On the Decay of Tropical Cyclone Winds Crossing Narrow Landmasses

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ABSTRACT

A method is developed to adjust the Kaplan and DeMaria tropical cyclone inland wind decay model for storms that move over narrow landmasses. The basic assumption that the wind speed decay rate after landfall is proportional to the wind speed is modified to include a factor equal to the fraction of the storm circulation that is over land. The storm circulation is defined as a circular area with a fixed radius. Application of the modified model to Atlantic Ocean cases from 1967 to 2003 showed that a circulation radius of 110 km minimizes the bias in the total sample of landfalling cases and reduces the mean absolute error of the predicted maximum winds by about 12%. This radius is about 2 times the radius of maximum wind of a typical Atlantic tropical cyclone. The modified decay model was applied to the Statistical Hurricane Intensity Prediction Scheme (SHIPS), which uses the Kaplan and DeMaria decay model to adjust the intensity for the portion of the predicted track that is over land. The modified decay model reduced the intensity forecast errors by up to 8% relative to the original decay model for cases from 2001 to 2004 in which the storm was within 500 km from land.

1. Introduction

Prior to the landfall of Hurricane Hugo in 1989, it had been 20 years since a category 4 or 5 hurricane struck the continental United States. Hugo was moving at about 22 kt (1 kt $\approx$ 0.5144 m s^{-1}) with 1-min maximum sustained surface winds of 120 kt when it made landfall just north of Charleston, South Carolina, and hurricane-force wind gusts penetrated as far inland as Charlotte, North Carolina (Case and Mayfield 1990). This storm helped to provide a renewed focus on the effects of inland winds from tropical cyclones.

Motivated in part by Hurricane Hugo and with support from the U.S. Federal Emergency Management Agency, Kaplan and DeMaria (1995, hereinafter KD95)

developed a simple empirical model for estimating tropical cyclone winds after landfall in the United States for storms south of 37°N. This model assumes that the intensity decay rate at any time after landfall is proportional to the intensity at that time, which results in an exponential decay equation for the maximum wind as a function of time after landfall. Kaplan and DeMaria (2001, hereinafter KD01) developed a version of the decay model for storms that make landfall in the New England area. The mathematical formalism is the same as that for the KD95 model, but the decay coefficients are different.

The KD95 decay model has been used in a number of applications, including real-time forecasting and emergency preparedness. Under the assumption that a storm is moving perpendicular to the coast, maps of the maximum penetration of winds of various thresholds for a given speed of motion and maximum wind at landfall can be created. Such maps have been incorporated into the Hurricane Evacuation (HURREVAC) program

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used by many emergency managers. The KD95 decay model has also been used to set bounds on the wind-model component of damage estimation models utilized by the state of Florida to help regulate insurance costs.

Beginning in 2000 the KD95 and KD01 decay models have been used to adjust the operational Statistical Hurricane Intensity Prediction Scheme (SHIPS) for the portion of the forecast track that moves over land (DeMaria et al. 2005). The SHIPS model provides 5-day intensity forecasts for the Atlantic Ocean and eastern North Pacific Ocean basins. The decay models are also utilized in the Statistical Typhoon Intensity Prediction Scheme (STIPS), which provides real-time intensity forecasts for the western North Pacific (Knaff et al. 2005). SHIPS verification results for the Atlantic and eastern Pacific show that the inclusion of the decay effects improves the intensity forecasts through 72 h. The improvements at days 4 and 5 are much smaller because of the track uncertainties and related errors in the timing of landfall. Although the decay model was developed for storms that moved inland over the continental United States, it is applied to all storms, including those that move over relatively small islands such as Puerto Rico and Jamaica and narrow landmasses such as western Cuba. Verification of the SHIPS forecasts indicates that the current formulation of the decay model reduces the maximum winds by too large a fraction for the island and narrow land cases. A similar bias was described by KD95 for storms that remained fairly close to the coast after landfall, and a method was developed to help to correct that error. However, the correction in KD95 was for storms that remained inland and is not well suited to cases that move quickly back over the water.

In this paper a new method for adjusting the decay model for the movement over narrow landmasses is described. The modified decay model is described in section 2, the fit of the model parameters is presented in section 3, and the impact of the new model on the operational SHIPS forecasts is described in section 4. The KD95 and KD01 models were developed using units of knots for the maximum intensity because the National Hurricane Center (NHC) storm archive measures the maximum wind rounded to the nearest 5 kt, and the official NHC forecasts use those units. Thus, knots are used in this paper instead of the more standard unit of meters per second.

