Joint Hurricane Testbed Final Report

April 3, 2007

Project: Estimating tropical cyclone wind radii utilizing an empirical inland wind decay model

Principle Investigator: John Kaplan
Hurricane Research Division
NOAA/AOML
4301 Rickenbacker Causeway
Miami, FL 33149

Co-Investigators: Jason Dunion
Hurricane Research Division
NOAA/AOML
4301 Rickenbacker Causeway
Miami, FL 33149

Nicholas Carrasco
CIMAS/HRD
4301 Rickenbacker Causeway
Miami, FL 33149

Mark DeMaria
NOAA/NESDIS
Fort Collins, CO 80523

1. Introduction

The National Hurricane Center (NHC) is required to issue forecasts of the radii of 34, 50, and 64 kt winds for tropical cyclones every 6 hours as part of their forecast/advisory package. The overarching goal of this project was to utilize the Kaplan and DeMaria decay model (Kaplan and DeMaria 1995, 2001) to provide guidance that could be used to help make such wind radii and maximum wind forecasts for systems that make landfall during the forecast period. A significant goal of this project was to devise methodology that would make it possible to run the decay model utilizing the official NHC track, intensity, and storm structure forecasts. The use of the official NHC forecast is important since while there are other objective models that provide guidance on both storm size and intensity, none provide guidance that is entirely consistent with the official NHC track and intensity forecast. This is an important issue for landfalling systems since Kaplan and DeMaria (1995, 2001) have shown that the post-landfall decay of a tropical cyclone is proportional to both the intensity at landfall and the length of time that a system spends over land. Thus, both the intensity and the timing of landfall are crucial factors that help determine the changes in post-landfall wind structure.

The Kaplan and DeMaria decay model is currently used in the SHIPS model (DeMaria et. al 2005) to predict the post-landfall decrease in maximum sustained wind speed near the storm center and by the Federal Emergency Management Agency (FEMA) to estimate the maximum potential wind speeds that might be experienced at inland locations. The decay model can also be utilized to provide a 2-dimensional post-landfall wind field (Kaplan and DeMaria 1995) and this is the application that is being employed to obtain the wind radii estimates in this study. To run the decay model, a forecast of the storm structure and intensity up to the time of landfall as well as a forecast track for the lifetime of the storm are required. This information was obtained from the official NHC forecasts that are archived in the ATCF file. In year 1 of the project the decay model was converted from an interactive to an automated model that could be run directly using input from the ATCF file. In the second year of the project, a revised version of the decay model (DeMaria et al. 2006) that improves the prediction for systems that traverse islands and peninsulas was tested. This version of the decay model was subsequently run in real-time at the NHC commencing at the end of September of 2006.

2. Year 1 Accomplishments (April 2005-April 2006)

a. Modification of decay model for real-time use

Software routines were developed to extract the storm track, intensity, and wind radii information that are required to run the decay model from the ATCF database. These routines were successfully employed to generate the necessary model input files for several recent landfalling storms including Hurricanes Charlie (2004), Dennis (2005), Katrina (2005), Wilma (2005), and Rita (2005). Many of the modifications required to convert the decay model from an interactive to real-time model were implemented. Specifically, the model was modified so that it could be run off of the input files that are generated using the ATCF software extractions routines described above. The model was also modified so that the decay model coefficients are determined as a function of storm latitude along the forecast track following the methodology of DeMaria et al. (2005). Furthermore, the model was modified to account for changes in storm speed along the forecast track when estimating the left to right storm motion induced asymmetry (Kaplan and DeMaria 1995). Code was also added to compute the 34,50, and 64 kt wind radii in each of the four quadrants at user specified forecast time intervals.

b. Wind swath generation

The Kaplan and DeMaria decay model assumes that the wind speeds of a tropical cyclone decrease exponentially as a function of time after landfall to some background wind speed following:

$$V_t = V_b + (RV_0 - V_b)e^{-\alpha t} \qquad (1)$$

where $\boldsymbol{V_t}$ is the maximum wind at time $\boldsymbol{t}$, $\boldsymbol{R}$=0.9 is the reduction factor that is applied at landfall to account for the increase in terrain roughness, $\boldsymbol{V_0}$ is the maximum wind at time $\boldsymbol{t}$=0 h, $\boldsymbol{V_b}$ is the background wind speed, and α is the exponential rate of decay of the wind. Swaths of the maximum sustained wind at any time ***(t)*** during a storm's landfall can be obtained by applying (1) to every point in the initial vortex wind field. In this study, the parametric wind models described in Kaplan and DeMaria (1995) and Knaff et al. (2007) were employed to generate the initial vortex. The parametric model described in Kaplan and DeMaria (1995) is given by:

$$V(r,\theta) = c_s[(\cos(\theta)] + V_x(r/r_m)\exp\{1/a[1 - r/r_x)^a]\} \qquad (2)$$

