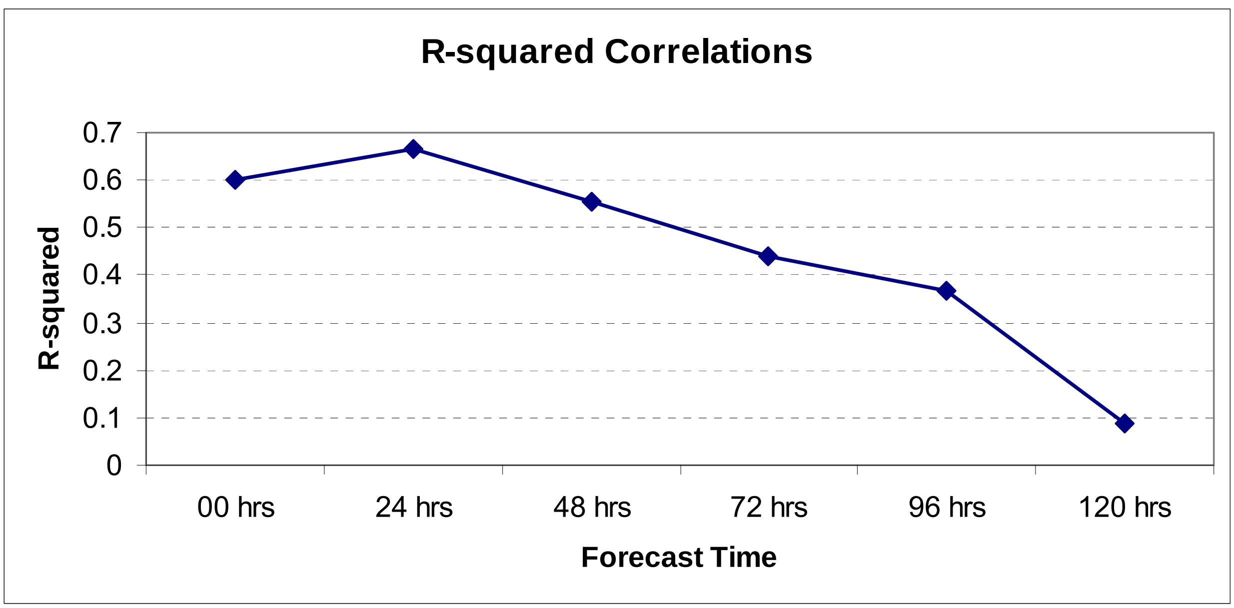

Figure 10: R-squared correlations for the actual vs. HWRF KEs for HWRF forecasts at 00, 24, 48, 72, 96, and 120 hours.