An Updated Statistical Hurricane Intensity Prediction Scheme (SHIPS) for the Atlantic and Eastern North Pacific Basins

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ABSTRACT

Updates to the Statistical Hurricane Intensity Prediction Scheme (SHIPS) for the Atlantic basin are described. SHIPS combines climatological, persistence, and synoptic predictors to forecast intensity changes using a multiple regression technique. The original version of the model was developed for the Atlantic basin and was run in near–real time at the Hurricane Research Division beginning in 1993. In 1996, the model was incorporated into the National Hurricane Center operational forecast cycle, and a version was developed for the eastern North Pacific basin. Analysis of the forecast errors for the period 1993–96 shows that SHIPS had little skill relative to forecasts based upon climatology and persistence. However, SHIPS had significant skill in both the Atlantic and east Pacific basins during the 1997 hurricane season.

The regression coefficients for SHIPS were rederived after each hurricane season since 1993 so that the previous season's forecast cases were included in the sample. Modifications to the model itself were also made after each season. Prior to the 1997 season, the synoptic predictors were determined only from an analysis at the beginning of the forecast period. Thus, SHIPS could be considered a ''statistical–synoptic'' model. For the 1997 season, methods were developed to remove the tropical cyclone circulation from the global model analyses and to include synoptic predictors from forecast fields, so the current version of SHIPS is a ''statistical–dynamical'' model. It was only after the modifications for 1997 that the model showed significant intensity forecast skill.

1. Introduction

Operational forecasting of tropical cyclone intensity change remains a challenging task. Forecast skill is often measured by comparison of errors with those from forecasts based upon climatology and persistence. In the Atlantic and eastern North Pacific basins, the CLIPER (Climatology and Persistence; Neumann 1972) and SHIFOR (Statistical Hurricane Intensity Forecast; Jarvinen and Neumann 1979) models are often used as baselines for track and intensity errors, respectively. These two models use statistical regression techniques to predict track or intensity. Input includes current storm position and intensity, their time tendencies, and Julian day. Figure 1 shows the average track and intensity errors of the official National Hurricane Center (NHC) forecasts normalized by the appropriate climatology and persistence errors, for a 5-yr sample (1993–97). This figure shows that the intensity forecasts were skillful in the short range (12–24 h), but did not have nearly as much skill as the track forecasts after 24 h.

Part of the reason for the limited intensity forecast skill is the lack of accurate guidance models. To help overcome this problem, a Statistical Hurricane Intensity Prediction Scheme (SHIPS) was developed for the Atlantic basin (DeMaria and Kaplan 1994a, hereafter DK94). SHIPS uses climatological, persistence, and synoptic predictors in a multiple regression scheme to forecast intensity (1-min maximum sustained surface winds) out to 72 h. The synoptic predictors are evaluated from the initial analysis of the aviation run of the National Centers for Environmental Prediction (NCEP) Medium Range Forecast model (hereafter, the aviation model). DK94 presented results from a jackknife procedure (where each storm was removed from the developmental sample, and the regression coefficients rederived), which suggested that SHIPS could improve upon SHIFOR by 10%–15%. The version of SHIPS described by DK94 was run in near–real time during the 1993–95 Atlantic hurricane seasons, and minor mod-

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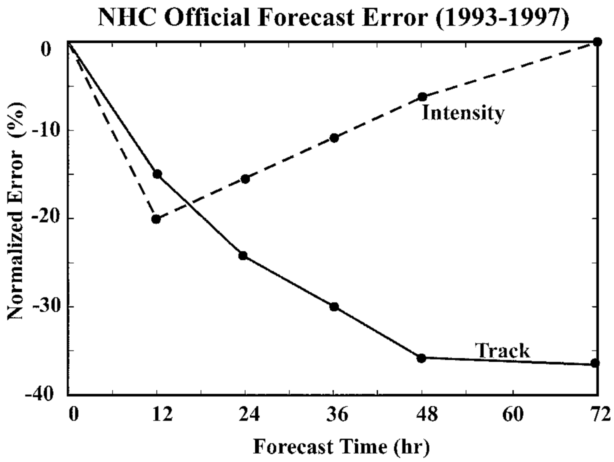

FIG. 1. The average NHC track and intensity forecasts for the period 1993–97. The errors were normalized by the average errors from climatology and persistence models (CLIPER for track and SHIFOR for intensity). A negative normalized error indicates improvement over climatology and persistence (forecast skill).

ifications were made after each year. These forecasts were run at the Hurricane Research Division (HRD) and made available to the NHC forecasters within about 6 h after synoptic time. Unfortunately, the SHIPS forecasts with completely independent data showed little improvement over SHIFOR.

For the 1996 season, SHIPS was incorporated into the NHC operational forecast cycle and a version was developed for the eastern North Pacific basin. The code was ported to NHC computer systems and the forecasts were generated within about 2 h after synoptic time. With this modification the predictions were available in time for preparation of the NHC official forecasts, which are issued at 3 h after synoptic time. Also, the climatological sea surface temperature (SST) analyses used to estimate one of the thermodynamic predictors were replaced with weekly analyses. Results from the 1996 season showed that SHIPS had modest skill relative to SHIFOR in the Atlantic, but it did not have skill in the east Pacific.

Although some improvements were made to SHIPS from 1993 to 1996, a major limitation was that forecast fields from the aviation model were not used to evaluate the synoptic predictors (only the initial analysis was used). To determine if predictors from forecast fields could be included, the 850–200-mb vertical shear (one of the most important synoptic predictors) evaluated from the aviation forecasts along the storm track were compared with the shear evaluated from the initial analysis along the track. These two estimates of shear were verified against the shear estimated from the actual analyses. Aviation model forecasts that were archived during the 1994 season were used for this comparison. Results showed that the average errors of the shear along the storm track calculated from the forecast fields from the aviation model were larger than those evaluated using only the initial analysis. The relatively large errors of shear with the forecast fields were primarily due to the aviation model representation of the tropical cyclone. The aviation model is a global spectral model (Surgi et al. 1998), which includes a tropical cyclone ''bogussing'' scheme (Lord 1991). Thus, the vertical shear evaluated from the forecast fields contains a contribution from the model tropical cyclone and the storm environment if the track of the model storm did not match the observed track. This result suggested that it is necessary to remove the aviation model representation of the tropical cyclone from the forecast fields before the synoptic predictors can be reliably estimated.

After the 1996 season, a filtering technique was developed to remove the tropical cyclone circulation from the initial analysis of the aviation run. These modified fields were then used to initialize a simple limited area model, with boundary forcing from the aviation model, to provide forecast fields for the evaluation of the synoptic predictors. This technique was applied to all of the cases from 1989 to 1996 and the model coefficients were rederived. The technique was also applied in the operational forecasts during 1997.