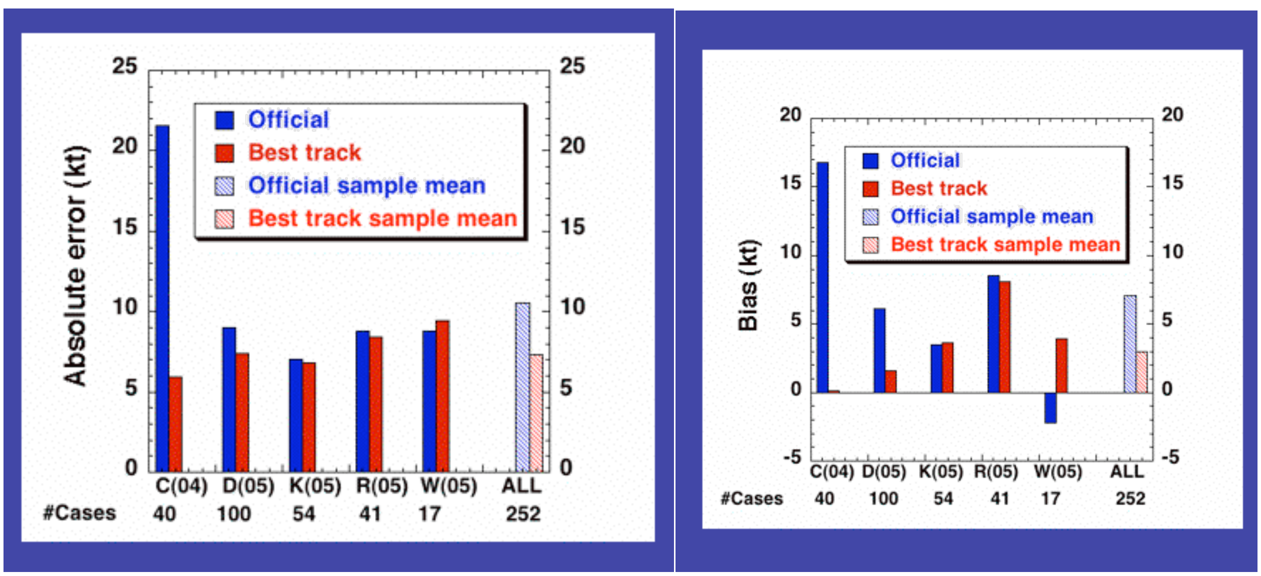
where $\boldsymbol{r}$ is the radius from the storm center, $\boldsymbol{r_m}$ is the radius of maximum winds, θ is the angle measured counterclockwise from a line perpendicular and to the right of the direction of motion, $\boldsymbol{c_s}$ is the left/right asymmetry due to storm motion determined using the empirical relationship determined by Schwerdt et al. (1979), $\boldsymbol{V_x}$ is the symmetric part of the maximum sustained wind obtained after subtracting out the storm motion($\boldsymbol{c_s}$), and $\boldsymbol{a}$ is a parameter that provides an estimate of the shape of the wind field. The parametric model described in Knaff et al. (2007) is given by:

$$\begin{aligned} V(r,\theta) &= (v_x - c_s)\left(\frac{r_m}{r}\right)^a + c_s\cos(\theta - \theta_O) \quad \text{for} \quad r \geq r_m \\ V(r,\theta) &= (v_x - c_s)\left(\frac{r}{r_m}\right) + c_s\cos(\theta - \theta_O) \quad \text{for} \quad r < r_m \end{aligned} \qquad (3)$$

where Θ_0 is the degree of rotation from the maximum wind located 90º to the right of the storm motion vector. Each of the parameters contained in (2) and (3) can be estimated from information contained in the official NHC forecast advisory. The vortex shape (***a***) in (2) and (3) is determined by fitting the 64, 50, and 34 kt wind radii contained in the forecast advisory. The parametric wind model generated using (2) or (3) that yielded the best fit to the NHC forecast wind radii was ultimately used to generate the initial decay model wind vortex for each forecast case.

To test the performance of the decay model swaths of the maximum sustained wind were generated for major U.S. landfalling hurricanes Charlie (2004), Dennis (2005), Katrina (2005), Rita (2005), and Wilma (2005). Wind swaths were generated by employing both the official NHC forecast track and landfall intensity (hereafter referred to as "Official swaths") and the best track storm positions and the best track landfall intensity (hereafter referred to as "Best track swaths"). All wind swaths were generated for the last synoptic time for which an official NHC forecast was issued. After a storm made landfall, the decay model was then employed to decay the initial vortex wind field generated using either (2) or (3) while the system remained over land. The decision to create both "Official" and "Best track" swaths was made both to demonstrate the sensitivity of the decay model to variations in the storm track and landfall intensity and to obtain a more accurate assessment of the skill of the decay model.

The aforementioned maximum wind swath estimates were evaluated at all in-situ surface observation locations where wind observations were made continuously throughout a storm's lifetime. This was accomplished by first determining the decay model estimated maximum wind at each observation location at any time during the duration of the storm. Prior to performing evaluations of the surface wind observations and decay model maximum wind estimates, all surface in-situ wind data were converted to a maximum sustained 1-min wind at 10 m for open-water or open terrain exposure using the methodology described in Powell et al. (1996a) and Powell et al. (1996b). Evaluations were performed for the time period when the storm made landfall until the system became extra-tropical or dissipated. Figure 1 shows the errors and biases between the decay model and in-situ observations for all 5 storms. The figure indicates that the model performed fairly well with an average mean absolute error of 7.3 kt and a mean bias of 3.0 kt (over-prediction of observed wind speeds) between the “Best track” swath and the observed wind estimates. The errors between the “Official” wind swath and the observed maximum sustained wind were higher with a mean absolute error of 10.5 kt and a mean bias of 7.1 kt. The figure indicates that this was due mainly to the large errors and high bias that were obtained for Charlie (2004). The relatively large “Official” swath errors obtained for Charlie resulted from the more northerly track, later landfall time, and weaker landfall intensity of the official NHC forecast track for this forecast time. Although the best track landfall wind speed was higher than the official wind speed, the later landfall time combined with the more northerly track resulted in less time for the storm to decay and thus on average higher winds at many of the inland observation locations.



