JHT First Year Final Report
August 1, 2003-July 31, 2004
Improvements in Deterministic and Probabilistic
Tropical Cyclone Surface Wind Predictions

PIs: John A. Knaff (CIRA) and Mark DeMaria (NESDIS/ORA)
TPC Contacts: Miles B. Lawrence, James M. Gross and Chris A. Sisko
JTWC Contact: Ed Fukada
NRL Contact: Buck Sampson

Background:

This proposal describes newly developed methods for improving deterministic and probabilistic surface wind predictions that will be evaluated in an operational setting.

The deterministic surface wind prediction improvements expand upon previous work with the Statistical Hurricane Intensity Prediction Scheme (SHIPS). A major limitation of SHIPS is that relies almost entirely on relationships between the storm environment conditions and intensity changes. Research results have shown that internal processes such as eyewall contraction and replacement can also have large impacts on hurricane intensity changes. Since theses processes can often be observed in aircraft reconnaissance observations and GOES imagery, a new component to the SHIPS model will be developed and evaluated where aircraft reconnaissance and GOES imagery will be utilized to better determine the inner core structure. Aircraft data are not currently used as SHIPS input, and the GOES 10.7 μm imagery is used in a rudimentary way that involves averages over large areas. The intensity forecast model with the inner core GOES and aircraft data will be a separate component that predicts deviations from the SHIPS prediction, and will be referred to as the GOES and Reconnaissance Intensity Prediction (GRIP) model. To account for nonlinear interactions between possible predictors, a neural network prediction method will be tested in addition to the multiple linear regression method that is currently used by SHIPS.

As part of the overall development of statistical tropical cyclone forecasting techniques, a new method for estimating the uncertainty associated with surface wind forecasts was proposed. The wind uncertainty estimate is obtained using a Monte Carlo Probability (MCP) model, where a large set of plausible tracks and intensities are determined by randomly sampling historical forecast errors distributions. Special procedures were developed to account for the effects of land, for the serial correlation between the track and intensity forecast errors, and for the relationships between intensity and wind structure. A prototype version of the MCP was developed for the Atlantic basin and provides fields of the probability of the surface wind exceeding specified wind thresholds over specified time intervals. In this work, the Atlantic MCP model will be generalized to include the East Pacific, Central Pacific, and West Pacific tropical cyclone basins. The code will also be generalized so that it can run as part of the Automated Tropical Cyclone Forecast (ATCF) system, and generate fields on the NWS National Digital Forecast Database grid system.

1. First Year Accomplishments

a. Improvements in Deterministic Surface Wind Predictions

The development of the GRIP model began by assembling the dependent dataset. The U.S. Air Force Reserve flight level data for all Atlantic and east Pacific tropical cyclone cases from 1995-2003 was obtained and put into a common format. This data is input to a variational analysis system, which combines observations in 12-hour intervals in a storm-relative coordinate system to produce tangential and radial flight level winds in a cylindrical coordinate system. Because this analysis must run in a fully automatic mode when implemented in real time, considerable effort was put into development of data quality control. The quality control includes the following three steps:

1. Gross error checking: Data is tested to make sure it is physically reasonable (wind speeds between 0 and 250 kt, directions between 0 and 360^{o})

2. An objective method for determining whether data coverage is sufficient: The maximum data gaps in the radial and tangential directions are calculated, and compared with the pre-specified smoothing parameters of the objective analysis. If the gaps are too large, the case is flagged as containing insufficient observations. Much larger gaps are allowed in the tangential than the radial direction. The smoothing parameters are set so that an analysis can be performed as long as there are at least two radial legs of data, separated by no more than 160 degrees of azimuth.

3. Comparison of input data to a pre-analysis: If the data coverage is sufficient, a preliminary objective analysis is performed, and then interpolated back to the observation points. If the magnitude of the vector difference between the interpolated analysis wind and the original wind vector exceeds a specified amount, the data is flagged as being in error. After this step, the objective analysis is repeated with the bad data points removed. If more than 10% of the data points are flagged, an analysis is not performed. This method is a generalization of a "buddy check"

The analysis provides radial and tangential winds at 16 azimuths at 5 km radial intervals out to 200 km from the storm center. Data coverage is usually sufficient to estimate azimuthal wave numbers zero (the azimuthal mean) and one. The initial statistical prediction will be based upon the azimuthal mean tangential wind field. Figure 1 shows radial profiles of the wave number zero tangential wind for Hurricane Lili from Oct 1-3, 2002, obtained from the objective analysis program. Similar profiles are available for 322 cases from 77 storms from 1995-2003.

