NOTES AND CORRESPONDENCE

On the Decay of Tropical Cyclone Winds after Landfall in the New England Area

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ABSTRACT

A version of the Kaplan and DeMaria empirical model for predicting the decay of tropical cyclone 1-min maximum sustained surface winds after landfall is developed for the New England region. The original model was developed from the National Hurricane Center (NHC) best-track wind estimates for storms that made landfall in the United States south of 37°N from 1967 to 1993. In this note, a similar model is developed for U.S. storms north of 37°N, which primarily made landfall in New York or Rhode Island and then moved across New England. Because of the less frequent occurrence of New England tropical cyclones, it was necessary to include cases back to 1938 to obtain a reasonable sample size. In addition, because of the faster translational speed and the fairly rapid extratropical transition of the higher-latitude cases, it was necessary to estimate the wind speeds at 2-h intervals after landfall, rather than every 6 h, as in the NHC best track. For the model development, the estimates of the maximum sustained surface winds of nine landfalling storms (seven hurricanes and two tropical storms) at 2-h intervals were determined by an analysis of all available surface data. The wind observations were adjusted to account for variations in anemometer heights, averaging times, and exposures.

Results show that the winds in the northern model decayed more (less) rapidly than those of the southern model, when the winds just after landfall are greater (less) than 33 knots. It is hypothesized that this faster rate of decay is due to the higher terrain near the coast for the northern sample and to the more hostile environmental conditions (e.g., higher vertical wind shear). The slower decay rate when the winds fall below 33 knots in the northern model might be due to the availability of a baroclinic energy source as the storms undergo extratropical transition.

1. Introduction

The landfalls of Hurricanes Hugo (1989), Andrew (1992), Opal (1995), and Fran (1996) have demonstrated that hurricanes can produce substantial property damage and loss of life inland because of the effects of strong winds. Prior to the operational implementation of the Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model in 1995 (Kurihara et al. 1995), the National Hurricane Center (NHC) had very little objective guidance for predicting the inland decay of storms. Consequently, Kaplan and DeMaria (1995) developed a simple empirical model for predicting the decay of tropical cyclone winds after landfall (hereafter: ''decay model''). This model is based upon the least squares fit of an exponential decay equation to the NHC best-track 1-min maximum sustained surface wind estimates for all tropical storms and hurricanes that made landfall in the United States south of 37°N for the period of 1967–93. In the simplest version of this model, the maximum winds inland are a function of the maximum winds at landfall and of the time after landfall. With the assumption of a track perpendicular to the coastline, it is then possible to estimate the maximum inland penetration of winds of a given speed, provided that the storm's landfall intensity and speed of motion are known. Using this algorithm, maps of the inland penetration of winds for storms with various intensities and speeds of motion at landfall have been incorporated into the hurricane evacuation (HURREVAC) software developed by the Federal Emergency Management Agency (FEMA) for use by the emergency management community (FEMA 1995).

A limitation of the decay model described by Kaplan

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TABLE 1. The storm name, landfall date and time, and maximum sustained surface wind just prior to landfall (V_0) estimated from the reanalysis and from the NHC best track for the nine storms used to develop the northern decay model. The average V_0 for the nine storms is also shown.

Name	Date (yr month day)	Time (UTC)	V_0 (reanalysis) (kt)	V_0 (NHC) (kt)
Unnamed	1938 09 21	2015	85	85
Unnamed	1944 09 15	0345	85	75
Carol	1954 08 31	1315	95	85
Donna	1960 09 12	1940	95	90
Doria	1971 08 28	0300	60	55
Agnes	1972 06 22	2010	50	55
Belle	1976 08 10	0510	90	80
Gloria	1985 09 27	1625	70	85
Bob	1991 08 19	1755	80	85
			78.9 (Avg)	77.2 (Avg)

and DeMaria (1995) is that it is only valid for storms south of 37°N. Their development was restricted to the more southern cases because it was hypothesized that the storms farther north may have different decay characteristics due to more frequent interactions with baroclinic weather systems, the more rugged terrain closer to the coast, and the cooler waters prior to landfall. In this note, a decay model is developed for these more northern cases and is compared with the southern version of the model.