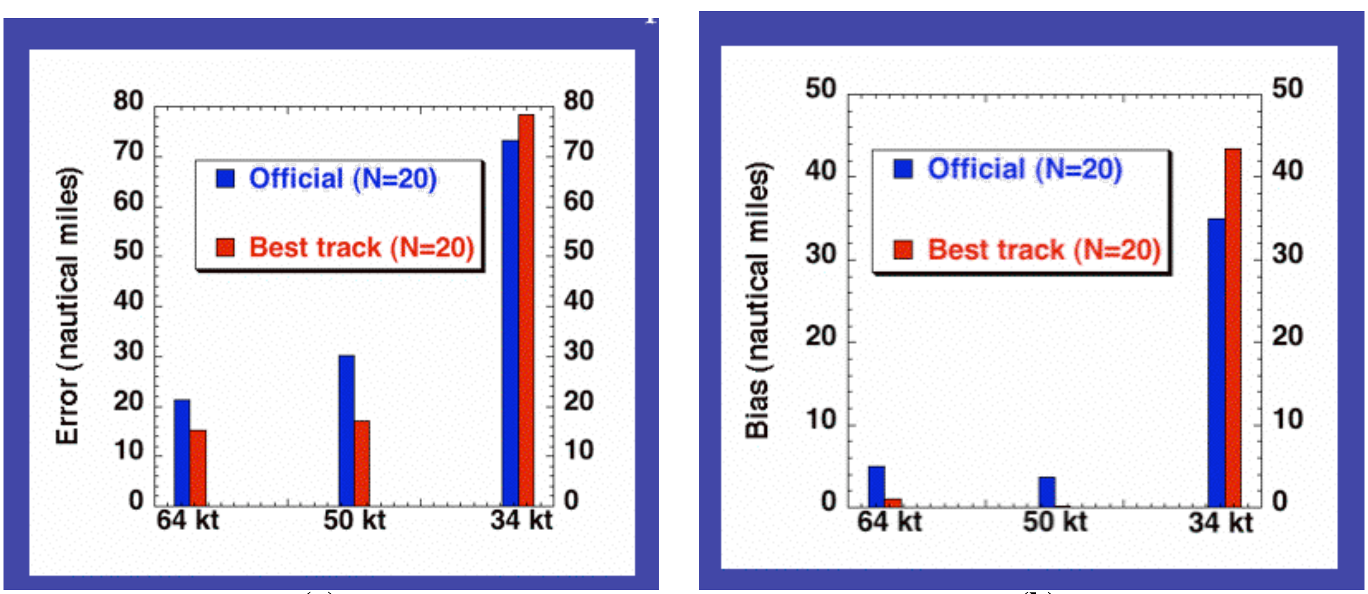
(a) (b)

Fig. 1. The absolute error (a) and bias (b) between the in-situ wind observations and the “Best track” and “Official” wind swath maximum sustained wind estimates. Results are shown for Charlie(C), Dennis (D), Katrina (K), Rita(R), and Wilma (W) individually and for all 5 storms combined (ALL). The number of cases for each storm and for the entire sample are also shown at the bottom of the figure.

c. Wind radii estimation

Estimates of the 64, 50, and 34 kt wind radii in each of the four quadrants (NE, SE, SW, NW) were obtained from the gridded (5 km X 5 km) decayed wind field for each of the 5 storms. This was accomplished by determining the maximum radius at which the various wind radii thresholds were observed in each quadrant at ~3 h after landfall. These wind radii were then compared to wind radii estimates obtained for the same time as the model estimates using the Hurricane Research Division's H*Wind analysis (Powell et al. 1996b). H*Wind is an objective analysis scheme that provides a means of analyzing all available data collected within a given time window in storm-relative coordinates. For the purpose of this study, the H*Wind analyses were performed using surface data from within ~3 h of the analysis time. A 3 h time window was employed since this ensured that only data collected when a storm was over land were employed in the analysis. The decision to estimate the wind radii at 3 h after landfall was made so that evaluations of the wind radii could be performed after a sufficient amount of storm decay had taken place and after sensitivity tests revealed that the data coverage was not sufficiently dense for analyses at later post-landfall times. Following the same methodology that was used previously when evaluating the wind swaths, wind radii estimates for each storm were obtained using both "Official" and "Best track" storm positions and "Official" and "Best track" landfall intensities. Also, the information required to generate the vortex shape parameter (***a***) was obtained from the NHC official forecast.

Figure 2 shows the errors and the biases between the decay model wind radii and those obtained from H*Wind for the 5 storm sample. These statistics were obtained using both "Official" and "Best track" wind radii estimates. The figure indicates that the decay model 64 and 50 kt wind radii estimates were in reasonably good agreement with the H*Wind estimates particularly when the "best track" input were used. However, the decay model 34 kt wind radii were not in as good agreement with the H*wind estimates. This is likely the result of the flat wind field at the lower wind speeds and the positive bias that was found in the decay model wind estimates at larger radii (not shown). It is encouraging that the biases between the decay model and H*Wind wind radii are quite small for the 64 and 50 kt wind radii, although there is a significant positive bias in the 34 kt estimates. Additional results from the first year of this project can be found in Kaplan et al. (2006).



(a) **(b)**

Fig. 2. Mean absolute error (a) and bias (b) between the decay model and H*Wind wind radii estimates.

3. Second year accomplishments (April 2006 - April 2007)

a) Preparation of decay model for the 2006 Hurricane season

During the second year of the proposal numerous modifications were made to the decay model code in preparation for real-time testing during the 2006 hurricane season. These modifications were required to implement an updated version of the decay model that is better designed to handle landfalling tropical cyclones that traverse islands and peninsulas (DeMaria et al. 2006). Specifically, a wind field on a cylindrical grid with a radius of 1100 km and 2.5 km radial and 15 deg. azimuthal spacing was generated every hour along the NHC forecast track. The shape of the wind field up until the time of landfall was determined by fitting the NHC OFCI forecasted storm structure, intensity, and storm speed along the forecast track using (3). Although the OFCI forecast wind radii were nearly always used to estimate the storm shape parameter (***a***) at every hour of the forecast, a default value was used for any time period when the OFCI forecasts did not contain at least 2 wind radii.