The GOES infrared satellite images were also azimuthally averaged, and interpolated to the same radial grid as the aircraft data. The azimuthally averaged tangential winds and IR data are available at 51 radial grid points from 0 to 200 km. This provides 102 possible predictors for the GRIP model. However, with a sample size of a little over 300, it is not feasible to test that many predictors. For this reason, the dimension of the dataset was reduced using a principal component technique.

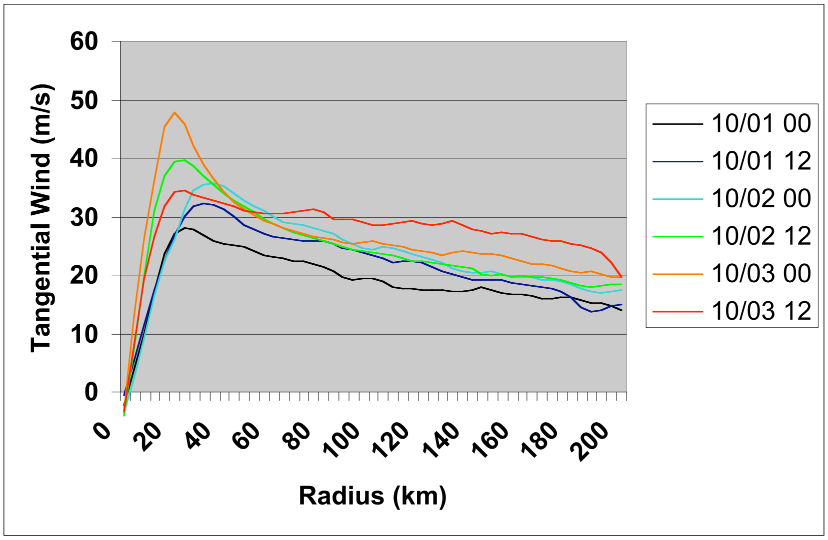


Figure 1. Sample radial profiles of mean tangential wind from Hurricane Lili 2002 generated by the variational objective analysis system.

The principal component technique was applied separately to the GOES and aircraft data. The method attempts to find patterns that are common to all of the 322 profiles using an objective mathematical procedure. If the profiles have similar structures, then any profile can be represented by a small linear combination of the most dominant patterns. The patterns are determined by finding the eigenvectors of the 51 by 51 covariance matrix formed from the 51 radial grid point values, using all 322 cases. Because the covariance matrix is real and symmetric, the eigenvectors are orthogonal. The eigenvalues of this matrix provide a measure of how much of the variability of the original dataset is explained by each eigenvector. If a few of the eigenvalues are much larger than the rest, then the profiles can be represented by only a few of eigenvectors (patterns).

Figure 2 shows the variance explained by each eigenvector for the GOES and aircraft data. This figure shows that 99% of the variance in the aircraft (GOES) data can be explained by only 6 (4) eigenvectors. Thus, the principal component technique does reduce the degrees of freedom of the data by about a factor of 10.

Figure 3 shows the structure of the first 6 aircraft and first 4 GOES eigenvectors. The first few eigenvectors represent the mean radii structure, while the higher-order eigenvectors may represent concentric structures in the wind and brightness temperatures, since they have multiple maxima. For the statistical analysis, each of the radial profiles was projected on to the eigenvectors (the principal components), so that the profiles are represented by a linear combination of the patterns, the first few of which are shown in Fig. 3. The first 5 principal components (aircraft and GOES) were then tested for their ability to predict intensity changes.