This paper describes the evolution of SHIPS from 1993 to 1997. In section 2, the modifications and performance of the Atlantic basin version of SHIPS are described for each year during the period 1993–96. The filtering technique for the evaluation of the synoptic predictors from forecast fields and performance of SHIPS during the 1997 season are presented in section 3. In section 4, the version of SHIPS for the east Pacific basin is described.

2. Modification and performance of SHIPS 1993–96

SHIPS uses a standard multiple regression technique to predict intensity changes at 12, 24, . . . , 72 h. The dependent variable is the change of the maximum sustained surface winds and the independent variables are climatological, persistence, and synoptic variables. The nominal accuracy of the maximum wind estimates is 5 kt, since the wind values are rounded to this interval in the NHC best track data file. However, the intensities of nearly all of the east Pacific cases and about half of the Atlantic cases (those east of 50°W longitude) were estimated primarily from satellite observations. Comparisons of satellite and aircraft reconnaissance intensity estimates (e.g., Olander and Velden 1997) suggest that the average error in the minimum central pressure is about 10 mb, which corresponds to a wind error of 10–15 kt. Although a discussion of the relationships between minimum surface pressure and maximum winds, and aircraft flight-level and surface winds, is beyond the scope of this paper, these factors are additional sources of error in the best track winds.

The DK94 version of SHIPS was developed from a sample of all named Atlantic tropical cyclones from

TABLE 1. Predictors used in the DK94 (first 11) and later versions of SHIPS.

1) POT	Maximum possible intensity-initial intensity
2) SHR	Magnitude of 850–200-mb vertical shear
3) DVMX	Intensity change during previous 12 h
4) REFC	200-mb relative eddy angular momentum flux convergence
5) PEFC (removed 1995)	200-mb planetary eddy angular momentum flux convergence
6) JDAY	Absolute value of Julian day—253
7) LONG (removed 1994)	Initial storm longitude
8) DTL (removed 1994)	Distance to nearest major landmass
9) SIZE (removed 1997)	850-mb relative angular momentum
10) DSHR (removed 1996)	Time tendency of vertical shear magnitude
11) POT2	POT^2
12) T200 (added 1995)	Average 200-mb temperature within 1000 km of storm center
13) U200 (added 1995)	Average 200-mb zonal wind within 1000 km of storm center
14) Z850 (added 1997)	Average 850-mb vorticity within 1000 km of storm center
15) LSHR (added 1997)	SHR times the sine of the initial storm latitude
16) D200 (added 1998)	Average 200-mb divergence within 1000 km of storm center
17) SPDX (added 1998)	Zonal component of initial storm motion vector
18) VMX (added 1998)	Initial storm maximum wind

1989 to 1992, and a few cases from the period 1982–88. The sample included the depression stages of each storm, but was restricted to cases that remained over water during the forecast period. The final sample included 510 cases at 12 h and 300 cases at 72 h, where the forecasts for each storm were separated by at least 12 h (all cases began at 0000 or 1200 UTC). Separate regressions were performed for each forecast interval, but for consistency of the forecasts with independent data, the same predictors were used for all forecast periods out to 72 h. A backward stepping procedure was used to select predictors that were significantly different from zero at the 95% level at one or more forecast intervals. A second backward stepping procedure was applied to the six quadratic combinations of the three most significant linear predictors, but with a 99% significance criterion. These significance criteria were also used in all modifications of SHIPS to be described later. The independent and dependent variables were normalized by subtracting the sample mean and dividing by the standard deviation (Steel and Torrie 1980). This normalization allows the direct comparison of regression coefficients for different variables and forecast intervals.

Table 1 lists the predictors used in the DK94 and later versions of SHIPS. The first 10 linear predictors are listed in order of the their importance in the DK94 model, as determined by the magnitude of the regression coefficients averaged from 12 to 72 h. The DK94 linear predictors were chosen from a pool of 15 climatological, persistence, and synoptic variables that were used previously in SHIFOR, or that were suggested by previous research studies as being correlated with intensity changes. The final regression explained about 37% of the variance of the intensity changes at 12 h and 56% at 72 h.

It may be surprising that the variance explained by the regression is larger for the longer forecast intervals. However, as explained in DK94, this increase is due to the fact that the intensity estimates are rounded to the nearest 5 kt, and the accuracy of the estimates is probably closer to 10 kt as described previously. For the 12-h forecasts, the average magnitude of the intensity changes is about 5 kt, which is the same order as the accuracy of the dependent variables. For the longer-range forecasts, the average intensity changes are larger, so the accuracy of the wind estimates is less of a problem.

The most important predictor is POT, which is the difference between the maximum possible intensity (MPI) and the current intensity. The MPI was estimated from the empirical relationship described by DeMaria and Kaplan (1994b), where MPI is a function of SST. The SST was estimated from the monthly climatological analysis presented by Levitus (1982), linearly interpolated to the date and position of the storm. The MPI was averaged along the track of the storm using the ''best track'' positions at 12-h intervals. When SHIPS was run in real time, the VICBAR model (Aberson and DeMaria 1994) was used to estimate the storm positions during the forecast period. The VICBAR tracks were used in place of the official NHC track forecasts because the official forecasts were not routinely available at HRD where SHIPS was first run. The square of POT was the only quadratic predictor included in the DK94 version of SHIPS.

DVMX, JDAY, and LONG in Table 1 are climatological and persistence variables that are evaluated at the beginning of the forecast interval. DTL is the distance to nearest major landmass and is evaluated at the end of the forecast interval using the method described by Merrill (1987). The remaining variables represent ''synoptic'' effects. The values of these predictors are determined from synoptic analyses, where the spline fitting technique described by Ooyama (1987) was used to combine rawinsonde, aircraft, and satellite cloud track wind data. The initial analyses from the aviation model were used as background fields for the spline analyses. All of the synoptic variables except SHR and DSHR are evaluated at the beginning of each forecast period.

TABLE 2. Normalized SHIPS errors (%) for Atlantic intensity forecasts 1993–97. A negative number indicates skill relative to SHIFOR (improvement over climatology and persistence). The sample size at each forecast interval is indicated in parentheses.