Once the wind field on the cylindrical grid was determined it was decayed at every grid point for time periods when the storm was overland using the updated version of the decay model (DeMaria et al. 2006) which is given by:

$$V^{t+1} = V_b + (V^t - V_b)e^{-F_m \alpha} \tag{4}$$

where V^{t+1} is the maximum wind at the end of each time step and V^t is the maximum wind at the beginning of each time step, F_m is the fractional area of the storm that is overland during each time step and α is the same as in (1). Following the methodology of DeMaria et al (2006), a circle with radius of 110 km was employed to compute F_m. Also, a 1 h time step was employed when running the decay model. For time periods when a storm moved back over water after having made landfall, the trend in the OFCI intensity forecast was employed to adjust the decayed winds. The resultant decayed wind field was then sampled every hour and the maximum wind and radius of 34,50 and 64 kt wind in each quadrant were estimated and written to a file.

After the decay model was fully tested, scripts were written to run the model in real-time on the JHT computer for all Atlantic and E. Pacific systems. The OFCI data from the NHC provided ATCF files on the JHT server were used as the input for the real-time runs of the decay model. It typically takes about 5-10 minutes to run the decay model for a landfalling system, but only a few seconds for a case that does not make landfall. The large discrepancy in computing time for landfalling and non-landfalling systems is due to the large number of computations that are required to compute F_m for systems that are either over or near land. After consultation with the NHC hurricane specialists, the decision was made to only print out estimates of the maximum wind, and 34,50, and 64 kt wind radii when a system crossed land during the forecast period. This decision seems reasonable since for systems that remain over water the decay model maximum wind and wind radii estimates are obtained by simply fitting the OFCI forecasted maximum wind and wind radii using (3) and thus are not actual forecasts of these quantities.

Commencing in the middle of September 2006, maximum wind and wind radii estimates were provided to the NHC for all landfalling Atlantic and E. Pacific systems. It is worth noting that although these estimates are currently provided at 6 h resolution, the decay model computes these values every hour so a higher resolution output could be obtained by simply changing one parameter in the decay model code.

b) Results

Since the decay model was not run in real-time until the middle of September, it was not possible to perform a reasonable verification of its performance for the 2006 Hurricane season. Thus, the model was re-run for all landfalling Atlantic and E. Pacific hurricanes from the 2004-2006 seasons. The results for this period can be considered independent since DeMaria et al. (2006) only used data up through the 2003 season when deriving the updated version of the decay model. Since the OFCI forecast data were not available until the middle part of the 2005 Hurricane season, the OFCL forecast data were employed as input to the decay model for the entire 2004-2006 sample. The decay model was generally run for the last forecast time prior to landfall for each of the 9 Atlantic and 2 E. Pacific hurricanes that comprised the 2004-2006 sample (Charley (2004), Frances (2004), Ivan (2004), Jeanne (2004), Cindy (2005), Dennis (2005), Katrina (2005), Rita (2005), Wilma (2005), John (2006), and Lane (2006)). The old version of the decay model that was employed in year 1 of the project was also run for these same cases so that comparisons could be made between the 2 versions. The decay model maximum wind and 64, 50 and 34 kt wind radii estimates were then compared to the NHC best track estimates of these same quantities as was suggested by one of the reviewers of the second year proposal for this project. Also, the results from both versions of the decay model were then compared to the operational forecasts from the AVNO, NGPS, and GFDL models and official (OFCL) NHC forecast for the same forecast times.

Figure 3 shows the absolute errors between the model predicted maximum wind and 64, 50, and 34 kt wind radii as a function of forecast time for the entire sample. Errors were computed for all 4 quadrants and then averaged for all storms for each 6-hourly forecast period for time periods when the system was either tropical or subtropical. The errors were then averaged for each 12 h forecast interval (i.e., 6-12, 18-24, 30-36…) to reduce the noise in the error analysis since some 6-hourly periods had relatively few forecast cases. It is important to note that t=0 h corresponds to the initial forecast time not the time of landfall in each of the figures. Also, wind radii errors were only computed for time periods when the NHC best track estimates for either the 64,50, or 34 kt wind radii were non-zero for any given quadrant. The figure shows that in general the new decay model had smaller errors than both the other objective models and the older version of the decay model during the first 24-h or so of the forecast period when most of the decay was taking place. The exception was for the 34 kt wind radii where the AVNO model provided the smallest errors. The larger errors in the decay model wind radii estimates during the 30-48 h time period is due primarily to an underestimation in the size of the wind field of hurricane Wilma (2005) just prior to the time that Wilma became extratropical. It is worth noting that the errors for the GFDL model maximum wind forecasts were comparable to those of the decay model during the first 24 h, but much higher for the later forecast times. Analysis of the bias of the model errors (not shown) indicates that this is due to an overestimation of the wind speed (high bias) by the GFDL model at the later forecast times. Figure. 4 shows the mean absolute errors between the model and best track maximum wind and wind radii estimates for all forecast times shown in Fig. 3 for the entire study sample. The figure indicates that the new decay model generally had the lowest mean average absolute errors of any of the models except for the 34 kt wind radii for which the AVNO model had the lowest errors as was mentioned previously. The average absolute error of the new decay model estimates for the 64, 50 and 34 kt wind radii were 18, 24, and 58 nautical miles respectively.