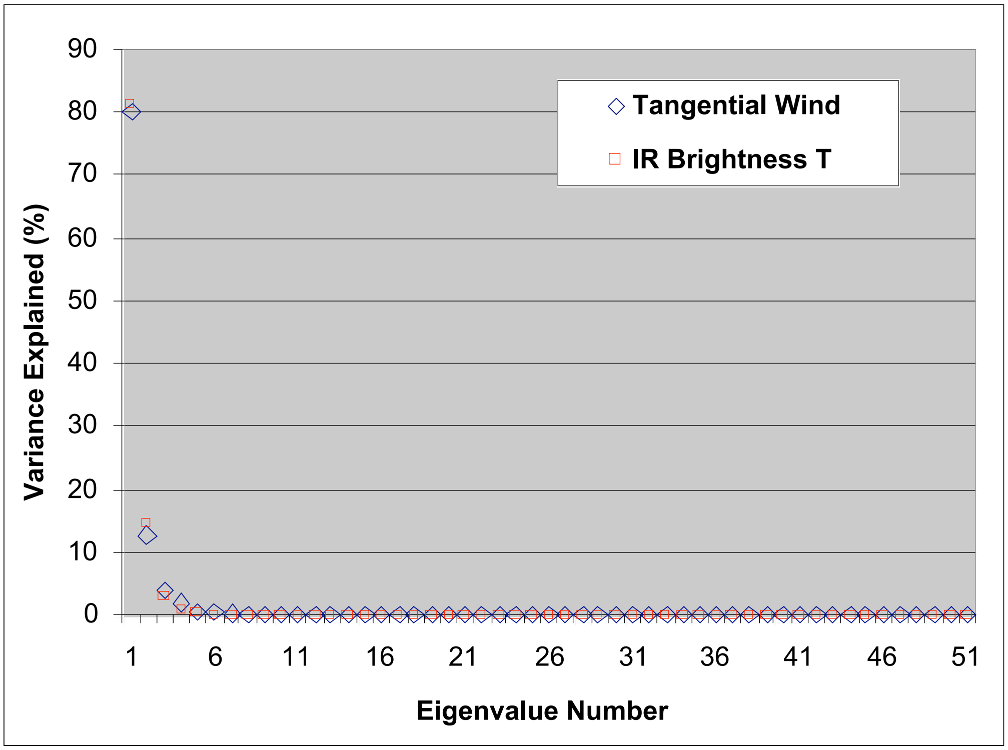


Figure 2. The percent of variance explained by each eigenvector of the principal component analysis of the aircraft and GOES data.

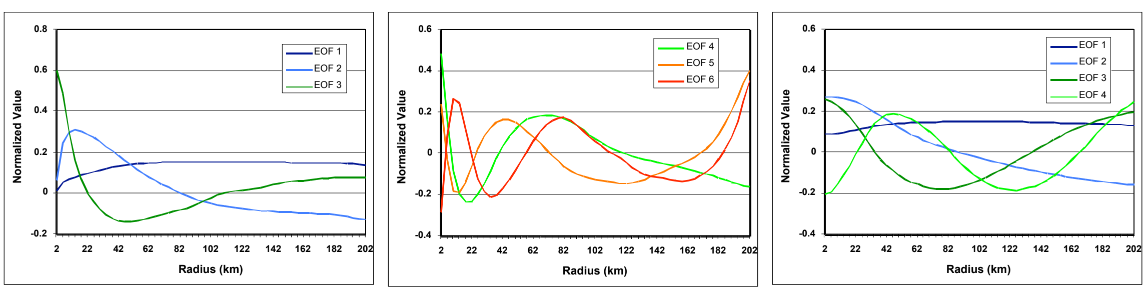


Figure 3. The first 6 eigenvectors (left and middle) from the aircraft data and the first 4 eigenvectors (right) from the GOES data. These eigenvectors explain 99% of the variability of the original data.

The dependent variable for the prediction is the difference between the intensity from the SHIPS model and the observed intensity. It is assumed that the SHIPS prediction already accounts for the synoptic influences on the intensity change. The inner core information will then correct the SHIPS prediction. An unanticipated benefit of this approach is that it will be possible to run the GRIP model in that Atlantic, east Pacific or central Pacific as long as the aircraft and GOES data are available. Although the aircraft data are normally restricted to the Atlantic, they are sometimes available in the Pacific as well. About 7% of the dependent cases were from the east Pacific.

Because the aircraft and GOES data are available only at the beginning of the forecast period, the influence on the longer-range forecasts should be small. Thus, it is anticipated that the GRIP model will only provide a forecast out to 72 h, and its main utility will be for the 12-48 h range. This assumption was confirmed when the principal components were tested as predictors of the deviations from the SHIPS forecasts. Using the condition that a coefficient must be statistically significant at the 99% level for at least one forecast time (the same rule used in the SHIPS model), a backward stepwise multiple regression procedure was applied with the first 5 principal components from the aircraft and GOES profiles as independent variables. Principal components 1 and 3 from the aircraft profiles and 1 and 4 from the GOES profiles were selected using this procedure, and the strongest statistical relationships were found at 12-48 h. The initial intensity was also included as an independent variable in this procedure, because the first principal component of the aircraft profile is highly correlated with the maximum winds. Including the maximum wind forces the regression to select information that supplements that found in the initial intensity value. The initial intensity was also selected as significant predictor in addition to the 4 principal components.