	Forecast interval (h)				
Year	12	24	36	48	72
1993	0 (133)	1 (112)	7 (94)	2 (80)	−23 (56)
1994	−3 (110)	−8 (91)	−5 (75)	−5 (59)	43 (32)
1995	1 (468)	1 (428)	1 (389)	5 (347)	14 (285)
1996	0 (341)	−1 (309)	−5 (279)	−5 (251)	−7 (210)
1997	−3 (104)	−7 (86)	−18 (70)	−28 (59)	−31 (44)

SHR was averaged along the storm track, analogous to MPI, but only the initial analysis was used to determine the values of SHR. Also, the time average included the SHR values to a maximum of 36 h. DSHR was estimated by subtracting the value of SHR at the 24-h storm position from the value at the beginning of the forecast period.

The skill of the DK94 version of SHIPS was evaluated by comparison of forecast errors with those from the operational SHIFOR model (Jarvinen and Neumann 1979), which uses climatological and persistence predictors to forecast intensity change. For this comparison, a jackknife procedure was applied to the forecast cases from 1989 to 1992, where all of the data from each storm were removed from the sample, and the SHIPS regression coefficients were rederived. The best track input was replaced by the operational initial position and intensity estimates, and the VICBAR tracks were used to estimate the positions during the 72-h forecast periods in order to simulate operational conditions. In addition, a method was developed to run the model at the intermediate synoptic times (0600 and 1800 UTC) because the NHC issues a 72-h forecast every 6 h. Since the analyses were only available at 0000 and 1200 UTC, the synoptic predictors for the intermediate synoptic times were estimated from a 6-h-old analyses, but with the updated track and initial intensity input. Results from this evaluation suggested that SHIPS could improve upon SHIFOR by 10%–15%, and these improvements were statistically significant at all forecast periods from 12 to 72 h. The significance test accounted for serial correlation between forecast cases, and used the 95% level to determine if the SHIPS errors were smaller than those of SHIFOR.

Encouraged by the results from the jackknife evaluation, the version of SHIPS described above was run in near–real time during the 1993 hurricane season. As described in the introduction, the 1993 forecasts were produced at HRD and made available to the NHC forecasters within about 6 h after synoptic time. Table 2 shows the average SHIPS intensity errors normalized by the appropriate SHIFOR errors. The sample in Table 2, and in all other comparisons of SHIPS and SHIFOR in this paper, include the depression, tropical storm, and hurricane stages of each storm, but exclude cases where the track crossed land. As shown in Table 2, for the 1993 Atlantic hurricane season SHIPS improved upon SHIFOR by 23% at 72 h. However, this improvement was not statistically significant, and the SHIPS errors were greater than or equal to the SHIFOR errors at 12–48 h.

An evaluation of individual 1993 forecasts showed that SHIPS tended to overforecast the intensity of very low latitude storms. Although the 1993 Atlantic hurricane season was relatively quiet, a much larger fraction of the storms were at low latitudes than in the developmental sample. Theoretical results (e.g., Jones 1995; DeMaria 1996) suggest that the ability of a vortex to remain vertically coupled in a sheared environment depends on the Rossby penetration depth, which is proportional to the Coriolis parameter. These results suggest that low-latitude storms are more sensitive to vertical shear than higher-latitude systems. To account for this effect in SHIPS, the vertical shear was scaled as follows:

$$S = \mathrm{SHR}/[c + \sin(\theta)], \tag{2.1}$$

where S is the scaled value of shear, θ is the storm latitude, and c is an empirical constant. The 1993 cases were added to the developmental sample, and the constant c was chosen to maximize the variance explained by the regression. Results showed that the value $c = 0.1$ was optimal, so that the scaled shear at 10°N is twice as large as the scaled shear at 27°N for the same value of SHR. The backward stepping procedure was repeated with the scaled shear and the inclusion of the 1993 data. In this case, the LONG and DTL listed in Table 1 were no longer significant predictors.

The revised version of SHIPS described above (with the scaled shear and without LONG and DTL) was run in near–real time during the 1994 hurricane season. Table 2 shows that during 1994, SHIPS improved upon SHIFOR by 3%–8% at 12–48 h (although these improvements were not statistically significant), but was about 43% worse than SHIFOR at 72 h. The 1994 Atlantic season was relatively quiet, and the poor performance at 72 h was primarily due to a single storm (Hurricane Florence). Florence was a late-season storm (4–10 November) that intensified to 95 kt at a relatively high latitude (37°N) and over fairly cold water (SSTs of 22°–24°C). SHIPS consistently underforecast its intensity. Examination of the synoptic analyses in the environment of Florence showed that the 200-mb temperatures were 1°–2°C colder than for the sample average. Examination of several other storms in the developmental sample (Isidore 1990, Bonnie 1992, and Charley 1992) that intensified over relatively cool water also had anomalously cold environments at 200 mb.

To improve SHIPS for the 1995 season, the cases from 1994 were added to the developmental sample, and the 200-mb temperature averaged over a circular area with a radius of 1000 km centered on the initial storm position (T200) was added as a potential predictor. As described previously, the original sample for SHIPS included a few cases from 1982 to 1988. However, the synoptic analyses for the cases prior to 1989 did not include temperature, so these cases were excluded from the developmental sample. Also, the spline analyses of temperature were not very reliable, due to the difficulty with quality control of the observations. Therefore, the spline analyses were replaced with the background fields for the spline analyses (the initial analyses for the aviation model). Results showed that T200 was the third most important predictor in the regression (behind POT and SHR). The regression coefficients for T200 are negative, which indicates that intensification is favored when the 200-mb temperature is colder than normal.

Also after the 1994 season, a coding error in the calculation of the 200-mb planetary eddy momentum flux convergence (PEFC in Table 1) was identified (P. Fitzpatrick 1995, personal communication). When the error was corrected, PEFC was no longer a significant predictor. With the error, a variable that was proportional to the area-averaged 200-mb zonal wind was being included as a statistically significant predictor. Based upon this result, the 200-mb zonal wind (U200) averaged over the same area as T200 was included as a new predictor. The regression coefficients for U200 are negative, indicating that intensification is favored when the 200-mb zonal wind is more easterly than normal. This relationship is consistent with operational forecast guidelines since 200-mb winds are more easterly than normal equatorward of an upper-level ridge, which is considered a favorable region for intensification.

The modified version of SHIPS described above (with the developmental sample from 1989 to 1994, the spline analyses replaced by the aviation model initial analyses, and with PEFC removed and T200 and U200 added as predictors) was run in near–real time during the 1995 Atlantic season. That season provided a very large sample of independent forecast cases, with 19 named storms. Unfortunately, SHIPS did not improve upon SHIFOR at any forecast interval (Table 2). The difficulty in 1995 appeared to be related to the T200 predictor that was added. In 1995, the average 200-mb temperature in the tropical regions was 1°–2°C warmer than normal for most of the hurricane season, which resulted in an underprediction of the storm intensity. This temperature increase was confirmed with rawinsonde observations, which indicates that it was not an artifact due to changes in the aviation model between the 1994 and 1995 hurricane seasons.