Before proceeding with the mathematical development, it should be pointed out that the decay model is a highly simplified representation of a very complex problem. Marks and Shay (1998) and Shen et al. (2002) provide summaries of the physical processes associated with landfalling storms, including the effects of the lower boundary (the ocean structure prior to landfall, and soil moisture, land surface type, variations in surface heat capacity, and topography after landfall), the synoptic environment, and the extratropical transitions. In addition, the low-level wind field has variability on a wide range of horizontal and vertical scales (Franklin et al. 2003). These factors can sometimes lead to significant deviations from the simple decay model.

2. Inland decay model modification

In this section the original decay model is briefly summarized and the modifications are described. Table 1 lists the various parameters and variables used.

In the KD95 decay model, it is assumed that the storm maximum surface winds just prior to landfall (V_p) are reduced by a constant factor R when the storm center crosses land to account for differences in the surface roughness over the land versus over water. The decay rate after landfall dV/dt is assumed to be propor-

TABLE 1. Variables and parameters used in the inland wind decay model development.

Variable	Definition
t	Time (h)
t_w	The time (h) when the storm center first moves back over the water
V	1-min maximum sustained surface wind (kt) as a function of time
V^τ	The value of V at time step τ
V_p	The maximum wind (kt) just before the storm center moves over land
V_a	The maximum wind (kt) just after the storm moves back over water
V_b	The background maximum wind (kt) that the storm decays toward over land
R	The reduction factor (nondimensional) applied to the maximum wind when the storm center moves from water to land
α	The decay constant (h^{-1}) in the inland wind model
F	The fraction (nondimensional) of the storm circulation area that is over land as a function of time
F_m	The mean value of F over one time step
R_s	The radius (km) of the storm circulation area
L	The length (km) of an idealized infinitely wide rectangular island

tional to the storm intensity minus a constant "background" intensity (V_b) that a storm can maintain over land. The basic decay equation is then given by

$$dV/dt = -a(V - V_b), \qquad (1)$$

where α is a proportionality constant. With the initial condition $V = RV_p$ at $t = 0$, the solution to the above differential equation is given by

$$V(t) = V_b + (RV_p - V_b)e^{-at}. \qquad (2)$$

This model has three free parameters (R, V_b, and α). For a sample of U.S. landfalling storms from 1967 to 1993, KD95 showed that optimal values of these parameters are 0.9, 26.7 kt, and 0.095 h^{-1}, respectively. For application to the SHIPS forecasts, if the storm center moves back over water after time t_w, the maximum wind is increased by a factor of $1/R$, again to account for land–ocean surface roughness differences. The intensity just after moving back over the water (V_a) is given by

$$V_a = V(t_w)/R. \qquad (3)$$

Because of the availability of a surface moisture source, it might be expected that the storm decay rate would be slower if a portion of the storm circulation remained over the water for an extended period of time. To account for this effect, the basic decay Eq. (1) is modified to give

$$dV/dt = -aF(V - V_b), \qquad (4)$$

where F is the fraction of the area of the storm that is over land. In general, F is time dependent and is a complicated function of the coastal geography and storm track; F will also depend on how the area of the storm circulation is defined. For the modified decay model, it will be defined as a circular area with a constant radius R_s. In the next section, the optimal value of R_s is obtained by fitting the modified decay model to observations. From a physical point of view, it might be expected that R_s would be related to the size of the inner core of the storm where the surface fluxes begin to cause a significant increase in the surface air entropy. As discussed by Shen (2004), the size of the inner core region is variable, but is on the order of a few times the radius of maximum wind.

From a mathematical point of view, note that in the limit as R_s approaches zero, $F = 1$ and the modified decay Eq. (4) is equal to the original decay Eq. (1). Thus, the $R_s = 0$ cases shown in the results below represent the original decay model

Some insight into the magnitude of the effect of the F factor in Eq. (4) can be gained for the case of an idealized storm moving at constant speed c across an infinitely wide island of constant length L. This situa-

tion is somewhat similar to a storm moving northward over western Cuba. To obtain a simple analytic solution, it will be assumed that the storm circulation area is a square with each side of length $2R_s$ rather than a circle of radius R_s. Even though the storm area is square in this idealized case, R_s will still be referred to as the storm "radius."