Because of the less common occurrence of landfall in the northeastern United States, it was necessary to include cases before 1967. In principle, the storm tracks and intensities could be obtained from the NHC best-track file (also sometimes referred to as ''HURDAT''), which contains data for Atlantic storms back to 1886 (Jarvinen et al. 1984). However, the time resolution of the NHC best track is 6 h, which is somewhat long for northern storms, which are moving much more rapidly than the southern cases. Also, the best track is less reliable before 1967, and, in some cases, the positions and intensities are simple linear interpolations of the values at 12-h or even 24-h intervals (Neumann 1994). To overcome these limitations, a reanalysis of the best track was performed for seven hurricanes and two tropical storms that made landfall in the United States north of 37°N from 1938 to 1991.

The reanalysis of the best track is described in section 2, and the development of the northern decay model and comparison to the southern version is presented in section 3. A summary and some concluding remarks are offered in section 4.

2. Track and intensity estimation

Table 1 shows the seven hurricanes and two tropical storms included in this study. This sample includes all of the landfalling cases for which enough surface observations were available from the archives at the National Climatic Data Center (NCDC) and the Hurricane Research Division (HRD) to document the intensity changes after landfall. The surface observations consisted primarily of daily logs of the aviation weather reports for the day the storm made its closest approach to a particular station. These reports usually contained the wind speed and direction, wind gust, surface pressure, and present weather information. Moreover, the reports contained notes describing the timing and magnitude of the maximum sustained winds and gusts and information of possible eye passage and wind shifts. The temporal resolution of these observations varied but was typically on the order of a few minutes at the time of the closest approach of the storm. For some stations, wind traces were also available.

In addition to the aviation weather reports, a limited number of observations from ships of opportunity and reconnaissance aircraft were also used in the best-track reanalysis. The ship observations typically included the wind speed and direction, surface pressure, present weather, sea surface temperature, and wave information. The aircraft reconnaissance data usually consisted of flight-level wind speed, wind direction, and pressure as well as aircraft estimates of surface pressure. Notes about the aircraft position relative to a cyclone's eye were also sometimes available.

The first step in the reanalysis was the determination of the storm tracks. The storm positions were determined subjectively at 3-h intervals from 12 h prior to landfall to 6 h after the storm was considered to be extratropical. The storm positions prior to landfall were determined using ship and aircraft data, and the overland positions were determined primarily from the aviation weather reports. If the data coverage afforded by these sources was insufficient for this purpose (as was true over Canada), the NHC best-track positions were employed instead. The tracks of the nine storms that were obtained by the above methods are shown in Fig. 1.

For this study, the time of landfall was defined as the time when the center of the storm crossed a smoothed representation of the coastline (with about 35-km resolution). Long Island was considered to be land. In all except one case, the storms made landfall in New York or Rhode Island and then moved across New England. It is important to note that there have been tropical cyclones that have made landfall along the Maine coastline in recent years. Specifically, Tropical Storms Esther (1961) and Heidi (1971) and Hurricane Gerda (1969) all crossed the Maine coast. However, these storms were not included in the current study because the NCDC and HRD data archives did not contain enough observations along the tracks of these systems to evaluate adequately their decay rates. However, because several of the storms shown in Fig. 1 passed through Maine before dissipating or becoming extratropical, the northern decay model was derived using some storms that affected the Maine region.