The 1995 cases were added to the developmental sample, and SHIPS was rederived for the 1996 season. The same predictors were included in the 1996 model as in the 1995 version, except that DSHR was eliminated because it was no longer significant. The T200 variable was retained, but was not nearly as important in the regression. To improve the accuracy of the POT predictor, the climatological SST analyses were replaced with the weekly SST analyses described by Reynolds and Smith (1993). These SST analyses are available in real time, and for all forecast cases in the developmental sample. This replacement increased the variance explained by the regression by about 2% at 72 h. Also for the 1996 season, SHIPS was made fully operational. The code was converted to the NCEP Cray computer so that it could be initiated by the NHC forecasters as part of the operational forecast cycle. In 1996, NCEP began to run the aviation model four times per day (rather than twice per day). To make the operational version of SHIPS timely, all forecasts (0000, 0600, 1200, and 1800 UTC) used a 6-h-old aviation analysis to estimate the synoptic predictors. As will be described in section 5, a version of SHIPS for the east Pacific was developed for the 1996 season. Because VICBAR is not run for east Pacific storms, and is not always timely, the track forecasts for SHIPS were obtained from the Limited Area Sine Transform Barotropic (LBAR) model. LBAR is a simplified version of VICBAR (Horsfall et al. 1997) that was implemented in 1996, and runs for Atlantic and east Pacific storms. When the model was moved from HRD to NHC, it was still necessary to use a model track rather than the official NHC track because the fully operational version of SHIPS is run before the official forecast is generated.

Table 2 shows that SHIPS had modest forecast skill for the 1996 season, although the improvements relative to SHIFOR were not statistically significant. A limitation of the 1996 version of SHIPS was that the synoptic variables were estimated from the initial analysis of the aviation model (forecast fields were not used). To overcome this problem, a method was developed to remove the tropical cyclone vortex from the aviation initial condition, and to provide forecast fields without the storm circulation. This method is described in greater detail in the next section.

3. Modification and performance of SHIPS 1997

As described in the introduction, the aviation model representation of the tropical cyclone makes it difficult to estimate the synoptic predictors in the storm environment during the forecast period. Prior to the implementation of the vortex bogussing system in 1992 (Lord 1991), the model representation of the storm was sometimes a problem at the initial time because the tropical cyclone was not always in the proper location. Figure 2 shows an example of this difficulty for Hurricane Gabrielle 1989, where the center of the storm in the initial analysis was about 200 km from the observed storm location. Thus, when a parameter such as vertical shear is determined, the winds near the true storm location are affected by the model tropical cyclone in addition to the storm environment.

A number of methods have been used to remove a vortex circulation from analyses. Kurihara et al. (1995) have developed a sophisticated procedure that involves the removal of a symmetric circulation centered on the observed storm position, and then reanalyzing the wind

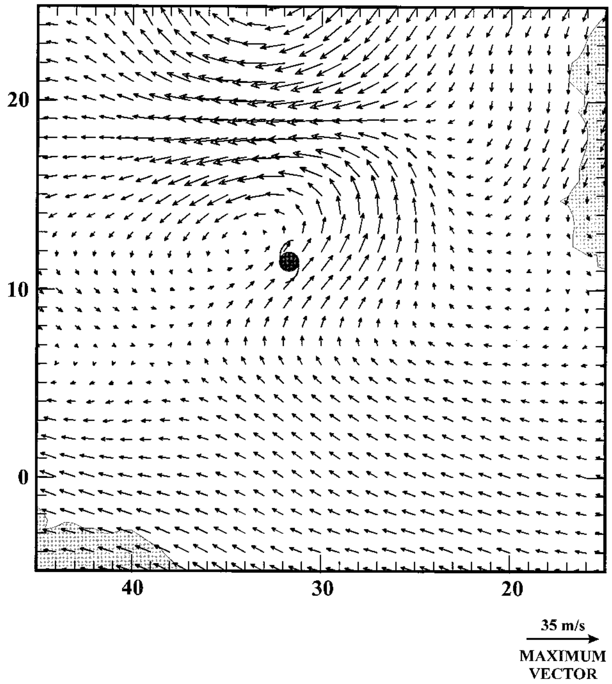

FIG. 2. The 850-mb wind from the aviation model initial analysis for 0000 UTC 1 Sep 1989. The actual location of Hurricane Gabrielle is indicated by the hurricane symbol.

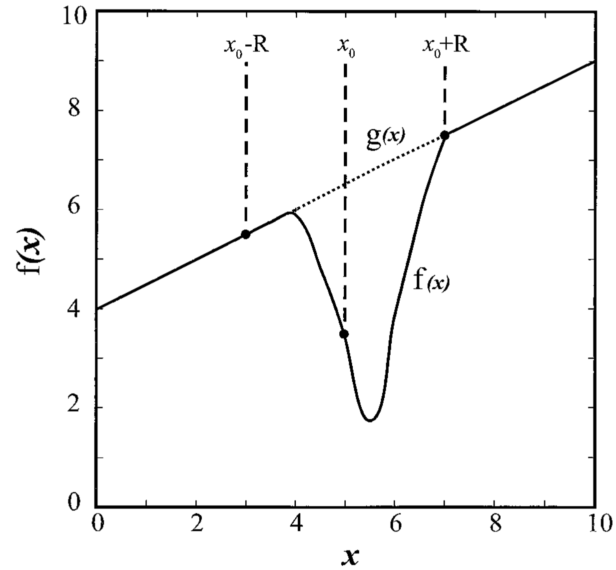

FIG. 3. The combination of a linear function and a Gaussian centered at $x = 5.5$ with an e-folding radius of 1.0 (solid line) and a linear function that matches $f(x)$ at $x = x_0 + R$ and $x = x_0 - R$ (dashed).

field inside of a specified distance from the storm center. Although this method provides a reasonable environmental flow field for the Geophysical Fluid Dynamics Laboratory hurricane model, it may not work as well for some of the earlier cases when the aviation tropical cyclone was not in the proper location. Low-pass filters have also been applied to remove the storm circulation (e.g., Elsberry et al. 1993; DeMaria 1985). These methods have been applied with some success, although the optimal frequency cutoff of the filter is probably storm dependent.