Figure 4 shows the percent improvement of the GRIP dependent forecast relative to the SHIPS predictions. As expected, the improvement (up to about 6%) tails off after about 48 h.

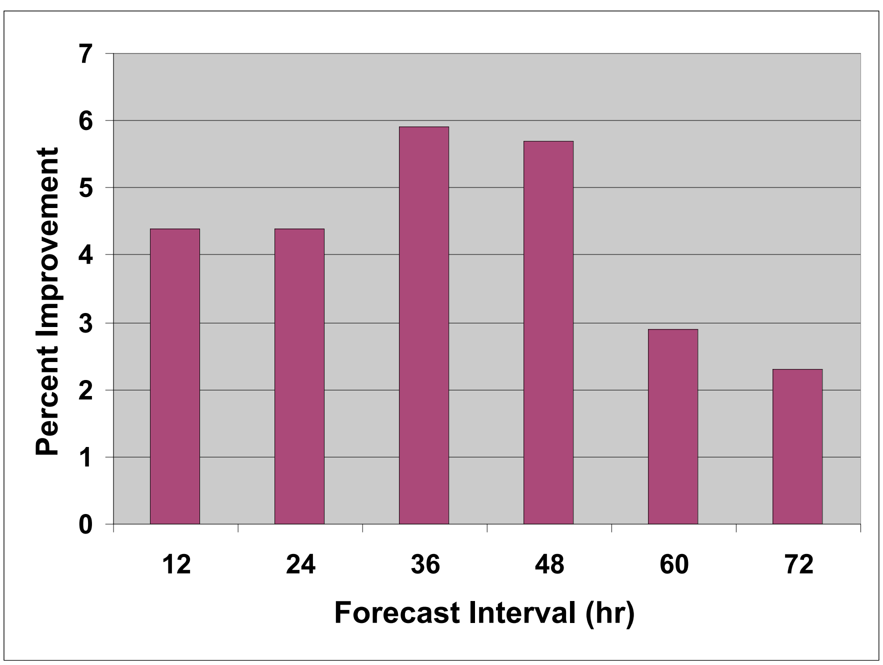


Figure 4. The improvement of the GRIP model relative to the SHIPS model for the dependent sample with aircraft data.

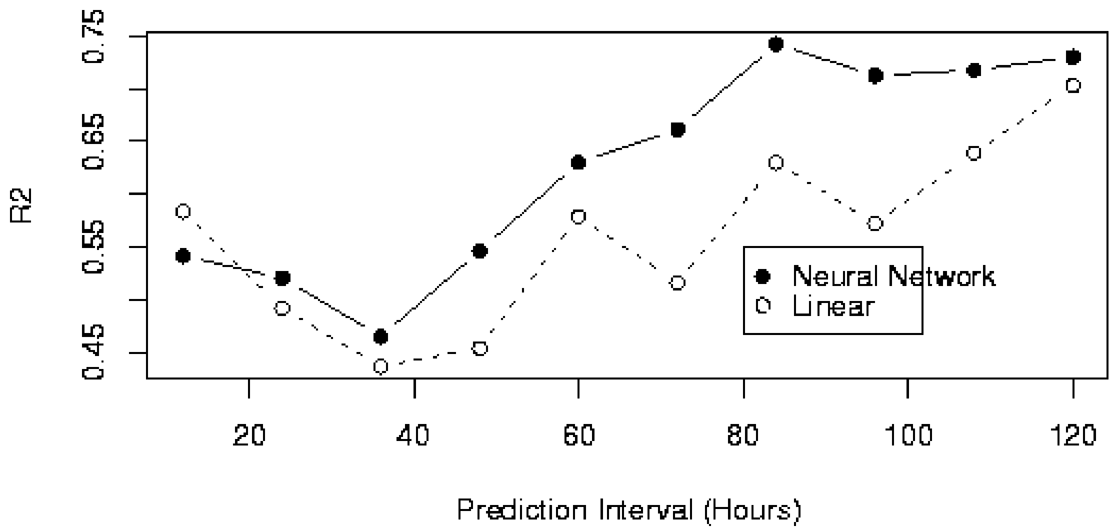
In the second year of the project, the GRIP model will be tested in real time during the 2004 hurricane season. Arrangements have already been made with Chris Sisko of TPC to make all of the aircraft flight level data available on the NCEP IBM in a format that can be used by the variational analysis system. It is anticipated that the real time testing will begin by August 1, and perhaps sooner. The initial version of the GRIP model will include only principal components from the symmetric tangential wind and GOES brightness temperatures. Work will continue to determine if there is predictive information in the symmetric radial wind field from the aircraft data, and the wave number one tangential wind field.