The determination of the time when extratropical transition took place was primarily based upon the designation in the NHC best track, although other available

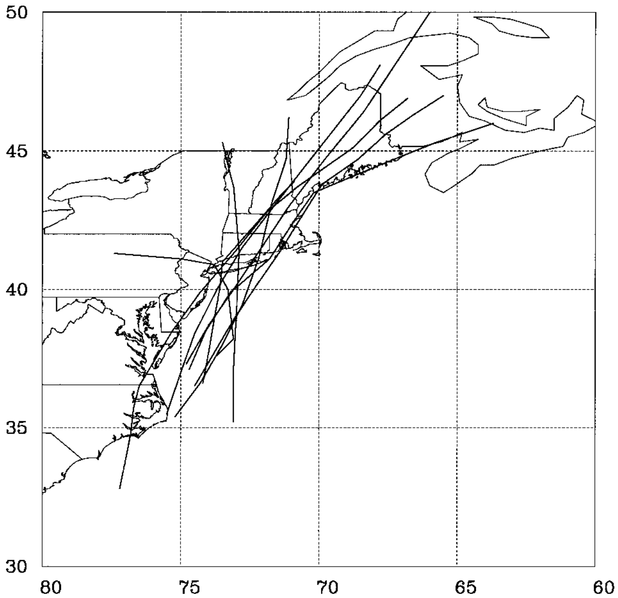

FIG. 1. Tracks of the nine landfalling tropical cyclones used to develop the northern decay model.

sources of information (e.g., meteorological journals or daily aviation weather reports) were also taken into account. The decision to include data within 6 h after extratropical transition was a compromise between increasing the sample size and avoiding contamination by including too much of the extratropical portion of each storm. The average difference between the reanalysis storm positions and those in the NHC best track (at 6-h intervals) was about 30 km.

The next step in the reanalysis was to normalize the wind observations to account for variations in anemometer heights, averaging times, and exposures using the procedures described by Powell et al. (1996). The first step in the normalization was to convert all of the wind observations at each location to a 10-min wind using gust-factor relationships. The maximum 10-min wind at each station was then determined. The second step was to adjust these maximum 10-min winds from their original reporting heights to 10 m using a logarithmic wind profile. This calculation requires a roughness length. In nearly all cases, a roughness length of 0.03 m was assumed, which is valid for a typical overland exposure at a location such as an airport. The one exception was for Hurricane Belle (1976), for which the roughness lengths were obtained from a previous study (Sethu-Raman 1979). In these cases, the 10-m winds were adjusted to a roughness length of 0.03 m. For locations at or near the coast, the 10-m winds were also calculated for a roughness length of 0.01 m, which is representative of overwater exposure. The third step was to adjust the 10-min winds at 10 m to 1-min winds using gust-factor relationships. After this procedure, the maximum wind, adjusted to a height of 10 m, an averaging time of 1 min, and a common exposure, was known at each location. A more in-depth discussion of the normalization procedures can be found in Powell et al. (1996).

One additional adjustment was applied to the normalized winds to account for the fact that the maximum winds are usually located in the right quadrant of the storm, relative to its direction of motion (Shea and Gray 1973; Frank 1977). The asymmetry factor due to the storm motion described by Schwerdt et al. (1979) was used to estimate the wind speed in the right quadrant, given the wind estimate and the azimuthal distance from the right quadrant.

Once the data were normalized and the asymmetry factor applied, the intensity of each storm along the track was determined by finding the maximum adjusted wind within a specified distance from the storm center. This distance was 70 km beyond the radius of maximum wind, where the maximum wind radii for four of the seven hurricanes (both unnamed hurricanes, Carol, and Donna) were obtained from the study by Ho et al. (1987) and the remainder (Belle, Gloria, and Bob) were obtained directly from aircraft flight-level data. The average maximum wind radius from the seven hurricanes (70 km) was used as the maximum wind radius for the two tropical storms, because no other information was available for these two cases. Sensitivity studies showed that the decay-model results were not very sensitive to the radius that was used to include the wind observations to estimate the maximum intensities. Similar results were obtained when values of 10–90 km beyond the maximum wind radii were used for inclusion of the wind observations. This insensitivity is not too surprising, given that the wind profiles for these higher-latitude storms tend to be less peaked than the profiles of the more intense lower-latitude storms. To illustrate, Willoughby's (1990) analysis of flight-level winds from several Atlantic hurricanes showed that Hurricane Gloria's (1985) wind profile became much flatter as it moved toward higher latitudes and was considerably less peaked than the wind profiles of the lower-latitude storms.