For the idealized storm and island described above, three separate cases need to be considered: 1) $R_s \leq L/2$, 2) $L/2 \leq R_s \leq L$, and 3) $R_s > L$. For the first case, the storm diameter is smaller than the island length, so the entire storm can fit on the island. When the storm center first reaches the island it is half on and half off the island so the fractional area F is ½ at $t = 0$. As the storm center moves farther over the island F linearly increases to 1 by $t = R_s/c$. The fractional area F stays equal to 1 until $t = L/c - R_s/c$, when the outer edge of the storm circulation reaches the other side of the island. After that time F linearly decreases to ½ when the storm center reaches the other side of the island at $t = L/c$. For the second case, the fractional area F is ½ when the storm center first reaches the island, linearly increases to $L/2R_s$ when the outer storm edge first reaches the other side of the island at $t = (L - R_s)/c$, remains equal to $L/2R_s$ until $t = R_s/c$, and then linearly deceases to ½ at the other side of the island at $t = L/c$. For the third case, F has a constant value of $L/2R_s$ from the time when the storm center first reaches the island to when it reaches the other side at $t = L/c$. With these assumptions it can be shown that the analytic solution of the modified decay Eq. (4) for the storm intensity after crossing the island (V_a) is given by

$$V_a = \langle V_b + (RV_p - V_b) \exp\{-a[(L/c) - (R_s/2c)]\}\rangle/R, \quad R_s \leq L, \qquad (5a)$$

and

$$V_a = \{V_b + (RV_p - V_b) \exp[-a(L^2/2cR_s)]\}/R, \quad R_s > L. \qquad (5b)$$

The properties of the above equations can be understood by considering the exponent of the exponential decay term for a few special cases. Equation (5a) is valid when the storm circulation radius is smaller than the island length. In the limit as R_s goes to zero, the exponent becomes $\alpha L/c$. The decay in this case is the same as that for the solution to the unmodified decay equation [Eq. (2)], where L/c is the time it takes to cross the island. When R_s is equal to one-half of the island length L in Eq. (5a) the exponent is ¾($\alpha L/c$), which indicates that the intensity will decrease less than in the original decay model. If R_s is equal to the island length the exponent in Eq. (5a) or (5b) becomes ½($\alpha L/c$),

which indicates even less decay. As R_s continues to increase beyond the island length, the exponent in Eq. (5b) approaches zero, which indicates no decay.

Figure 1 shows the storm maximum winds just after crossing an idealized 100-km island calculated from Eq. (5) as a function of R_s and the storm intensity just prior to crossing the island, assuming a typical speed of motion of 12 kt. At this speed, it would take 4.5 h to cross the 100-km island, which is roughly the north–south length of western Cuba. As mentioned previously, the solution for $R_s = 0$ is the same as that from the original decay model. Figure 1 shows that for fairly weak storms (50 kt, e.g.) the model predicts a modest decay, which becomes even less as R_s increases. For stronger storms, the decay is much more dramatic. For example, the 100-km island would reduce the intensity of a 130-kt storm to about 95 kt for $R_s = 0$ (the original decay model). However, this decay is much less as R_s increases. For $R_s = 100$ km, the postisland intensity would be about 110 kt.

Figure 2 shows the postisland intensity for an idealized island of length 300 km (roughly the largest north–south length of Hispaniola), again assuming a 12-kt speed of motion. The storm would take 13.5 h to cross the island in this case. As expected, the maximum winds are reduced by a much larger fraction for the larger island. However, the amount of decay is less sensitive to R_s. For example, the 130-kt wind would be reduced to ~58 kt with $R_s = 0$ and ~63 kt with $R_s = 100$ km. Thus, the modification will have only a minor impact on

FIG. 2. Same as Fig. 1, but for an island of 300-km length.

storms crossing large landmasses (the cases considered in the KD95 decay model), but a much larger effect on the cases crossing narrow sections of land.

3. Selection of the storm circulation radius

In this section observed storm intensities will be used to determine the value of the storm circulation radius R_s that optimizes the modified decay model for the more realistic case of a circular circulation area and where the fractional area F is computed from the actual land–ocean distributions. A rectangular grid with a maximum grid spacing of 25 km is set up around the storm center for the calculation of F. At all points that are within R_s of the storm center, it is determined whether each point is over land or water. The fractional area is the number of overwater points divided by the total number of points. The grid spacing on the rectangular grid is reduced so that there are at least four grid intervals from 0 to R_s. This adjustment is needed for $R_s < 100$ km.

