14A.3 STATISTICAL TROPICAL CYCLONE INTENSITY FORECAST IMPROVEMENTS USING GOES AND AIRCRAFT RECONNAISSANCE DATA

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1. INTRODUCTION

Although some modest improvement has been made in operational tropical cyclone intensity forecasting in the past few years, the skill of the National Hurricane Center (NHC) intensity forecasts is only ½ to 1/3 that of the track forecast skill at 12-120 h (DeMaria et al 2005, hereafter D05). Because of the inherent difficulty in predicting intensity changes, statistical forecast methods such as the Statistical Hurricane Intensity Prediction Scheme (SHIPS) remain competitive short-range (12-72 h) forecast models. This is not the situation for track forecasting, where the accuracy of three dimensional prediction systems exceeded that of the simpler statistical techniques more than a decade ago (DeMaria and Gross 2003).

D05 showed that small improvements to the SHIPS model were obtained by including predictors from GOES channel 4 (10.7 μm) imagery and oceanic heat content (OHC) estimated from satellite altimetry data. Two simple GOES predictors were found to be statistically significant predictors of intensity change, including the percent of the area in the annular region from 50 to 200 km from the storm center with channel 4 brightness temperature (T_B) colder than -20^{o}C, and the standard deviation of T_B around an azimuth, radially averaged from 100 to 300 km. In this paper, an investigation is performed to determine if additional predictive skill can be obtained from GOES predictors that represent the radial structure of T_B, and from objective analyses of aircraft reconnaissance data. The underlying prediction equation assumed by the SHIPS model is also described, and a more general model is proposed.

2. THE SHIPS MODEL

The 2003 version of the SHIPS model is described in detail in D05. Sixteen independent variables that include climatology, persistence, atmospheric parameters such as vertical shear, and sea surface temperature (SST) are used to predict intensity changes (maximum sustained surface wind changes) from 12-120 h. An experimental version was also run in 2002 and 2003, where satellite input provide a correction to the basic SHIPS prediction when they were available. The satellite version was declared operational by NHC in 2004 and become the version provided to the forecasters. Most of the forecasts since 2004 included the satellite data.

Four changes were made to SHIPS for 2005. The empirical decay model was found to have a low bias (too much decay) for storms that moved over islands and narrow land masses. A revised decay model was implemented in 2005 to help correct this problem (DeMaria et al 2006). The second change is that prediction equations were developed for forecasts at 6 h intervals, rather than at 12 h intervals. Thus, separate regression equations were derived for forecast periods of 6, 12, 18, …, 120 h. The 6 h intervals were added to the dependent dataset as well, which doubled the sample size (although the effective sample size was not doubled due to serial correlations between the intensity changes separated by 6 h). The third change is that the database was extended back to 1982, which was the first full year when the Reynold's SST analyses were available. Previous versions of SHIPS used data back to 1989. The 1982-2004 sample includes 6554 cases with at least a 6 h forecast. The fourth change is that the SST was adjusted using an empirical eye wall ocean cooling parameterization developed by Joe Cione. The adjusted SST better matches what actually affects the surface fluxes near the storm center. This modification was implemented only in the Atlantic version of SHIPS.

3. GOES AND RECONNAISSANCE DATA

The GOES data are the same as described in D05. The T_B values relative to the storm center are azimuthally averaged on a 4 km radial grid, which extends from the storm center to the nearest edge of the sector over which the data were collected. The radial grid nearly always reaches at least 400 km. The standard deviations of T_B at each radial point are calculated from the azimuthal values on this same grid. The GOES data were obtained from the CIRA IR archive (Zehr 2000), which includes most tropical cyclone cases in the Atlantic and east Pacific back to 1995.

The flight level data from all available U.S. Air Force Reserve reconnaissance flights since 1995 were also collected. The data for each storm were divided into 6 h intervals to match the other SHIPS data. A three hour overlap was included to allow enough aircraft data to perform an objective analysis. For example, for a 6 UTC analysis, all of the data from 00 to 09 UTC were included.