Using the above procedure, 44 inland wind estimates were obtained along the tracks of the nine storms. There were no wind estimates north of the U.S.–Canadian border because of an absence of NCDC and HRD wind data in that region. The average time resolution of the 44 inland wind observations was 2 h. For comparison, the southern decay model was developed from 401 wind estimates with a time resolution of 6 h. The average time after landfall of the 44 wind estimates for the northern storms was 5 h, as compared with 17 h for the southern storms. There were very few observations in the northern sample beyond about 12 h after landfall because of the increased translational speeds (the median speed of the northern sample at landfall was 33 kt, as compared with 11 kt for the southern sample) and the fairly rapid extratropical transition.

The development of the decay model requires an estimate of the storm intensity at landfall. These estimates

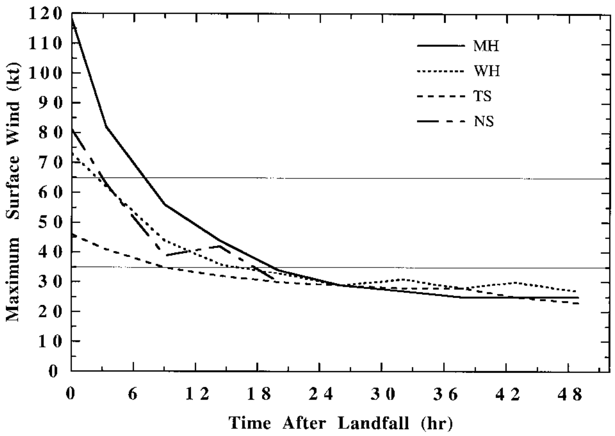

FIG. 2. The maximum sustained surface wind as a function of time after landfall for the average tropical storm (TS), weak (nonmajor) hurricane (WH), and major hurricane (MH) for the southern model sample, and the average for all storms in the northern sample (NS). The solid horizontal lines depict the threshold of hurricane (65 kt) and tropical storm (35 kt) force winds.

were obtained from the wind observations at the stations at or close to the coast, normalized using a roughness length valid for marine exposure, as described previously. Table 1 shows the landfall maximum wind estimates (defined as V_0) for the nine storms in the northern sample. These wind estimates are presented in knots because the decay model was developed for operational use by FEMA and NHC, and both of these agencies issue forecasts and warnings in units of knots rather than meters per second. Similar to the NHC best track, the wind estimates were rounded to the nearest 5 kt. For comparison, the landfall maximum wind estimates from the NHC best track are also shown in Table 1. The NHC best track estimates were from the positions just before landfall, which were, on average, 3 h prior to landfall, because of the 6-h time resolution of the NHC data. Table 1 shows that the average difference between the two landfall intensity estimates was less than 5 kt. However, the reanalysis landfall intensity estimates are more consistent with the inland wind estimates.

3. Model development

The mathematical form of the decay model was based upon a combination of physical and empirical considerations. Theory and observations (e.g., Powell et al. 1991) have shown that the surface winds associated with landfalling tropical cyclones decrease rapidly within the first few kilometers inland solely because of the increase in surface roughness. This effect is included by multiplying the landfall intensity estimate (V_0) by a reduction factor R.

The decay after landfall was modeled by considering the observed decrease in wind speed as the storms moved inland. For example, Fig. 2 shows the average maximum sustained surface winds as a function of time

TABLE 2. The absolute error (AE), root-mean-square error (rmse), variance explained (r^2), and model parameters (R, α, and V_b) for the southern and northern decay models.