The data used to select the storm circulation radius are basically the same as that used by KD95 to develop the original decay model, supplemented with additional cases. The NHC Atlantic tropical cyclone best-track file from 1967 to 2003 (KD95 used 1967–93), which contains the storm latitude, longitude, and maximum winds (to the nearest 5 kt) at 6-h intervals, is the starting point for the model development. KD95 included a few storms prior to 1967 in the developmental database, but these are not included here. However, the best track over the entire Atlantic basin is included. KD95 re-
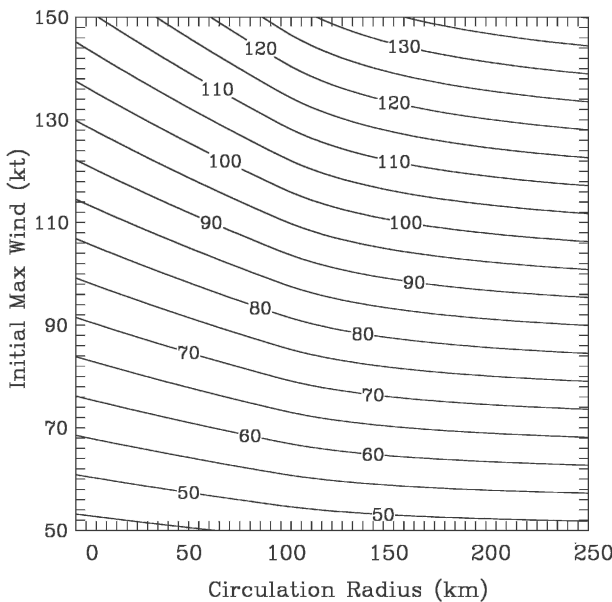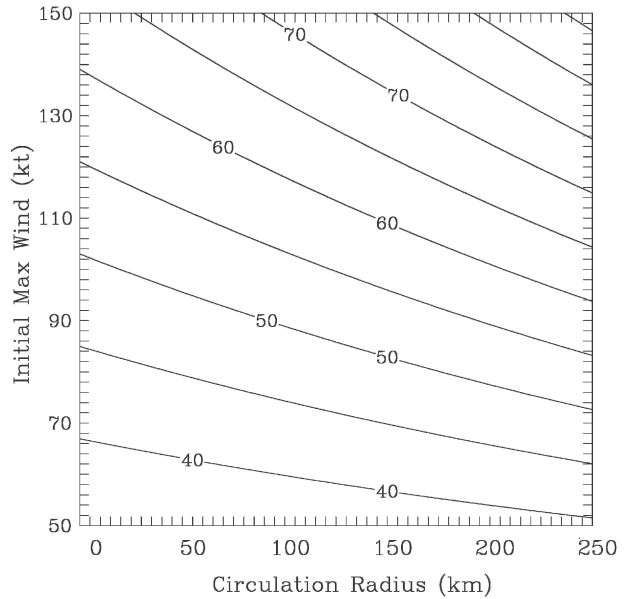

FIG. 1. The maximum winds after crossing an island of 100-km length at a speed of 12 kt as a function of the storm circulation radius and the intensity before crossing the island.

stricted the sample to storms that made landfall in the continental United States south of 37°N.

The landfall cases are selected by linearly interpolating the 6-h best-track positions to 1-h positions. The distance to the nearest landmass is calculated at the 1-h positions using a land mask file that includes continents and large islands (Hispaniola, Cuba, Puerto Rico, Jamaica, and Trinidad). If the storm passes over land at any of the 1-h points, the section of the best-track file is extracted that starts with the first 6-h point before the storm moves over land and ends with either the first 6-h point that was back over water, or the last point over land where the storm was still classified as a tropical cyclone. For storms that move over an island and then make landfall later, more than one section of the best track is used. Thus, a single storm can contribute multiple cases to the input file. The total sample is divided into cases where the storm moves back over water within 48 h, and those that do not. The cases that move back over water over within 2 days are usually those those move over islands or peninsulas such as south Florida or the Yucatan. For simplicity, the cases that move back over the water within 2 days are referred to as the island cases, and the others are referred to as continent cases.

The first point prior to landfall for each best-track section is considered $t = 0$. Table 2 shows the number of island and continent points in the final sample used to optimize R_s. There are 129 best-track sections for the

TABLE 2. The number of best-track points for the island and continent cases, where $t = 0$ is the last best-track point before landfall.