A simpler method for removing the storm circulation for SHIPS was developed as a two-dimensional extension of linear interpolation. First, consider a one-dimensional function $f(x)$ on some domain $[0, L]$. Now, suppose $f(x)$ contains a small-scale perturbation within a distance R of the point x_0 (but necessarily centered at x_0) as illustrated in Fig. 3. The perturbation could be removed by linearly interpolating $f(x)$ between the points $x_1 = x_0 - R$ and $x_2 = x_0 + R$. Letting $g(x)$ represent the linearly interpolated function, $F(x)$ the replacement for $f(x)$ valid over the entire domain, $f_1 = f(x_0 - R)$, and $f_2 = f(x_0 + R)$, then

$$F(x) = \begin{cases} f(x) & \text{for } |x - x_0| \geq R \\ g(x) & \text{for } |x - x_0| < R, \end{cases} \tag{3.1}$$

where

$$g(x) = mx + b \tag{3.2}$$

$$m = (f_2 - f_1)/(x_2 - x_1) \quad \text{and} \tag{3.3}$$

$$b = f_1 - mx_1. \tag{3.4}$$

Another way to formulate the linear interpolation problem is to use (3.1) as the definition of the modified function $F(x)$, and define $g(x)$ as the solution to Laplace's equation in one dimension as follows:

$$d^2g/dx^2 = 0 \tag{3.5}$$

$$g(x_0 - R) = f_1 \tag{3.6}$$

$$g(x_0 + R) = f_2. \tag{3.7}$$

It is straightforward to show that (3.2)–(3.4) is the solution to the boundary value problem (3.5)–(3.7). The advantage to writing the linear interpolation as a boundary value problem is that this form can be generalized to two dimensions. Suppose there is a perturbation of the function $f(x, y)$ within a distance R of the point (x_0, y_0), and let $F(x, y)$ represent the modified version of the function $f(x, y)$. Then,

$$F(x, y) = \begin{cases} f(x, y) & \text{for } r \geq R \\ g(x, y) & \text{for } r < R, \end{cases} \tag{3.8}$$

where

$$\nabla^2 g = 0 \tag{3.9}$$

$$g(x, y) = f(x, y) \quad \text{at } r = R \tag{3.10}$$

$$r = [(x - x_0)^2 + (y - y_0)^2]^{1/2} \tag{3.11}$$

and ∇^2 is the two-dimensional Laplacian operator. For

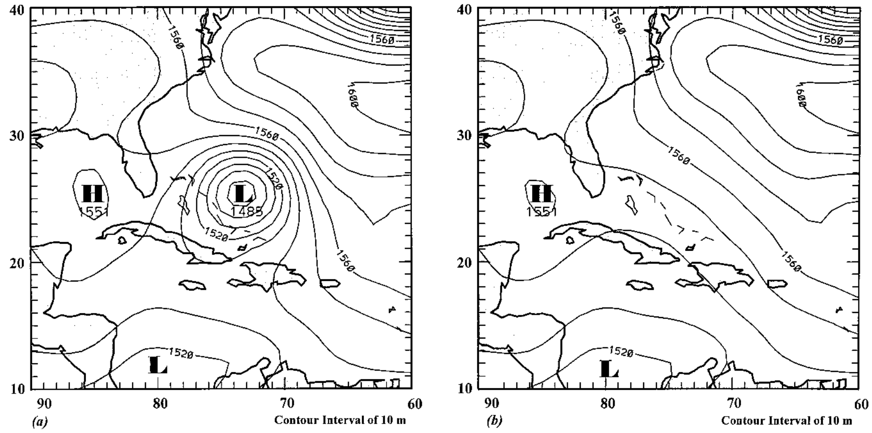

FIG. 4. The 850-mb geopotential height from the aviation model at 0000 UTC 4 Sep 1996 (a) before and (b) after the application of the Laplacian filter. Hurricane Fran was located very close to the height minimum near the center of (a).

the remainder of this paper, the solution to (3.8)–(3.11) will be referred to as a Laplacian filter.

For development of SHIPS, the aviation model initial analyses of wind, temperature, geopotential height, and relative humidity were saved on a 2° lat–long grid (2.5° prior to 1996) at all mandatory levels (except 925 mb) from 1000 to 100 mb. Equations (3.8)–(3.11) were used to remove the vortex circulation from these analyses, where Laplace's equation (3.9) was solved using a standard relaxation technique for all grid points within a radius R of the best track storm position. The value of *R* was 800 km at 1000 mb and decreased linearly as a function of pressure to 500 km at 100 mb. These values of R were chosen to cover the typical aviation model representation of the storm circulation as a function of pressure. Figures 4 and 5 show the 850-mb geopotential height field and the 200-mb wind field for Hurricane Fran (1996) before and after application of the Laplacian filter. Figure 4 shows that the filter effectively removed the vortex circulation from the analysis. In Fig. 5, the storm circulation was not well represented at 200 mb, and the filter had only a small effect on the wind field at this level.

The above procedure removes the tropical cyclone circulation from the initial analysis of the aviation model. In principle, the Laplacian filter could also be used to remove the circulation from the model forecast, provided that the point (x_0, y_0) was chosen close enough to the location of the storm in the aviation model forecast. One difficulty with this approach is that only the initial conditions from the aviation forecasts were archived. It would then be necessary to use the ''perfect prog'' approach where analyses are used to estimate the predictors during the forecast period for the model development, and forecast fields are used operationally (Neumann 1988). However, it is likely that the predic-

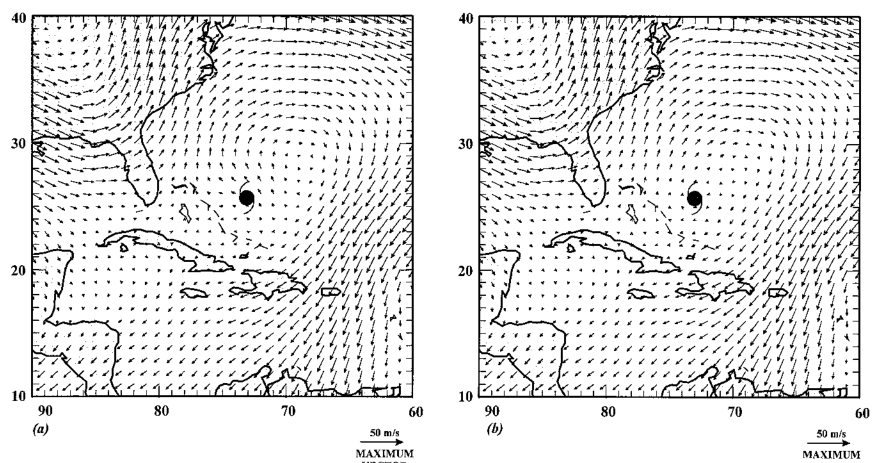

FIG. 5. The 200-mb wind from the aviation model at 0000 UTC 4 Sep 1996 (a) before and (b) after the application of the Laplacian filter. The location of Hurricane Fran is indicated by the hurricane symbol.

tors from the analyses would be more accurate than those from the forecast fields, and the strength of the relationship between the predictors and the intensity changes would be overestimated by the regression. Another difficulty is that the convective heating associated with the model tropical cyclone can significantly modify the storm environment (Ross and Kurihara 1995). However, the storm in the model forecast is rarely in the proper location, especially later in the forecast period. For example, during the 1997 Atlantic hurricane season, the average 72-h track error of the aviation model was about 550 km. Therefore, the environment is being modified by a heat source that is not always in the proper location.