The aircraft data for each 6 h period were put in storm relative coordinates and objectively analyzed to

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an evenly spaced cylindrical grid using the variational analysis system described by Mueller et al (2006). The analysis grid has a radial spacing of 4 km out to 200 km and an azimuthal spacing of 22.5^o. The variational analysis fits the data to the grid with smoothness constraints, after application of a quality control routine. The quality control automatically determines whether the data coverage is adequate for an analysis.

The advantage to using a cylindrical system is that more smoothing can be applied in the azimuthal direction than in the radial direction, which is consistent with the data coverage. The Air Force Reserve typically flies an alpha pattern with four radial legs. For the post-processed 10 second aircraft data, the radial spacing is about 2 km, while the azimuthal spacing is about 90^o. In real time, the data is only available at 30 s intervals. The radial smoothing is chosen to be consistent with what is available in real time.

Figure 1 shows an example from Hurricane Jeanne (2004) of the 30 s flight level data from the real time data feed at NHC after it is put in storm-relative coordinates. The objectively analyzed wind field is shown in Figs. 2-3. There are 808 wind fields available from 1995-2004 that also had corresponding satellite data. An additional 169 cases were obtained from the 2005 season. The analyses for the 1995-2004 cases utilized the post-processed 10 s data. The 2005 cases used the 30 s winds from the NHC real time data feed because the post-processed data are not available yet. As will be described later, the 2005 cases will be used for an independent evaluation of the algorithm developed from the 1995-2004 cases.

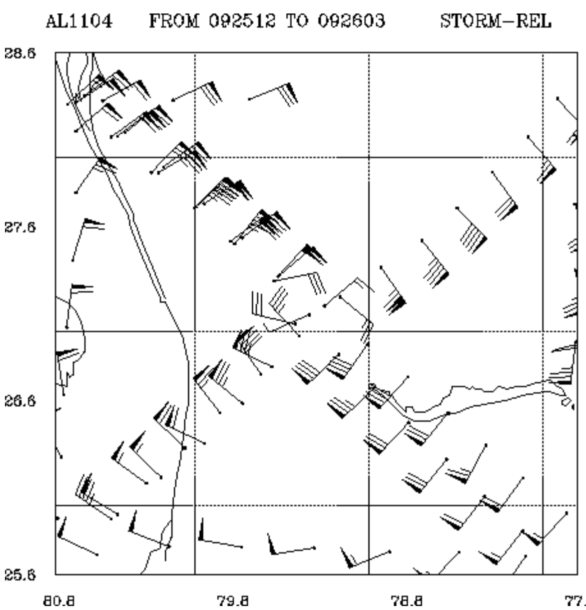


Figure 1. The flight level winds in storm-relative coordinates for the objective analysis of Hurricane Jeanne on 26 Sep 2004 at 06 UTC. For display purposes, only every 5th wind vector of the 30 s data is plotted.

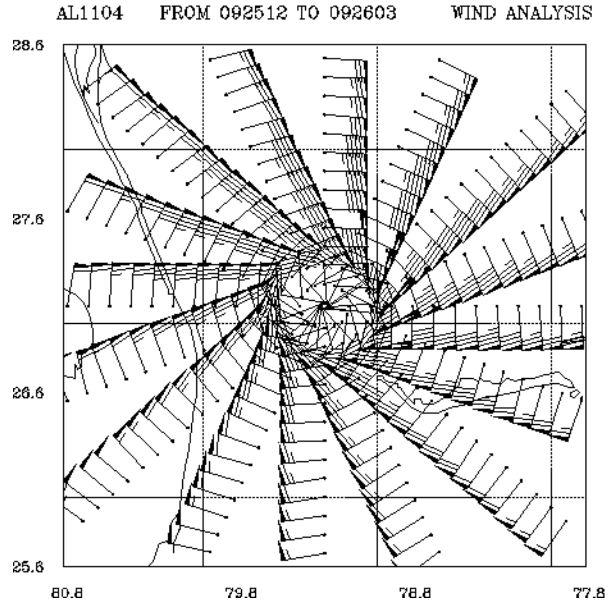


Figure 2. The objectively analyzed flight level winds for the Hurricane Jeanne case example.