	AE (kt)	Rmse (kt)	r^2 (%)	R	α (h^{-1})	V_b (kt)
Southern	6.5	8.8	91	0.9	0.095	26.7
Northern	8.8	11.4	62	0.9	0.187	29.6

inland for the nine storms in the northern sample and for the hurricanes and tropical storms in the southern sample. This figure shows that the decay rate is larger during the time when the maximum surface winds are larger. However, at longer time periods (12–24 h), the winds decay to a background wind (defined as V_b) rather than to zero. A possible physical interpretation of the background wind is the intensity that a tropical cyclone can maintain over land under ''ideal'' conditions. For example, Hurricane David (1979) remained in a tropical air mass with low vertical shear after its landfall in south Florida and maintained its intensity for several days (and reintensified slightly) after its initial decay from a hurricane to a tropical depression (Bosart and Lackmann 1995). Thus, the decay rate is assumed to be proportional to the difference between the current intensity and this background wind. With this assumption, the decay of the maximum sustained surface winds after landfall is given by

$$dV/dt = -\alpha(V - V_b), \quad (1)$$

where α is a proportionality constant. It is also assumed that the initial reduction of the wind due to the change in surface roughness occurs instantaneously, and that $t = 0$ corresponds to the time of landfall. Thus, the initial condition for (1) is given by

$$V(t = 0) = RV_0. \quad (2)$$

The solution to (1)–(2) is given by

$$V(t) = V_b + (RV_0 - V_b)e^{-\alpha t}. \quad (3)$$

The decay model [(3)] requires the determination of the parameters R, V_b, and α. For the southern decay model, R values of 1.0, 0.9, 0.8, or 0.7 were first assumed, and a least squares fit to the 401 inland observations was used to evaluate V_b and α. Then, the value of R was chosen where the least squares fit explained the maximum amount of variance of the inland winds. For the southern model, $R = 0.9$ explained the most variance, which resulted in values of V_b and α of 26.7 kt and 0.095 h^{-1}. As shown in Table 2, the southern decay model explained 91% of the variance of the observations and had a mean absolute error of 6.5 kt.

A more general version of the southern decay model was also developed to account for storms that moved almost parallel to the coast or moved very slowly inland after landfall. These storms decayed more slowly, probably because of their close proximity to water. However, this generalization only explained an additional 2% of

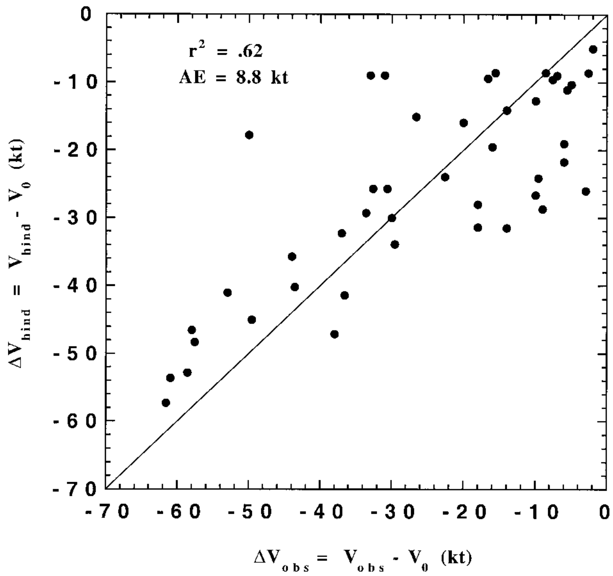

FIG. 3. A scatter diagram of the observed (ΔV_{obs}) vs model-predicted (hindcast) (ΔV_{hind}) reduction in the maximum sustained surface wind after landfall for the 44 data points in the northern decay model sample. The variance explained (r^2) and absolute error (AE) of the model are also shown. The solid diagonal line denotes a perfect prediction.