To overcome the above difficulties, an alternate approach was used. The analysis from the aviation model (after the application of the Laplacian filter) was used to initialize a simple limited area model, which was run for 72 h to provide the forecast fields. For this purpose, the LBAR model described by Horsfall et al. (1997) was generalized to include vertical structure. The hydrostatic primitive equations on a Mercator projection with a sigma vertical coordinate are solved using the energy-conserving vertical finite difference method described by Arakawa and Lamb (1977). The spectral method described by Chen et al. (1997) is used in the horizontal. This spectral method divides the dependent variables into a boundary part, which satisfies Laplace's equation on the interior of a limited area domain with inhomogeneous boundary conditions, and the residual part that satisfies homogenous boundary conditions, and is expanded in a double sine series. The transform method (Orszag 1970) is used to evaluate the nonlinear terms. A centered time-differencing scheme is used to solve the equations for the amplitudes of the sine function expansions.

To estimate the predictors for the multiple regression analysis, it was necessary to run the limited area model out to 72 h for every forecast case back to 1989. For this reason, it was necessary to make the model as efficient as possible. The model includes 10 equally spaced sigma levels, where the model top is at 100 mb. The sine expansions in x and y are truncated at wavenumber 16 on a 5120 km $\times$ 5120 km domain, centered on the initial storm location, which results in a transform grid spacing of 150 km. This resolution is roughly equivalent to a T64 truncation in a global spectral model with spherical harmonic basis functions. The boundary conditions for the cases back to 1989 were obtained from the initial analyses from the aviation model. Operationally, the boundary conditions are obtained from the aviation model forecasts. Thus, the development of the new version of SHIPS does use perfect prog boundary conditions, since these are obtained from analyses for the model development, and from forecasts in real time. However, the accuracy of the predictors in the developmental and operational cases is probably more similar than if analyses were used for the total field in the model development, and forecasts were used operationally.

The limited-area model solves the "dry" primitive equations, and does not include any parameterizations of boundary layer or diabatic processes, since its primary purpose is to fill in the wind and temperature fields in the region that is influenced by the tropical cyclone. The spectral method used to solve the model equations ensures that the wind and temperature at the boundaries matches that of the aviation model. However, due to the lack of physical parameterizations in the limited area model, a method was developed to increase the influence of the aviation model on the limited area model solution. For this purpose, nudging terms were added to the prognostic equations for wind and temperature. For example, the equation for the zonal wind has the form

$$\partial u/\partial t + \ldots = -\alpha(u - u_a), \qquad (3.12)$$

where u_a is the zonal wind from the aviation model and α is the nudging coefficient. The coefficient α decreases from a value of 1.4×10^{-4} s^{-1} at the boundary to zero at a distance of 1500 km from the nearest boundary. This term provides a more gradual transition from the aviation model fields to those of the limited area model.

To develop SHIPS for the 1997 Atlantic season, the limited area model was run for all forecast cases from 1989 to 1996. This sample included 1025 cases at 12 h and 605 cases at 72 h, from 85 different storms. The predictors from the version of SHIPS used in 1996 were included as potential predictors, with two modifications. The SIZE predictor, which is an estimate of the angular momentum of the outer storm circulation at 850 mb, was not included because the Laplacian filter removes most of the storm circulation from the analysis and the forecast fields. This predictor was replaced by an 850-mb environmental vorticity parameter (Z850), which is the relative vorticity at 850-mb averaged over a circular area within a radius of 1000 km of the storm position. The other modification was to replace the scaled shear parameter in (2.1) with the original shear variable (SHR), and a new quadratic predictor given by the product of the shear and the sine of the initial storm latitude (LSHR). This modification eliminates the need to estimate the empirical constant c in (2.1), but still allows the effect of shear to vary with latitude.

Table 3 shows the values of the normalized regression coefficients, where the linear predictors are listed in order of their importance. For the regression, POT was evaluated along the track of the storm, out to 72 h, as described previously, but with all of the linear synoptic predictors (SHR, T200, U200, REFC, Z850) evaluated only at the beginning of each forecast period. Then, the most significant synoptic predictor (SHR in this case) was averaged along the storm track out to a maximum of 12 h, out to a maximum 24 h, etc., where the values were determined from the limited area model forecasts. The averaging period that maximized the variance explained by the model was chosen for the operational

TABLE 3. Normalized regression coefficients for the 1997 version of SHIPS for the Atlantic basin. Coefficients that are significant at the 95% level are underlined, r^2 is the percent of the total variance explained by the regression, and N is the developmental sample size.

Variable	Forecast interval (h) 12	24	36	48	60	72
POT	+0.62	+0.69	+0.73	+0.79	+0.84	+0.96
SHR	−0.35	−0.43	−0.43	−0.43	−0.44	−0.42
DVMX	+0.40	+0.30	+0.23	+0.18	+0.13	+0.08
T200	−0.08	−0.13	−0.15	−0.18	−0.20	−0.22
U200	−0.08	−0.11	−0.15	−0.19	−0.20	−0.21
Z850	+0.09	+0.12	+0.13	+0.13	+0.14	+0.14
REFC	+0.07	+0.07	+0.07	+0.09	+0.12	+0.14
JDAY	−0.03	−0.03	−0.04	−0.05	−0.08	−0.10
POT2	−0.30	−0.24	−0.21	−0.22	−0.24	−0.34
LSHR	+0.23	+0.27	+0.26	+0.25	+0.24	+0.24
r^2	36	40	45	50	53	54
N	1025	929	836	752	676	605

TABLE 4. The mean, 90th, 95th, and 99th percentiles of the SHIPS and SHIFOR error distributions (kt) for the combined 1996–97 Atlantic forecast sample. The SHIPS values are listed first and N is the sample size.