Time (h)	Continent points	Island points	Total points
0	159	129	288
6	159	129	288
12	101	109	210
18	92	60	152
24	80	38	118
30	66	21	87
36	57	9	66
42	48	6	54
48	39	0	39
54	30	0	30
60	23	0	23
66	21	0	21
72	13	0	13
78	10	0	10
84	8	0	8
90	8	0	8
96	7	0	7
102	6	0	6
108	3	0	3
114	3	0	3
6–114	752	394	1146

island cases and 159 for the continent cases, which came from 170 different storms. By definition, there are no island cases after 48 h. There were a few continent cases that were classified as tropical cyclones for up to 114 h after the last best-track point before landfall.

To select the best value of R_s, the basic decay model defined by (4) was integrated numerically with 1-h time steps for all the best-track sections listed in Table 2. All of the best-track sections start over water. If the storm remains over water during any 1-h time step, the change in the model V is set to the change in V from the best track determined by linearly interpolating the best-track intensities to 1-h intervals. When the storm first moves over land the maximum wind is multiplied by the reduction factor 0.9 to account for surface roughness differences, similar to KD95. When the storm is over land at the beginning of a time step, the maximum wind at the end of the time step ($V^{\tau+1}$) is calculated from an approximate solution to (4) given by

$$V^{\tau+1} = V_b + (V^\tau - V_b)e^{-F_m \alpha}, \qquad (6)$$

where F_m is the mean value of $F(t)$ from t to $t + 1$ and V^τ is the maximum wind at the beginning of the time step. The values of α and V_b in Eq. (6) are the same as those in KD95 for storms south of 36°N and the same as those from KD01 for storms north of 40°N. Linear combinations are used for α and V_b between 36° and 40°N. If the storm moves back over the water the maximum winds are divided by the reduction factor R, and the maximum wind change during each time step is again given by the corresponding change from the best track.

The predicted and observed maximum wind changes in the first time step are identical because the $t = 0$ positions are all over water. After the storm moves over land the predicted and observed changes differ because the decay model is not perfect. From Table 2, there are a total of 752 best-track points at 6-h intervals for the continent cases (6–114 h) and 394 island best-track points for the island cases (6–42 h). The decay model forecasts for all cases were made with values of R_s ranging from 0 to 250 km in increments of 10 km. The mean absolute error (MAE) and the bias were calculated for the continent and island samples and the total 1146-point sample for each value of the circulation radius. The bias is defined as the model minus the best-track maximum wind. A negative bias indicates that the decay model is underpredicting the wind speeds.

Figure 3 shows that the MAE is about 9 kt for island cases for $R_s = 0$ and decreases fairly rapidly as R_s increases. The MAE for the continent cases also decreases slightly as R_s increases from 0 to about 50 km. For the total sample, the MAE decreases as R_s in-
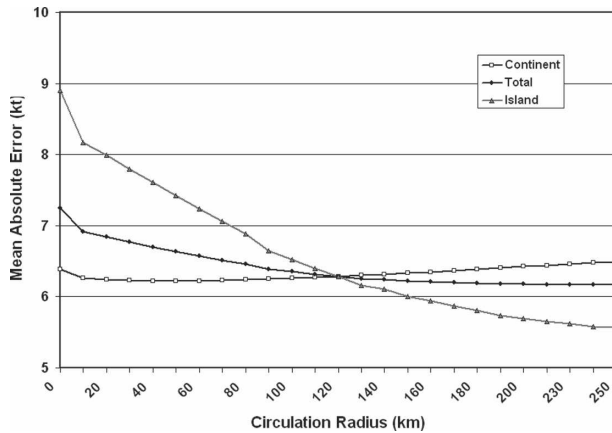
FIG. 3. The mean absolute error of the modified decay model as a function of storm circulation radius (R_s) for the island, continent, and total samples.

creases from 0 to about 100 km and then decreases at a much slower rate after that. The minimum MAE for the total sample occurs for $R_s = 220$ km, although most of the improvement is realized as R_s increases from 0 to about 100 km.