In addition, work is proceeding to determine if neural network methods can provide improved prediction. This part of the project is in collaboration with Dr. Charles Anderson from the Colorado State University Computer Science Department, who is an expert on computer learning techniques. The size of the sample with the aircraft data available does not warrant the use of a more sophisticated prediction method because the chance of over-fitting is high. However, the complete SHIPS database now has more than 3000 cases in the Atlantic and 4000 cases in the east/central Pacific. A neural network prediction model is being developed from this input, and will be compared with the standard SHIPS model, which utilizes a multiple linear regression technique. Figure 5 shows a comparison of the regression and neural network models for the Atlantic dependent sample from 1982-2003. This figure shows that, for the dependent sample, the neural network model explains a larger fraction of the variance, and has smaller absolute errors. The cases obtained during the 2004 season will provide an independent test to determine if the improvements in Fig. 5 can be obtained in real time, or are due to over-fitting of the dependent sample by the neural network model.

b. Improvements in Estimating Surface Wind Speed Probabilities

A major emphasis of the first year of funding was the creation historical forecast databases necessary for the development of the Monte Carlo wind probability model (MCP). These consisted of track and intensity errors associated with the official NHC (in the Atlantic and Eastern North Pacific), CPHC (in the Central Pacific) and JTWC (in the western North Pacific) forecasts. Along with the compilation of these errors, the time period of the sample was also considered. For the NHC and CPHC regions (Atlantic and eastern North Pacific) the time period 1997-2003 was chosen as it covers one extreme El Nino event and several very active Hurricane Seasons in the Atlantic. The time period 2001-2003 was chosen in the western North Pacific as the track errors had shown a significant improvement in the time period 1999-2000 and five-day forecasts were available during this time. Note at the time of writing of this report, final 2003 best track data for the western North Pacific were not yet available.

The prototype Monte Carlo model made use of a simple rendition of a climatology and persistence model to produce perturbations of wind radii based on intensity, storm speed, and latitude. Much time in the first year was utilized to improve the Atlantic wind radii climatology model, develop similar models for the eastern/central North Pacific and western North Pacific and to examine the details associated with the persistence of wind radii and their anomalies. As was the case in the Atlantic,



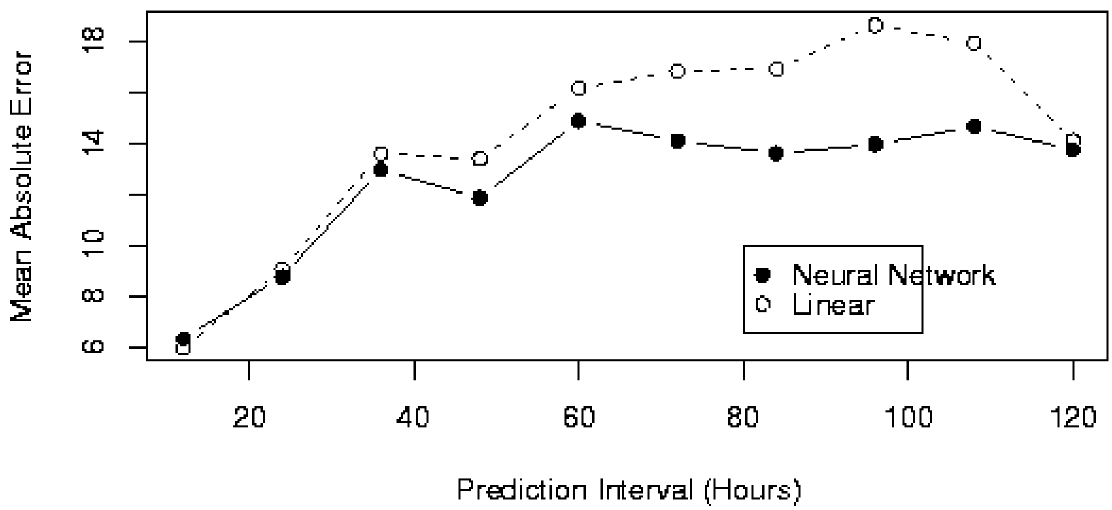


Figure 5. Comparison of the variance explained and the mean absolute maximum wind error (kt) for the neural network and linear regression fits to the 1982-2993 Atlantic SHIPS database.