Percentile	Forecast interval (h) 12	24	36	48	72
Avg	8/8	11/11	13/14	15/17	19/21
90th	16/17	21/24	25/29	28/33	38/42
95th	20/20	25/27	30/34	36/41	44/54
99th	25/27	31/37	45/48	50/54	58/74
N	445	395	349	310	254

version of SHIPS. Using this procedure, SHR is averaged along the storm track out to a maximum of 48 h, T200 and REFC are averaged to 24 h, and U200 and Z850 are only evaluated at the initial time. Because no synoptic predictors are included beyond 48 h, it is only necessary to run the limited area model out to two days for the operational forecasts.

Table 3 shows that most of the predictors were statistically significant at the 95% level at all forecast intervals, and the signs of the coefficients are consistent with physical reasoning. The predictors POT, DVMX, Z850, and REFC have positive coefficients that indicate that intensification is favored when the current intensity is well below the maximum potential intensity, a storm has intensified in the previous 12 h, the synoptic environment at 850 mb is more cyclonic than average, and the upper-level relative eddy angular momentum fluxes are more positive than average. The predictors SHR, T200, U200, and JDAY have negative coefficients, which indicates that intensification is favored when the shear is low, the 200-mb temperature is colder than average, the 200-mb zonal wind is more easterly than average, and the date is close to the most active day of the Atlantic hurricane season. The positive coefficients for LSHR indicate that the negative effect of shear on intensity will be partially canceled for higher-latitude storms. The negative coefficient for POT2 reduces the effect of POT on intensity change for large values of POT. This reduction might be due to weak systems that have large values of POT, but lack the organization to intensify rapidly.

The variance explained by the model is also shown in Table 3. These values are about the same as those in DK94. This similarity appears to indicate that all of the modifications, including the addition of time-dependent synoptic predictors, have not added much to the model, relative to the original version described by DK94. However, compared with the results in DK94, there are fewer predictors in Table 3 that are not significant, and the sample size is more than twice as large. Also, the variance explained by the model was evaluated separately for the period 1989–92 (the majority of the DK94 sample). In this case, the variance explained ranged from 42%–65% at 12–72 h, which is 5%–9% larger than in DK94.

The version of SHIPS described above was run operationally during the 1997 Atlantic hurricane season. Table 2 shows that SHIPS improved upon SHIFOR at all forecast intervals from 12 to 72 h, with a maximum improvement of 31% at 72 h. Statistical tests showed that this improvement was significant at 36, 48, and 72 h, which is encouraging because the NHC official intensity forecasts have the least skill at these time periods (Fig. 1). Table 2 also shows that the sample size was fairly small. All of the 72-h forecasts came from only three storms (Tropical Storm Ana and Hurricanes Claudette and Erika). Thus, although these results are very promising, and the model skill passed a standard statistical significance test that accounts for serial correlation, further evaluation will be required to confirm the ability of the model to improve upon SHIFOR by up to 31%.

The skill of the 1997 version of SHIPS indicates that the mean of the SHIPS error distribution was smaller than that of the SHIFOR distribution. Other measures of skill that compare various percentiles of the error distributions could also be defined. However, because the 1997 sample size was fairly small, it was difficult to calculate percentiles. To get some idea of the error distributions, the 90th, 95th, and 99th percentiles were calculated for the combined 1996 and 1997 Atlantic samples, as shown in Table 4. Although the 1996 version of SHIPS did not include the Laplacian filter or the forecasted synoptic predictors, it did have modest skill relative to SHIFOR. Table 4 shows that SHIPS tended to have larger improvements relative to SHIFOR for the higher percentiles than for the mean. For example, the mean SHIPS error at 72 h for the combined 1996–97 sample was about 10% less than that of SHIFOR, but the 95% percentile was about 18% less than that of SHIFOR. This result suggests that SHIPS is more likely to reduce the largest forecast errors, which tend to occur for rapidly intensifying or decaying cases.

TABLE 5. Normalized SHIPS errors (%) for east Pacific intensity forecasts 1996–97. A negative number indicates skill relative to SHIFOR (improvement over climatology and persistence). The sample size at each forecast interval is indicated in parentheses.

	Forecast interval (h)				
Year	12	24	36	48	72
1996	−4 (129)	9 (111)	15 (94)	18 (79)	22 (54)
1997	1 (323)	−5 (290)	−9 (254)	−9 (220)	−12 (167)

TABLE 6. Normalized regression coefficients for the 1997 version of SHIPS for the east Pacific basin. Coefficients that are significant at the 95% level are underlined, r^2 is the percent of the total variance explained by the regression, and N is the developmental sample size.

	Forecast interval (h)					
Variable	12	24	36	48	60	72
POT	$\underline{+0.72}$	$\underline{+0.88}$	$\underline{+0.89}$	$\underline{+0.88}$	$\underline{+0.87}$	$\underline{+0.87}$
DVMX	$\underline{+0.54}$	$\underline{+0.42}$	$\underline{-0.30}$	$\underline{+0.21}$	$\underline{+0.14}$	$\underline{+0.09}$
U200	$\underline{-0.09}$	$\underline{-0.10}$	$\underline{-0.11}$	$\underline{-0.11}$	$\underline{-0.10}$	$\underline{-0.10}$
SHR	−0.06	−0.07	−0.02	$\underline{+0.04}$	+0.10	$\underline{+0.14}$
T200	−0.03	−0.04	$\underline{-0.05}$	$\underline{-0.06}$	$\underline{-0.07}$	$\underline{-0.08}$
Z850	+0.01	+0.01	+0.02	+0.03	$\underline{+0.05}$	$\underline{+0.06}$
JDAY	+0.03	+0.02	+0.02	+0.04	−0.02	−0.04
REFC	+0.02	+0.02	+0.01	+0.01	−0.01	−0.01
POT2	$\underline{-0.39}$	$\underline{-0.41}$	$\underline{-0.34}$	$\underline{-0.26}$	$\underline{-0.21}$	$\underline{-0.17}$
LSHR	−0.10	−0.02	−0.09	$\underline{-0.17}$	$\underline{-0.23}$	$\underline{-0.27}$
r^2	54	56	58	61	64	66
N	1433	1340	1245	1150	1058	966

4. Development of SHIPS for the east Pacific

When SHIPS was made fully operational in 1996, a version was also developed for the east Pacific. The developmental sample included the same years as for the Atlantic (1989–95). For convenience, the same predictors used for the Atlantic version were included in the east Pacific model, but with different regression coefficients. The empirical relationship for estimating the MPI as a function of SST was replaced with a method appropriate for the east Pacific (Whitney and Hobgood 1997). The exponential relationship between SST and MPI in the Atlantic becomes a linear function in the east Pacific. Analogous to the 1996 Atlantic version of SHIPS, the SSTs were estimated from weekly analyses. One other modification was that 20 August was considered the peak of the east Pacific hurricane season (WMO 1993) for the calculation of the JDAY variable (rather than 10 September for the Atlantic).