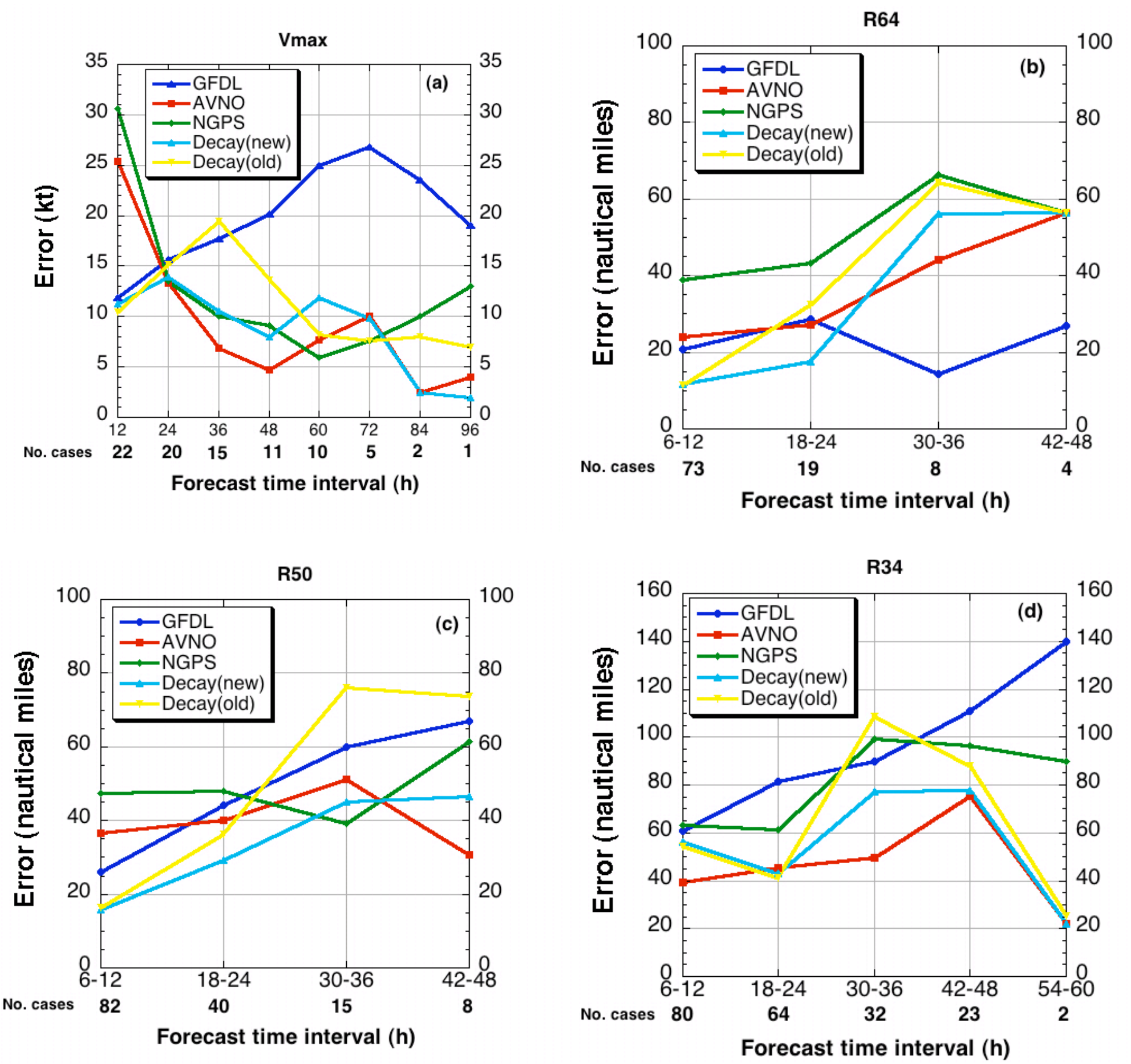


Fig. 3. Absolute errors between the NHC best track and AVNO, NGPS, GFDL and new and old decay model estimates of the a) maximum wind, and b) 64 kt, c) 50 kt, and d) 34 kt wind radii for the entire 11 hurricane sample as a function of forecast time. The errors averaged for each 12 hour time interval (i.e.,6-12, 18-24,30-36 …) are provided.