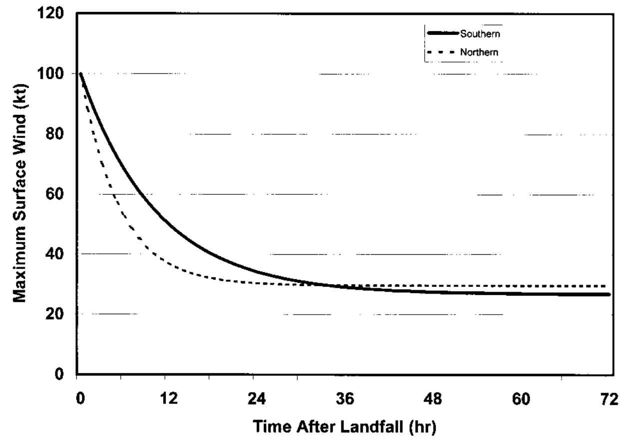

FIG. 4. The maximum sustained surface wind as a function of time after landfall of a storm with a maximum wind of 111 kt just prior to landfall (100 kt after the coastal reduction factor of 0.9 is applied) for the southern and northern models.

the variance of the observations. Therefore, this effect is not included in the northern decay model. Also, the much smaller northern sample size would make it difficult to estimate reliably the additional parameters required for this correction.

As described above, the three parameters of the southern decay model were estimated from a least squares fit to 401 observations from 67 storms. Because the size of the northern sample is much smaller (44 observations from 9 storms), a least absolute deviation method was used to estimate the model parameters. This method minimizes the absolute error of the difference between the model and observations and is less sensitive to data ''outliers'' than are least squares methods (Mielke et al. 1996). Using this method, the values R, V_b, and α were found to be 0.9, 29.6 kt, and 0.187 h^{-1} for the northern decay model (Table 2).

Figure 3 shows a scatter diagram of the model fit to the observations. The northern model explains 62% of the variance of the observations, with a mean absolute error of 8.8 kt, as compared with 91% of the variance and a mean absolute error of 6.5 kt for the southern model. The better fit of the southern model might be due to the smoothing and the reduced time resolution (6 h) of the NHC best-track data. The better fit of the southern model might also be due to the less complex meteorological environment encountered by storms that make landfall in the southern region combined with the less frequent interactions with topography of these southern cases.

As noted above, the results of Kaplan and DeMaria (1995) indicated that, on average, a storm's proximity to the coastline had a relatively small effect on a storm's decay rate after landfall. Nevertheless, this effect can be more substantial for individual storms. For example, Doria (1971) decayed much more slowly than was simulated by the northern decay model during the first 12 h after landfall when the storm remained very close to the coastline. Thus, some subjective increase in the northern decay model predicted wind speed might be required for storms with tracks that are similar to Doria's. This adjustment might be necessary because the proximity of these storms to the coastline represents a significant deviation from that of the average storm that was used to develop the northern decay model.

Table 2 shows that the reduction factor R is the same for the southern and northern decay models, but the background wind V_b and coefficient α are larger for the northern model. Because the size of the northern sample is small when compared with the southern sample, a sensitivity test was performed in which each of the nine storms was removed from the sample (one at a time) and the coefficients V_b and α were rederived for the case with $R = 0.9$. In all nine cases (with each storm removed), α was always larger than that of the southern model, and V_b was larger in seven of the nine cases. This result indicates that the larger value of α for the northern model is not due to a single storm in the sample. Although less definitive, this result also suggests that V_b is also larger for the northern sample.

The decay rate of the maximum sustained surface winds after landfall is determined by (3). Using the values of V_b and α in Table 2, it can be shown that the decay rate in the northern model is greater than that of the southern model for $V > 33$ kt but is less for $V < 33$ kt. Figure 4 compares the wind decay of a storm with a maximum wind of 111 kt just prior to landfall ($RV_0 = 100$ kt) for each model. This figure shows that, initially, the winds in the northern model decay more rapidly. However, at later times, the northern model winds decay more slowly, and after about 34 h the winds in the northern model are greater than those in the southern model.