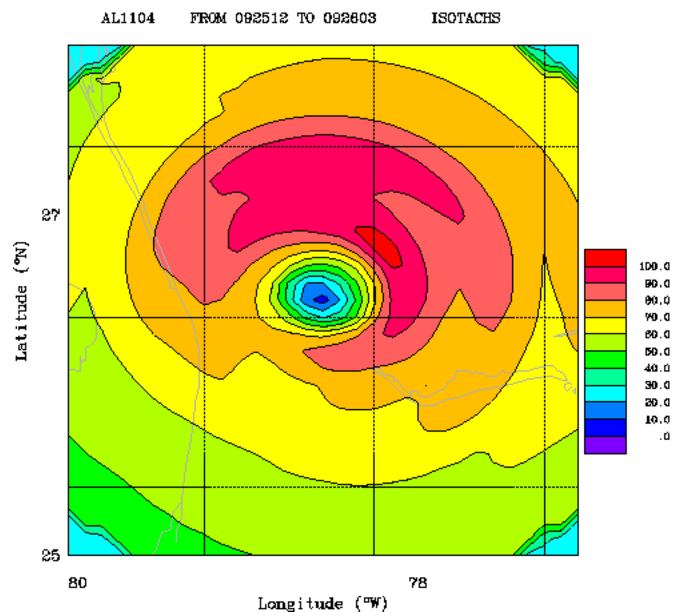


Figure 3. The istotachs (kt) of the objectively analyzed flight level winds for the Hurricane Jeanne example.

4. STATISTICAL ANALYSIS

As described by D05, the satellite data is included in the operational SHIPS model by applying a correction to the forecast based upon the basic 16 predictors. This method was used because the developmental sample with the satellite data was much smaller than the total sample. Thus, a second regression was performed with the satellite predictors as the independent variables, and the residuals from the fit from the basic SHIPS model with the 16 predictors as the dependent variable.

As described by Thomas et al (2006) in a study of the inclusion of predictors from microwave satellite imagery with SHIPS predictors, the residual approach reduces the impact of the additional information. Also, since the sample with reconnaissance data is even smaller than the set with GOES data, it would be necessary to predict the residuals of the residual model. To avoid these problems, the approach taken is to develop a completely independent prediction model using only those cases for which GOES and reconnaissance data are available. This system will be referred to as the GOES and Recon Intensity Prediction (GRIP) model.

For the GRIP model development, the sample includes the 808 cases from 1995-2004 that include GOES and reconnaissance data. Because these cases also include the OHC data from satellite altimetry, that information is also included in the GRIP model.

The starting point for the statistical development is the 16 basic SHIPS predictors and the OHC averaged along the storm track. These are supplemented by the additional predictors from the GOES data and objective analyses of the reconnaissance data. Tables 1 and 2 list the additional predictors from the GOES and recon data. The first two GOES variables in Table 1 are already included in the operational SHIPS model through the residual correction method, but their contribution may change when they are included directly. The other variables in Table 1are related to the radial structure of the GOES data. The 10th variable in Table 2 was motivated by the observation that storms tended to intensity more rapidly when they are small. When the KE becomes larger than the average for a given maximum wind storms tend to intensity less (Maclay 2006).

Table 1. Potential predictors from the GOES data

1. 100-300 km radially averaged T_B standard deviation
2. Percent area from r=50 to 200 km with T_B < -20^{o}C
3. Maximum T_B from 0 to 30 km (eye temperature)
4. Radius of maximum T_B from 0 to 30 km
5. Minimum T_B from 20 to 120 km (eyewall “cold ring” temperature)
6. Radius of minimum T_B from 20 to 120 km

The OHC and the 16 variables in Tables 1 and 2 were added to the basic 16 SHIPS variables, and the usual backward stepwise regression method was applied. Variables were removed until all remaining predictors were statistically significant at the 1% level for at least one forecast interval. This procedure resulting in five variables that significantly added predictive information, relative to the basic 16 SHIPS variables as shown in Table 3. The first three variables in Table 3 are those that are already included in the operational SHIPS residual model. The GOES eye and eyewall variables from Table 1 provided no additional predictive information. Two of the 10 recon variables from Table 2 provided significant predictive information. The coefficients of the two recon variables in Table 3 had signs that were expected from physical considerations. When the tangential wind averaged around the radius of maximum wind is larger, the storm intensifies. When the KE deviation from the mean value is negative, intensification is predicted.