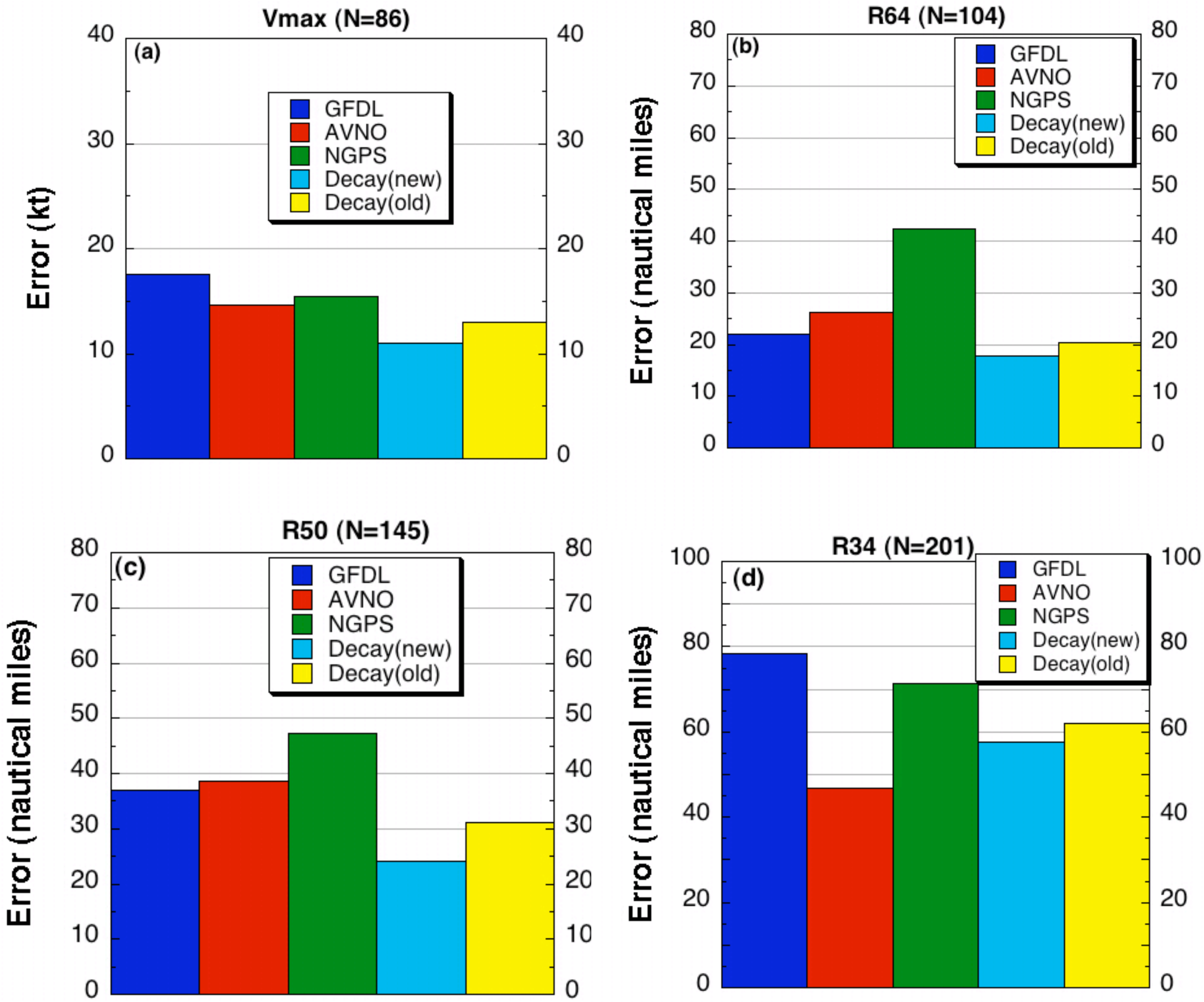


Fig. 4. Mean absolute errors between the NHC best track and AVNO, NGPS, GFDL and new and old decay model estimates of the a) maximum wind (t=0-96h), b) 64 kt (t=0-42 h), c) 50 kt (t=0-48h), and d) 34 kt (t=0-54 h) wind radii for the entire 11 hurricane sample for all forecast times shown in Fig. 3. The time interval over which the errors were tabulated is provided in parentheses.

Figure 5 shows the errors between the decay model and the OFCL maximum wind and wind radii estimates for the study sample. Since the official forecasts do not contain wind radii estimates at 6 h resolution the sample sizes are much smaller than those that were obtained for the model comparisons depicted in Fig. 4. The figure shows that the decay model errors were nearly identical to those of the official forecasts for the maximum sustained wind, but were worse than the official forecast errors for the 64, 50 and 34 kt wind radii. While the official forecasts were very good for these cases, presumably they may have been further improved had they had access to the decay model estimates that were generally better than the objective model guidance to which the NHC typically has routine access.