Figure 4 shows the bias as a function of R_s. For $R_s = 0$ the decay model has a small positive bias for the continent cases but a fairly large negative bias for the island cases. As R_s increases, the bias of the island cases improves at a fairly rapid rate, although the bias for the continental cases increases slowly. For the total sample the bias is near zero for $R_s = 110$ km. Because the total sample bias is near zero for $R_s = 110$ km and there is only a very small improvement in the total sample MAE for larger values, 110 km is considered the optimal choice for R_s. The value of 220 km would also be a reasonable choice using the simpler condition of mini-
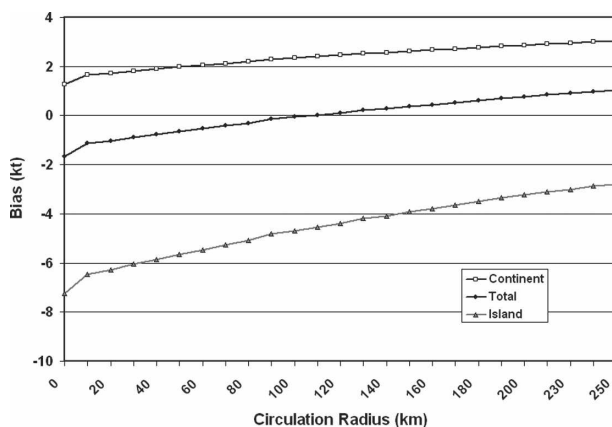

FIG. 4. The bias of the modified decay model as a function of storm circulation radius (R_s) for the island, continent, and total samples.

mizing the mean absolute error. However, in a large sample of cases, there should be little difference between these two values because the MAE is only about 2% smaller for $R_s = 220$ km than with $R_s = 110$ km.

Kimball and Mulekar (2004) examined the radius of maximum wind for a large sample of Atlantic tropical cyclones. Their results showed that the median radius of this sample is about 55 km. Thus, the R_s values of 110 and 220 km are 2 and 4 times the radius of the maximum wind of a typical tropical cyclone.

Although choosing R_s of 110 or 220 km minimizes either the bias or the MAE of the total sample, the island and continent cases have different behaviors in Figs. 3 and 4. The MAE for the continental cases is minimized for $R_s = 50$ km, but the MAE island cases are still decreasing for a MAE of 250 km. Also, the continent cases have a high bias and the island cases have a low bias for all values of R_s from 0 to 250 km. Additional runs were performed, and the MAE for the island cases does eventually reach a minimum for R_s of about 320 km, and the bias was reduced to about −2 kt. This result suggests that there may be differences in the basic decay model between the continent and island cases, and it might be possible to further improve the model by first determining a new set of the basic model parameters (R, V_b, and α) for the very low latitude storms. As was shown in KD01, these parameters for storms in the New England area were different from those for the Gulf and East Coast region, presumably because of extratropical transition and terrain effects. Most of the island cases in the current study are in the deep Tropics or over Florida. It is possible that the soil moisture or the environmental moisture fields are sufficiently different in these regions to effect the basic decay parameters. This additional optimization is left as a topic for future research.

It might also be possible to further improve the decay model by making R_s a function of the observed storm size. However, reliable outer wind field observations of tropical cyclones are not always available, so the version of the decay model with a fixed value of R_s will be considered in the remainder of this paper.

To provide an example of how the new decay model compares with the old one, both models were applied to a 6-day period of Hurricane Dennis beginning at 1200 UTC 5 July 2005, as shown in Fig. 5. In this example, R_s was set to 110 km. The storm became tropical storm strength (35 kt) at that time ($t = 0$ in Fig. 5) as it entered the Caribbean Sea from the east. The storm made landfall in south-central Cuba at about 78 h, and moved off the north coast about 10 h later. The storm made its final landfall near Pensacola, Florida, at about 126 h. The decay models are applied only during the times
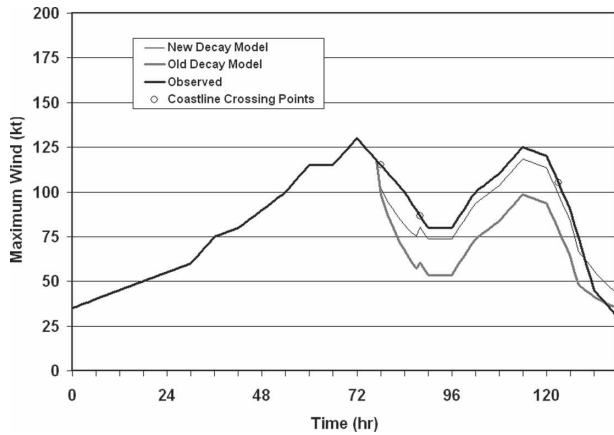
FIG. 5. The best-track maximum winds and the predictions by the new and old versions of the decay model for 6 days of Hurricane Dennis beginning at 1200 UTC 5 Jul 2005. The open circles represent the coastline-crossing times.