Table 2. Potential predictors from recon analyses

1. Radius of maximum symmetric tangential wind (RMSTW)
2. Value of maximum symmetric tangential wind
3. Radius of maximum wind
4. Value of maximum wind
5. Tangential wind gradient just outside the RMSTW
6. 100-180 km average radial wind
7. 100-180 km average tangential wind
8. Radial wind averaged from r= -20 km to r=20 km from the RMSTW
9. Tangential wind averaged from r=-20 km to r=20 km from the RMSTW
10. Difference between the 0-200 km kinetic energy (KE) and the average KE of storms of the same intensity determined from the total recon sample

To determine the relative contributions of each of the variables in Table 3 to the intensity prediction, each variable was removed one at a time, and the difference in the variance explained by the total model fit and the variance without that variable was calculated. This variance difference provides a measure of how much additional information is provided by the variable that was removed. The variance difference when all five variables in Table 3 were removed was also calculated.

Figure 4 shows the variance added by each variable in Table 3 at each forecast time. The explained variance increases by almost 10% at the shorter time periods with five extra predictors. The first recon variable (the tangential wind averaged near the RMSTW) and the second GOES variable (the Tb standard deviation) are the most important for the increase in the earlier time periods. At the later times, the OHC and the second recon variable (the KE deviation) are most important

Table 3. The satellite and recon variables that provide additional intensity prediction information

OHC – The OHC averaged along the storm track
GOES1 – 100-300 km radially averaged T_B standard deviation
GOES2 - Percent area from r=50 to 200 km with T_B < -20^{o}C
RECON1 - Tangential wind averaged from r=-20 km to r=20 km from the RMSTW
RECON2 - Difference between the 0-200 km KE and the average KE of storms of the same intensity determined from the total recon sample

The mean absolute errors of the fit of the model to the intensity changes with the basic 16 variables and with the additional 5 variables from Table 3 were calculated. Figure 5 shows that the additional five variables in the GRIP model improves the mean absolute error by up to 11% relative to the basic 16 SHIPS predictors, with the maximum impact for the 48 h forecast. The improvements in Fig. 5 are much larger than those in the residual SHIPS model described by D05. This increased improvement is due to the additional predictive information from the recon data, and because the new variables are included directly with the 16 basic SHIPS predictors.

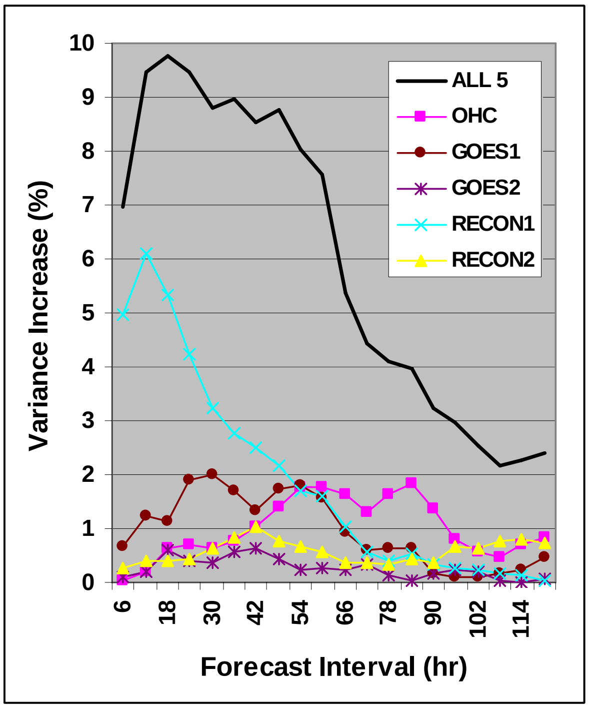


Figure 4. The increase in variance explained when the satellite and recon predictors in Table 3 are included.