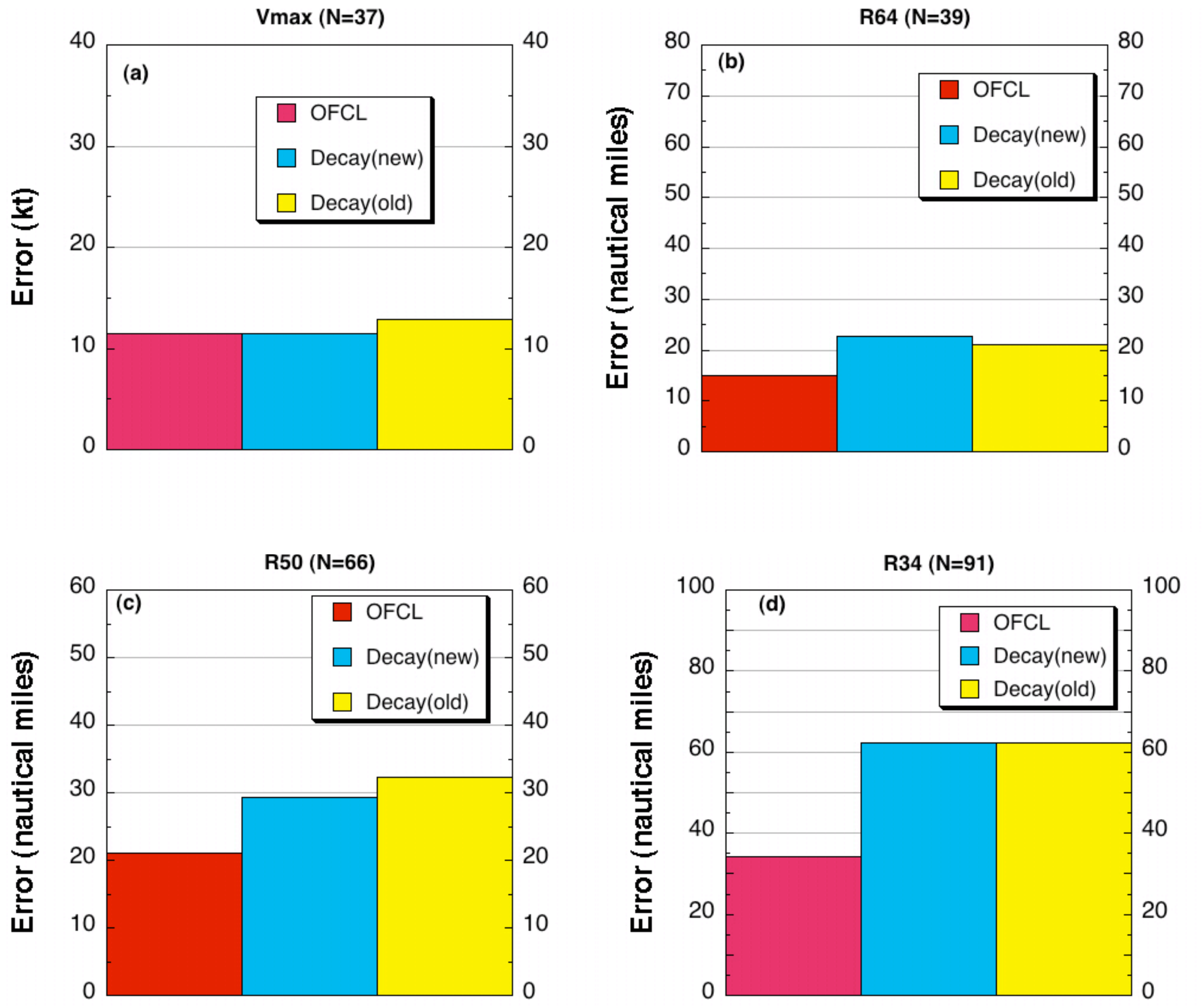


Fig. 5. Mean absolute errors between the NHC best track OFCL and new and old decay model estimates of the a) maximum wind (t=0-96h), and b) 64 kt (t=0-36 h), c) 50 kt (t=0-48h), and d) 34 kt (t=0-48 h) wind radii for the entire 11 hurricane sample for all forecast times. The time interval over which the errors were tabulated is provided in parentheses.

Figure 6 shows the predicted maximum sustained wind and wind radii for Hurricane Frances (2004). This case was chosen since it provides an example of a case that had 2 landfalls during the forecast period. The forecasted maximum wind (a) and 64 (b), 50 (c), and 34 (d) kt wind from 18 UTC on 4 September until Frances was declared extratropical are presented. The 64, 50, and 34 kt wind radii depicted are the averages of all 4 quadrants at each 6 hourly forecast time. The forecasts from the AVNO, NGPS, GFDL, and new decay models as well as the OFCL forecast are presented. Only the new decay model forecasts are shown both to improve the readability of the figure and because it had been shown previously that the new version was superior to the older one.

The figure indicates that both the decay model and the official forecast did a good job of predicting the decay of the maximum wind while the GFDL model forecasts were too high and the AVNO and NGPS forecasts were too low. The high bias of the GFDL forecasts and low bias of the AVNO and NGPS forecasts is likely due, in part, to the former model having too high an intensity at landfall and the latter 2 global models having too low an intensity at landfall. It is worth noting that the decay model predicted maximum wind was nearly constant while Frances remained over water (t=29-43 h) since the model attempts to match the trend in the official intensity forecast when systems are over water and the OFCL forecasted intensity remained constant during this time period.