when the storm was crossing land, which was again determined by linearly interpolating the 6-h-observed (from the forecast/advisory) positions to 1-h intervals. When the storm was over water, the intensity changes during each 1-h interval are set to the observed intensities. The small increases in the decay model intensities at 88 h in Fig. 5 are because of the division by the factor R (0.9) when the storm center moved back over the water after crossing Cuba.

The observed storm intensity in Fig. 5 decreased from 115 to about 80 kt after crossing Cuba. The old decay model reduced the intensity to about 50 kt, which is much weaker than that of the observations. The new decay model only reduced it to about 75 kt, which is much closer to what was observed. After the final landfall in Florida, the two decay models behaved similarly because Dennis moved rapidly inland, and the land fraction $F(t)$ became equal to 1 after a short time. In this calculation, there is a difference in the initial intensity used for decay model for the Florida landfall because of errors introduced by the track across Cuba.

4. Impact on the SHIPS intensity forecast model

The KD95 and KD01 decay models are used to adjust the operational SHIPS model intensity forecasts for the part of the track that is over land (DeMaria et al. 2005). This calculation begins with an intensity forecast developed from statistical relationships that do not include the effects of land. This intensity is then adjusted using the decay model for the portion of the forecast track that crosses land. The model that includes the decay over land is referred to as D-SHIPS. The land adjustment for D-SHIPS is a postprocessing step so it is

straightforward to rerun the predictions with the modified decay model given the unadjusted SHIPS intensity and the forecast track. Both of these are available in the model guidance archive maintained by NHC in the Automated Tropical Cyclone Forecast (ATCF) system format (Sampson and Schrader 2000). Substantial changes were made to SHIPS in 2001 (DeMaria et al. 2005), including the extension of the forecast from 3 to 5 days. For the evaluation of the modified decay model, all Atlantic cases from 2001–04 were rerun and then compared with best-track intensities.

Figure 6 shows the percent improvement in the D-SHIPS forecast errors with the modified decay model for the 2001–2004 sample (1329 cases at 12 h, decreasing to 554 cases at 120 h). The modified decay improves the forecasts by almost 4% for the total Atlantic sample even though less than one-half of the cases were impacted by land. Figure 6 also shows the percent improvement for all of the cases for which the best-track position was within 500 km from land (586 cases at 12 h, decreasing to 173 cases at 120 h). A distance of 500 km was chosen to allow for the track forecast error. Even if the best track was 500 km from land, the forecast track might still be affected by land at some of the longer forecast periods. For the cases near land, the errors were reduced by up to about 8% at the longer time periods. The error differences between the forecasts with the original and modified decay equations were statistically significant at the 95% level at 36–96 h for the total and near-land samples in Fig. 6, where the estimate of statistical significance corrected for serial correlation. Based upon these positive results, the new decay model was implemented in SHIPS for the 2005 season.
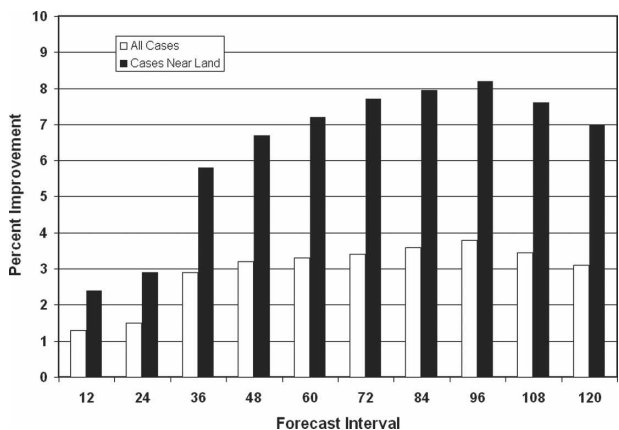

FIG. 6. The percent improvement in the mean absolute intensity error of the 2001–04 operational SHIPS forecasts when the original decay model is replaced by the modified decay model with a storm circulation radius of 110 km. Results are shown for the total sample and the sample in which the best track was within 500 km of land.