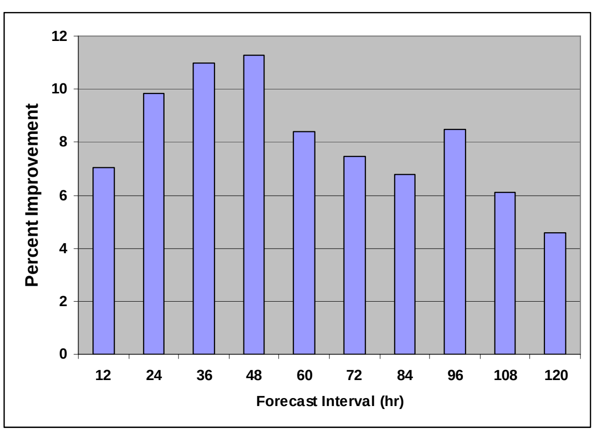


Figure 5. The percent improvement (reduction in mean absolute intensity error) due to the inclusion of the satellite and recon data in the GRIP model.

5. INDEPENDENT EVALUATION

Although the results in Fig. 5 are encouraging, the true evaluation of the model is its performance on independent cases, and under operational conditions with track errors, and where the atmospheric predictors are determined from GFS model forecasts, rather than from analyses. To further test the GRIP model, all of the 2005 cases were run using purely operational input, and the results were compared to the operational SHIPS forecasts (which already includes the GOES and OHC information using the residual method). Two sets of GRIP model coefficients were tested. The first were those developed from the 1995-2004 sample, which provides a purely independent test. As described previously, the 2005 sample of cases with recon data was very large (169 cases). The GRIP model coefficients were re-derived with those cases added, which increased the sample size by more than 20%. This second set of coefficients does not provide a valid operational evaluation, but helps to demonstrate the impact of a larger sample size.

Figure 6 shows the improvements in the GRIP model relative to SHIPS for the 2005 cases. With the independent coefficients, the forecasts were improved at 12 and 24 h, but were degraded at the longer time periods. This degradation is probably due to the small sample size, which does not provide an adequate fit to the basic 16 SHIPS predictors. With the dependent coefficients, the GRIP model forecasts are improved out to about 72 h, with little difference after that time. This result shows that the satellite and recon data can provide additional short term intensity predictive information. The accuracy of the model at the longer time periods will continue to improve as a larger sample of recon cases becomes available.

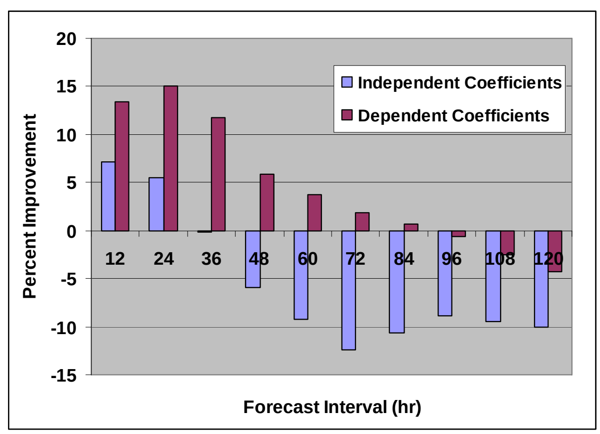


Figure 6. The improvements in the GRIP model relative to SHIPS for the 2005 Atlantic forecasts for the case with independent and dependent coefficients.

6. AN ALTERNATE PREDICTION EQUATION

The intensity forecast from the SHIPS model can be written as

$$
\begin{aligned}
V_6 &= V_0 + \Delta V_6 \\
V_{12} &= V_0 + \Delta V_{12} \qquad (1)\\
\vdots \quad & \quad \vdots \quad \vdots \\
V_{120} &= V_0 + \Delta V_{120}
\end{aligned}
$$

where ΔV_6 ΔV_{12} , …, ΔV_{120} are estimated from the predictors using the multiple regression relationships. Note that the intensity change over the entire forecast interval is estimated, and the regressions for each interval are completely independent. Thus, it would be possible to make the 120 h forecast without first calculating any of the earlier ones. Equations (1) can be rearranged to give

$$V_{j+1} = V_j + \alpha_{j+1/2}\,\Delta t \qquad (2)$$

where

$$\alpha_{j+1/2} = (\Delta V_{j+1} - \Delta V_j)/\Delta t \qquad (3)$$

and j=1, 2, …, 20 for Δt=6 h. Equation (2) is a finite difference form of the differential equation given by