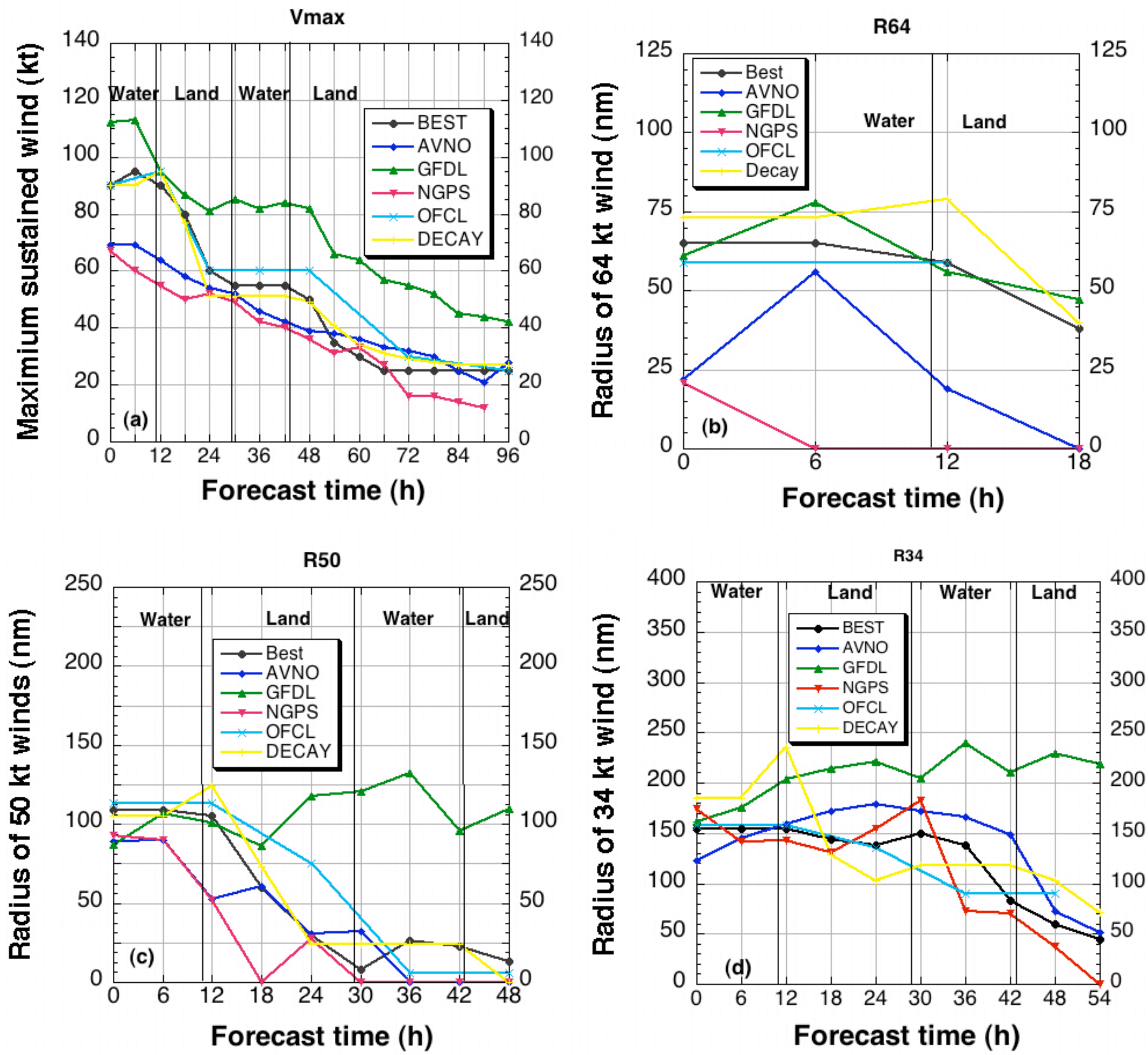


Fig. 6. The predicted maximum sustained wind (a), radius of 64 (b), 50 (c), and 34 (d) kt wind for Hurricane Frances (2004) for the AVNO, GFDL, NGPS, OFCL and new decay model. The wind radii values depicted are the 4 quadrant averages at each verification time. The 6 hourly NHC best track estimates for each parameter are shown for comparison. The underlying surface (water or land) is indicated during the entire forecast interval. Note that Frances was over land during the time periods from about t=10-29 h and from t = 43-96 h.

Figure 6 shows that the GFDL model did a good job of predicting the changes in the radius of 64 kt wind despite having too high an intensity at landfall, while the decay model post-landfall 64 kt wind radii estimates were quite good even though the 64 kt wind radii estimates at landfall were too high. Both the AVNO and NGPS model 64 kt wind radii estimates were too low which is likely the result of the coarse resolution of both models. The post-landfall decay model radii of 50 kt wind estimates were quite good while the AVNO and NGPS model forecast were too low and the GFDL model too high. The OFCL forecasts were somewhat high early and a little low toward the end of the period which may represent a compromise between the GFDL, AVNO and NGPS forecasts. The decay model 34 kt wind radii estimates were too high just after landfall but were in fairy good agreement with the best track estimates for the remainder of the forecast period. The ANVO and OFCL estimates were generally quite good for the entire forecast period while the GFDL 34 kt wind radii forecasts were too high for the entire forecast period. The results in Fig. 6 indicate that while the decay model's fit to the NHC forecast wind radii is certainly not perfect the model is capable of making reasonably accurate post-landfall prediction of the wind radii provided that the errors are not unreasonably large. Additional results from year 2 of this project are contained in Kaplan et al. (2007).

c) Installation of real-time decay model code

As noted previously, the decay model was successfully installed and run in real-time on the JHT computer from the middle of September of 2006 until the end of the 2006 Hurricane season. All of the code required to test and run the decay model in real-time is currently on the JHT server in the directory /home/decay/final. The readme file (readme_decay.txt) in that directory provides the user with the directions required to install and run the model in real-time.

4. References

DeMaria, M., M. Mainelli, L.K. Shay, J. Knaff and J. Kaplan, 2005: Further improvements to the Statistical Hurricane Intensity Forecasting Scheme (SHIPS). *Wea. Forecasting*, **20**, 531-543.

_____, J.A. Knaff, and J. Kaplan, 2006: On the decay of tropical cyclone winds crossing narrow landmasses. J. Appl. Meteor, **45**. 491-499**.**

Kaplan, J., and M. DeMaria, 1995: A simple empirical model for predicting the decay of tropical cyclone winds after landfall. J. Appl. Meteor., **34**, 2499-2512.

________, and __________, 2001: On the decay of tropical cyclone winds after landfall in the New England area. *J. Appl. Meteor.,* **40***, 280-286.*

________, J. Dunion, N. Carrasco, and M DeMaria, 2006: Estimating tropical cyclone wind radii using an empirical inland wind decay model. Minutes of the 60th Interdepartmental Hurricane Conference. [Available at http://www.ofcm.noaa.gov/ihc06/linking_file_ihc06.htm].

_______, M. DeMaria, N. Carraso, and J. Dunion, 2007: Tropical cyclone wind radii estimation using an empirical inland decay model. Minutes of the 61st Interdepartmental Hurricane Conference. [Available at http://www.ofcm.noaa.gov/ihc07 /linking_file_ihc07.htm].

Knaff, J. A., C.R. Sampson, M. DeMaria, T. P. Marchok , J. M. Gross and C.J. McAdie: 2007: Statistical tropical cyclone wind radii prediction using climatology and persistence. *Wea. Forecasting*, *In press.*

Powell, M.D., and S.H. Houston, 1996a: Hurricane Andrew's landfall in South Florida. Part I: Standardizing measurements for documentation of surface wind fields. Wea. Forecasting, **11**, 304-328.

_____, and S.H. Houston, and T. A. Reinhold, 1996b: Hurricane Andrew's landfall in South Florida. Part II: Surface wind fields and potential real-time applications. Wea. Forecasting, **11**, 329-349.

Schwerdt, R.W., F.P. Ho, and R.R. Watkins, 1979, Meteorological criteria for standard project hurricane and probable maximum hurricane wind fields, Gulf and East coasts of the United States. pp 317. [Available from National Technical Information Service. U.S. Dept. of Commerce, Sills Bldg. 5285 Port Royal Road, Springfield, Va. 22161].