developmental wind radii were obtained from the operational estimates, as wind radii are not part of the best track. In the Atlantic, where routine aircraft reconnaissance is carried out, the developmental dataset covered the period 1988-2003. In the other two basins the period 2002-2003 was used, as operational estimates of wind radii during this time were able to utilize remotely sensed surface wind data (e.g., QuikSCAT, ERS-2, SSMI etc.).

The wind radii climatology model was developed using the following parametric model (eq. 1)

$$V(r,\theta) = (v_m - a)\left(\frac{r_m}{r}\right)^x + a\cos(\theta - \theta_O) \quad \text{for} \quad r \ge r_m$$

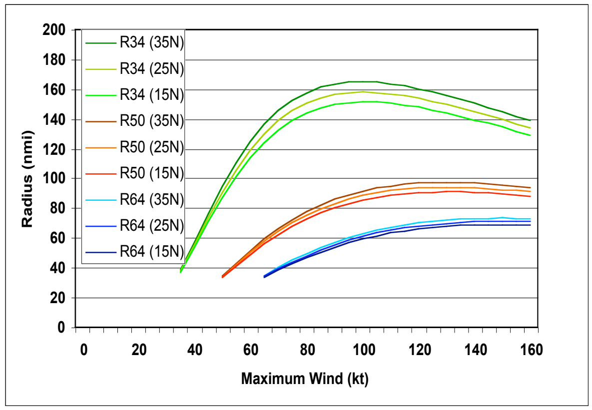
$$V(r,\theta) = (v_m - a)\left(\frac{r}{r_m}\right) + a\cos(\theta - \theta_O) \quad \text{for} \quad r < r_m \qquad (1)$$

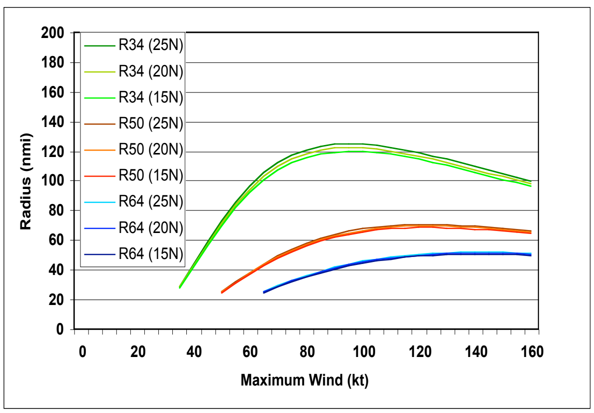
where θ is 90^0 to the right of the motion vector and x, r_m , a, and θ_0 are free parameters. The free parameters are assumed to be functions of latitude, storm speed and intensity as shown in equation 2.

$$\left.\begin{array}{l} \theta_O = t_0 + t_1\gamma + t_2 c \\ a = a_0 + a_1 c + a_2 c^2 + a_3\gamma \\ x = x_0 + x_1 v_m + x_2\gamma \\ r_m = m_0 + m_1 v_m + m_2\gamma \end{array}\right\}, \text{where} \left\{\begin{array}{l} \gamma \equiv \text{Lat - 25.} \\ c \equiv \text{Storm Speed} \\ v_m \equiv \text{max wind} \end{array}\right\} \qquad (2)$$

The final wind radii climatology models are determined by finding the coefficients in (2) that minimize the square error between the parametric wind model's wind radii estimates and the observations. The symmetric climatology models for these three basins are shown in Fig 6. Finally it was noted that there is an unrealistic tendency for the 34-kt wind radii to shrink for storms with higher intensities. For this reason, a bias correction is applied to the climatological estimate of R34 for storms that have intensities greater than 94 kt.