Table 5 shows the normalized forecast errors for the 1996 season. This table shows that SHIPS did not have any forecast skill in 1996, except at 12 h. However, the skill at 12 h was not statistically significant. Analogous to the Atlantic, the 1996 SHIPS forecasts did not estimate predictors from forecast fields and did not include the Laplacian filter for removing the vortex circulation from the aviation model analyses.

For the 1997 season, the 1996 cases were added to the developmental sample and the east Pacific model was rederived using the same methodology as for the Atlantic. Table 6 shows the normalized regression coefficients for the 1997 east Pacific version of SHIPS, where the linear predictors are listed in order of their average magnitude. Comparing Tables 3 and 6 shows that the east Pacific sample was 40%–50% larger than that for the Atlantic, and the regression explained 12%–18% more of the variance at 12–72 h. The order of importance of the predictors in the east Pacific is somewhat similar to that in the Atlantic, although fewer of the coefficients are statistically significant. The POT and PER variables have larger coefficients in the east Pacific (except at 72 h), but most of the other predictors have smaller coefficients. This reduction suggests that it may be more difficult to improve upon climatology and persistence in the east Pacific. Two of the variables (JDAY and REFC) were not significant at any forecast interval. The lack of significance of the JDAY predictor might be due to the fact that the east Pacific hurricane season is less peaked than the Atlantic season (WMO 1993). The relatively low latitude of the east Pacific storms (sample average latitude of 17°N) relative to the Atlantic (sample average latitude of 24°N) may explain why the REFC coefficient was not significant, since the storms are less likely to be affected by upper-level troughs. Even though they were not significant, these variables were included in the model. As can be seen in Table 6, the coefficients for these two predictors are very small, so that they have little effect on the forecast.

The signs of most of the coefficients in Table 6 are the same as those in Table 3, consistent with physical reasoning. The exceptions are JDAY, REFC, and SHR at some forecast intervals. As described above, the coefficients for JDAY and REFC were not significant and the magnitudes were small. However, the SHR coefficient was significant at 72 h, but has a positive sign, indicating that higher shear favors intensification. This apparent contradiction is related to the interaction with the LSHR predictor. For the Atlantic sample (Table 3), the magnitude of the SHR coefficient is always larger than that of LSHR, so the combined effect is a negative correlation that decreases in magnitude with increasing latitude. In the east Pacific, the majority of the relationship is included in the LSHR term, which has a negative coefficient. Thus, the combined effect of the SHR and LSHR terms still results in a negative correlation with intensification.

Table 5 shows that SHIPS improved upon SHIFOR at all forecast periods except 12 h. Although the percent improvement over SHIFOR is not as large as for the Atlantic, the skill was still statistically significant at 36, 48, and 72 h. As described above, the synoptic predictors were generally less important in the east Pacific, so it is not surprising that the improvement over climatology and persistence is less than for the Atlantic.

Table 7 shows the 90th, 95th, and 99th percentiles of the SHIPS and SHIFOR error distributions for the combined 1996–97 east Pacific sample. Similar to the At-

TABLE 7. The mean, 90th, 95th, and 99th percentiles of the SHIPS and SHIFOR error distributions (kt) for the combined 1996–97 east Pacific forecast sample. The SHIPS values are listed first and *N* is the sample size.

Percentile	Forecast interval (h)				
	12	24	36	48	72
Avg	8/8	13/13	18/18	21/22	23/24
90th	18/17	26/28	36/39	42/46	44/51
95th	22/24	37/40	44/47	51/58	52/62
99th	41/44	53/60	67/80	70/81	67/70
N	452	401	348	299	221

lantic forecasts, SHIPS tended to show greater improvement relative to SHIFOR for the higher percentiles than for the sample mean.

5. Concluding remarks

Updates to the Statistical Hurricane Intensity Prediction Scheme (SHIPS) for the Atlantic basin were described, and a version for the eastern North Pacific was developed. SHIPS combines climatological, persistence, and synoptic predictors to forecast intensity changes using a multiple regression scheme. The primary modifications relative to the original version of SHIPS described by DeMaria and Kaplan (1994a) are the replacement of the climatological SSTs with weekly SST analyses; the inclusion of synoptic predictors estimated from initial and forecast fields, rather than from initial analyses alone; and a larger developmental sample. To remove the influence of the aviation model representation of the storm from the fields used to estimate the synoptic predictors, a Laplacian filter was applied to the model initial condition. These filtered fields were then used to initialize a simple 10-level dry-adiabatic atmospheric model, forced by the aviation model fields on the boundaries. This procedure provided large-scale analyses and forecast fields that are not influenced by the storm circulation. The version of SHIPS with the predictors from forecast fields can be considered a ''statistical–dynamical'' model, while the previous versions were ''statistical–synoptic'' models, using the terminology of Neumann and Pelissier (1981).

The statistical–dynamical versions of SHIPS for the Atlantic and east Pacific were implemented in 1997. Results showed that the SHIPS forecasts had statistically significant skill (relative to climatology and persistence forecasts) at 36, 48, and 72 h in both basins. The SHIPS forecasts showed a larger improvement over climatology and persistence for the Atlantic sample.

The above results are encouraging, although further cases are necessary to confirm these results. The model will be run during the 1998 season, with a few minor modifications. The 1997 cases will be added to the developmental sample, and preliminary tests suggest that three additional linear predictors will be included, as listed at the bottom of Table 1. For the Atlantic, the area averaged (1000-km radius) 200-mb divergence is significant, and for the east Pacific, the initial storm intensity and the zonal component of the storm motion are also significant. However, the magnitudes of the coefficients for these predictors are smaller than those of the first few predictors in Tables 3 and 6, so it is not expected that the version of SHIPS for 1998 will be significantly different than the 1997 version. Preliminary results from the 1998 season suggest that the model has forecast skill after 24 h in the Atlantic and east Pacifc basins.

The current version of SHIPS only considers environmental influences on intensity change. Further improvements may be possible by including satellite information near the storm center, as was demonstrated by Fitzpatrick (1997) for western Pacific storms. Another method for providing storm-scale information would be to include aircraft reconnaissance data when it is available (typically, only for the Atlantic). Samsury and Rappaport (1991) have developed a method for short-term intensity prediction based solely on flight-level wind profiles. Another possibility for improvement is to replace the multiple regression technique with a neural network approach. Baik and Hwang (1998) have shown that a simple climatology and persistence intensity prediction scheme for western North Pacific storms based upon a neural network was superior to a multiple regression model with the same input parameters. These enhancements are topics for future research and development.

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