$$dV/dt = \alpha(t) \qquad (4)$$

Thus, the SHIPS model can be interpreted as fitting the parameter α in (4) to observations of related variables such as SST and vertical shear. This parameter should be a very complex and nonlinear function of all the factors that control intensity changes. In the SHIPS model it is assumed to be a linear or quadratic function of the some of the factors related to the intensity tendency. Because many different types of processes are lumped together in α, it is not hard to understand why a very large sample size would be needed to estimate the functional form of this parameter. As described above, the small sample size is probably the main reason why the GRIP model (developed from 808 cases) did not improve on the operational SHIPS prediction (developed from 6554 cases) beyond 24 h.

A natural question to ask is whether an equation that is more general equation than (4) could be used as the starting point for fitting a model to observations. One possibility is to start with an equation that directly accounts for the maximum potential intensity (MPI). Several theoretical studies (Miller 1958; Bister and Emanuel 1998) have suggested that the maximum intensity that a tropical cyclone can reach is limited by the SST, the upper level environmental temperature and the lower level atmospheric moisture. The SHIPS model already includes an empirically derived MPI that is a function only of SST, which will be denoted by V_{SST}. An alternative to (4) is to consider the evolution of the maximum wind to be governed by

$$dV/dt = \kappa V - \beta V(V/V_{SST})^n \qquad (5)$$

where VSST is known from the SST along the storm track, the parameters β and n are assumed to be constant for all storms, and the parameter κ is a time dependent function that can be estimated from the SHIPS input parameters. Equation (5) is a slightly more general form of a differential equation that is often used to model species population growth (e.g., Boyce and DiPrima 1969). The first term on the right represents the species reproductive rate, and the second term on the right represents the mortality due to a limited food supply when the species population becomes large. For a constant V_{SST}, (5) has an analytic solution, and for variable V_{SST}, it can be solved numerically.

The behavior of (5) can be understood by considering two asymptotic forms. First, when $V << V_{SST}$ the second term on the right can be neglected, and the solution is simple exponential growth or decay, depending on the sign of κ. For positive κ, V eventually becomes close to V_{SST} and a steady state (V_{steady}) is reached (dV/dt = 0), which is given by

$$V_{steady} = V_{SST}(\kappa/\beta)^{1/n} \qquad (7)$$

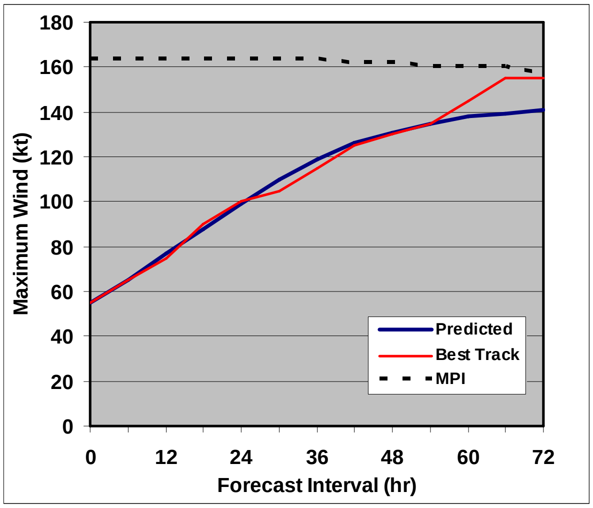
For the case where the growth rate (κ) and the relaxation time scale towards V_{SST} (β) are equal, the storm intensity approaches its MPI.

To determine the applicability of (5) as the underlying model for intensity prediction, the 1982-2004 SHIPS sample with a least a 72 forecast (3281 cases) were used. The parameters β and n were assumed to be constant for all 3281 cases, and a single value of κ was chosen for each case to determine the best fit of the numerical solution of (5) to the best track maximum winds at t+6, t+12, …, t+72 h. This analysis showed that the best fit was obtained when n=2 and β^{-1} = 24 h. The average error of the model fit to the best track maximum winds from 6 to 72 h was only 4.8 kt, with the maximum error of 8 kt at 72 h. These errors are close to the noise level of the best track data, where the intensities are rounded to the nearest 5 kt.