Persistence of wind radii can be combined with the climatology model in two ways. The first is associated with the symmetric aspects of the storm, which can be accounted for through the x parameter (or cyclone size) in the climatology model. It was found that the size parameter x persisted over a 12-h period with regression coefficients ranging from .7 to .4 depending on basin. Using these basin specific regression coefficients at each 12-hour time period the persistence of cyclone size is accomplished. The asymmetric portion of the initial conditions also should be allowed to persist. This was a shortcoming found in the prototype MCP. The initial asymmetries were found to persist in a systematic manner that closely followed an exponential decay with an e-folding time of 32 hours. In application, the parametric model is fit to the initial wind radii, which produces the initial x parameter. The wind radii differences between those predicted by the parametric model and the observed initial wind radii estimates are then calculated. These differences, which are added back to the parametric wind models wind radii estimates, are then allowed to decay exponential as the forecast time increases. This results in wind radii estimated by the model at t=0 to be identical to the operational estimates. Asymmetries also persist to some degree through 72 hours at which time wind radii estimates are essentially climatologically based. The wind radii CLIPER model used in the MCP is produced by the combination of the persistence of initial cyclone size and asymmetries with the basin-specific climatological model. A stand-alone version of the wind radii CLIPER model has been supplied to both NRL and NHC for independent testing and possible use as a wind radii forecast aid.





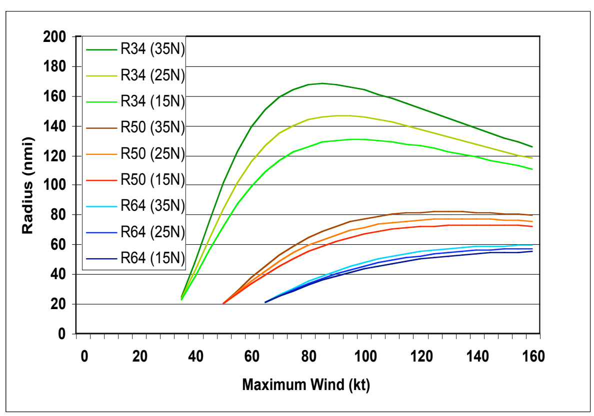


Figure 6: A family of curves based on latitude associated with the climatological wind radii models developed for the North Atlantic (top), eastern and central North Pacific (middle) and the western North Pacific (bottom).

During the first year, the MCP model was adapted to the eastern/central and western North Pacific basins. The code was supplied to NHC and NRL for testing and possible implementation for the bulk of the 2004 season. Once 2003 best track data is available for the west Pacific, track and intensity error files as well as the wind radii climatology model will be updated for that basin. The inclusion of these data will increase the sample size by roughly 1/3 and should result in an improvement in the error statistics. These prototype models still require testing and possible modification for completion of this project in 2005.

As can be imagined, the MCP can be a time consuming and CPU intensive process, especially if highly detailed spatial information such as that needed for the National Digital Forecast Database grid is desired (10 km grid over the entire continental U.S. and surrounding coastal waters). The final task of the first year was to develop a method to adapt the MCP to produce output for the NDFD grid. To accomplish this task an adaptive gridding strategy along with interpolation was utilized. It was found that a 30 km grid was all that was required to estimate the wind speed probabilities produced by the MCP. However, even with a 30 km grid spacing, the MCP with enough realization to give reliable probabilities (n=2000) takes more than 1 hour to run on a domain as large as that covered by the NDFD.

To alleviate this problem an adaptive gridding approach was developed. In this approach, a coarse grid (user selected) is used for the N. Atlantic domain and a finer grid (user selected) is applied to the area around the storm track. Then the areas within the finer grid that are far from the storms projected path are eliminated and points contained in that portion of the fine grid are not used. The final NDFD grid then can be interpolated from the coarse grid far from the storm track and from the fine grid near the storm track. This should allow for the creation of the NDFD grid in a timely and efficient manner. Adaptive grid routines were provided to NHC for testing and evaluation.

2. Things not Completed/Pending Items

This project is progressing as originally planned. There was some uncertainty in the use of the principal component technique for the aircraft and GOES data, since it was not obvious how many PCs would be needed. If the number were too large, then the number of predictors would be unreasonably large relative to the number of cases in the developmental sample. However, the number of PCs needed to explain 99% of the variance in the samples was even less than anticipated, so it appears that this method is viable. The efficiency of the MCP model and the method to treat the wind radii were uncertainties in the initial formulation, but these were addressed with the adaptive grid and the development of the wind radii climatology and persistence method.

In the second year of this project, the GRIP model and the MCP model will be run in real-time at the operational forecast centers, and a thorough evaluation will be performed.

3. Things that did not succeed

So far, this project is proceeding as planned.