Figure 3 showed that when the modified decay model with R_s = 110 km is applied to the best-track positions over land the errors for the total sample are reduced from 7.3 to 6.4 kt, which is about 12%. The error reduction for the operational SHIPS forecasts is less than 12% because the track forecast errors introduce errors in the timing and location of landfall. In addition, there are other contributions to the SHIPS intensity errors that partially offset the improvements resulting from the modified decay model.

The original motivation for investigating the biases of the decay model came from the evaluation of a new version of D-SHIPS with additional predictors from Geostationary Operational Environmental Satellite (GOES) imagery and ocean heat content (OHC) estimates derived from satellite altimetry data (DeMaria et al. 2005). The satellite version of SHIPS was run in parallel in 2002–03 and became operational at NHC in 2004. The OHC has large gradients in the Atlantic basin, and the highest values are in the western Caribbean, in the Loop Current and warm eddies in the Gulf of Mexico, and along the Gulf Stream. Storms in these regions routinely interact with islands and narrow landmasses such as Jamaica, Cuba, and Florida. Thus, the biases in the decay model adjustments to SHIPS may have influenced the assessment of the impact of the satellite data. For this reason all of the operational D-SHIPS forecasts with and without the satellite data for the 2002–04 sample west of 50°W were rerun with the modified version of the decay model. Results showed that the modified decay model improved the forecasts both with the satellite data and without by about the same amount, relative to the original decay model. Thus, the intensity forecast improvement in the modified decay model with the satellite data (up to 3.2% at 48 h) was about the same as that described by DeMaria et al. (2005) for the 2002–03 sample. This result confirms that the problems with the decay model in the western Atlantic did not influence the evaluation of the impact of the satellite data on the SHIPS forecasts.

5. Concluding remarks

A method to account for movement over islands and narrow landmasses in the Kaplan and DeMaria tropical cyclone inland wind decay model was presented. In the modified decay model the decay rate is proportional to the current intensity times the fraction of the storm circulation area that is over land. Analytic solutions for the idealized case of a square storm area moving over an infinitely wide island of uniform length showed that the modified decay equation significantly reduces the amount of decay for small islands but has only a minor

effect for larger landmasses. For application to real cases, the storm circulation area is defined as a circle with a constant radius of 110 km. This value minimized the bias of the Atlantic landfall storms from 1967 to 2003 and is equal to about 2 times the typical radius of maximum wind of Atlantic tropical cyclones. The modified model reduces the error by about 12% relative to the original decay model.

The operational SHIPS model uses the inland decay model to adjust the intensity forecasts for the portion of the forecast track that is over land. The SHIPS forecasts for 2001–04 were rerun with the modified decay model, and the errors for the entire sample were reduced by up to 4% at the longer forecast intervals. The errors for those cases within 500 km from land were reduced by up to 8%. The operational SHIPS model for the 2005 season was modified to include the updated decay model formulation.

Previous studies (e.g., Ho et al. 1987; Emanuel et al. 2004) have shown that tropical cyclones tend to decay more slowly when they move across the Florida Peninsula relative to those that make landfall in other regions. These differences are usually attributed to differences in land surface types. The results presented in this study suggest that some of this difference might be because of the smaller fraction of the storm circulation over land for storms that cross Florida.

In addition to land surface differences, there are also considerable terrain differences in the landmasses that affect Atlantic tropical cyclones. In this study, the decay rate does not depend on the terrain height. In the development of the decay model for the New England area KD01 showed that the decay constants were different from those for the southeast United States and suggested that the difference was partially because of the higher terrain in the northern sample. The mountains in the Caribbean and Central America are also much higher than those in the southeast United States, so the terrain might also be a factor in those regions. The decay model constants for the New England region acted to make the winds decay faster for intense systems, but slower for weaker ones. The slower decay for the weaker systems may have been because of extratropical transition. The results of the current study showed that the fractional area factor improved the total sample, but the island cases could be improved further by utilizing a much larger storm circulation radius than the continental cases. The island cases were mostly in the deep Tropics or near Florida. Thus, there may be other factors such as soil or atmospheric moisture that are different for these low-latitude systems. Further improvements to the decay model that take

into account these effects are left as a topic for future research.

The decay model was derived for cases from the Atlantic basin. Previous studies (e.g., Brand and Blelloch 1973, 1974) have documented the decay rates of typhoons crossing the Philippines and Taiwan. It would be interesting to see how well the simple decay model explains the storm behavior in other ocean basins.

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