Figure 7 shows examples of the fit of (5) for a case from Hurricane Mitch (1998) and Hurricane Erin (2001). In the Mitch case, the initial intensity was well below the MPI and the storm intensified rapidly until its maximum winds approached the MPI. In the Erin case, the MPI decreased due to movement over cold water, and the intensity decreased in response to the change.

The above analysis shows that even with κ held fixed over a 72 h period, the solution to (5) provides a very good fit to the best track intensities. The challenge for an operational forecast is to provide an accurate estimate of the parameter κ as a function of time, from the basic SHIPS predictors. Because the upper bound intensity is built into (5), it is expected that a smaller sample size can be used to determine κ empirically compared to determining α in (4). Several versions are being tested. First, a very simple form is being developed where κ is estimated only from the vertical shear and the initial value of κ, which can be estimated from the previous 12 h intensity change. This version uses the full SHIPS sample. A second version that uses the basic 16 SHIPS variables is being tested, and a third version that uses the smaller sample of cases with the satellite and recon data, are also being evaluated.

Results of these tests will be reported in the conference presentation.



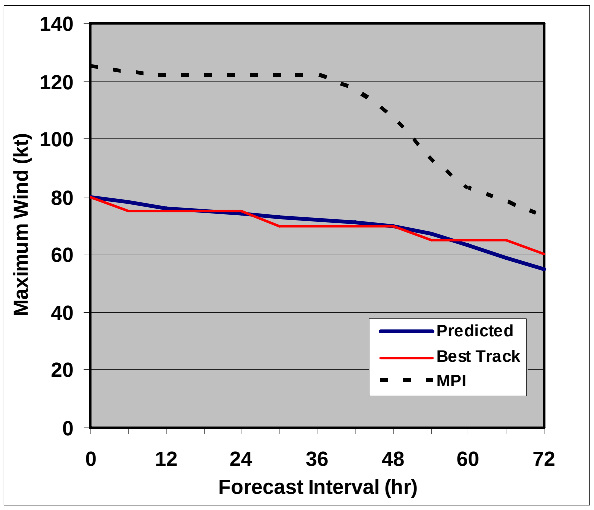


Figure 7. The 72 h solution to (5) with n=2 and β^{-1} = 24 h (blue lines) for a Hurricane Mitch beginning at 00 UTC on 24 Oct 1998 (top) and for Hurricane Erin beginning at 12 UTC on 12 Sep 2001(bottom). The best track intensities (red) and MPI (dashed black) are also shown. From the best fit, κ^{-1} = 29 h for the Mitch case and κ^{-1} = 77 h for the Erin case.

7. CONCLUDING REMARKS

Results from this work show that there is additional intensity prediction information in variables determined from satellite data and objective analyses of aircraft reconnaissance observations, relative to the basic SHIPS model. The impact of this data for the dependent sample is greater when the new predictors are directly combined with the other SHIPS predictors than for the case when satellite data was added using a residual method that is currently employed by the operational SHIPS model. The disadvantage of including the additional information directly is that the sample size is restricted to the cases where all data types are available. For the 1982-2004 SHIPS sample, there are 6554 cases with at least a 6 h forecast, but only 808 cases with satellite and reconnaissance data available.

A separate prediction model was developed that includes the satellite and recon input (the GOES and Recon Intensity Prediction, GRIP) model from the 808 available cases from 1995-2004. An evaluation on 169 independent cases from the 2005 season, which were run under fully operational conditions, showed that the GRIP model improved upon the SHIPS forecasts by about 5% at 12 and 24 h. However, the forecasts were degraded at later times. This result suggests that the GRIP model sample size was too small to adequately determine the prediction coefficients. The additional cases from 2005 will increase the sample size by more than 20% for testing during the 2006 season.

An analysis of the SHIPS prediction system shows that it can be interpreted in terms of a model fitting approach, where the underlying prediction equation is very simple. A more general prediction system is proposed that implicitly includes the effects of maximum potential intensity (MPI). With the MPI effects already included, the fitting of the other model parameters may not require as large of a sample size. Testing of this new underlying prediction system will continue during the 2006 hurricane season.

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