The more rapid decay of the northern sample for $V > 33$ kt is consistent with the study of Rogers and Davis (1993). They used the NHC best track for the period of 1900–79 to show that the maximum sustained surface winds of storms making landfall north of 32.5°N decayed more rapidly than those of storms that made landfall south of 32.5°N. In contrast, Ho et al. (1987) evaluated the pressure deficit (the difference between the storm's central pressure and the pressure of the surrounding environment) of hurricanes that made landfall along the Atlantic coast (north of 32°N) and found that these hurricanes filled less (more) rapidly than hurricanes that made landfall along the Gulf of Mexico (Florida) coastline.

One possible explanation for the disagreement between the comparisons of the northern and southern model decay rates discussed in this study and those discussed in Ho et al. (1987) might be related to differences in the domains that were used to select the storm samples. To illustrate, all of the storms in the northern decay model sample made landfall north of 37°N, but three of the eight storms in the Ho et al. (1987) Atlantic sample made landfall between 32° and 37°N. Thus, it is possible that the aforementioned differences in the comparisons of the decay rates are partially due to the inclusion of storms south of 37°N in the Atlantic sample of Ho et al. (1987). Another possible explanation for the differences between the comparisons of the northern and southern storm decay rates is that the Ho et al. (1987) pressure deficit measurements were not made over the same radial distance for all storms. Consequently, regional variations in storm size alone could produce differences in the pressure gradient and thus the maximum surface wind. To illustrate, Merrill (1984) found that Atlantic hurricanes typically increase in size as they move northward, which suggests that the same pressure deficit could result in weaker maximum winds for the larger, higher-latitude storms.

One plausible explanation for the larger decay rate in the northern model is the higher terrain near the coast. The average terrain along the tracks of the northern sample was 43% higher than that of the southern sample, and the numerical modeling studies of Bender et al. (1985) and Tuleya (1994) indicate a more rapid wind decay for storms that move over higher and rougher terrain. The larger wind decay rate might also be due to the more hostile synoptic environment that typically exists at higher latitudes. For example, Sinclair (1993) has shown that as a tropical cyclone moves toward higher latitudes weakening can result from the combined effect of increased vertical shear, a loss of upper-level outflow, and entrainment of cooler air at low levels.

As described above, the northern decay model predicts a smaller wind decay rate than the southern model for winds below 33 kt. Mathematically, this smaller decay rate is primarily due to the larger value of V_b in the northern model. Although there is less confidence in the difference in V_b between the northern and southern models (as indicated by the sensitivity test described above), the slower decay rate for the northern storms might be due to a baroclinic source of energy as the systems become extratropical. Only 20% of the storms in the southern sample became extratropical, as compared with 67% in the northern sample.

4. Summary and conclusions

Kaplan and DeMaria (1995) developed a simple empirical model for predicting the decay of tropical cyclone 1-min maximum sustained surface winds after landfall. The model was developed from the NHC best-track wind estimates of storms that made landfall in the United States south of 37°N from 1967 to 1993. In this note, a similar model is developed for U.S. storms north of 37°N, which primarily made landfall in New York or Rhode Island and then moved across New England. Because of the less frequent occurrence of New England tropical cyclones, it was necessary to include cases back to 1938 to obtain a reasonable sample size. In addition, because of the faster translational speed and the fairly rapid extratropical transition of the higher-latitude cases, it was necessary to estimate the wind speeds at 2-h intervals after landfall, rather than every 6 h, as in the NHC best track. For the model development, the estimates of the maximum sustained winds of nine landfalling storms (seven hurricanes and two tropical storms) at 2-h intervals were determined by an analysis of all available surface data. The wind observations were adjusted to account for variations in anemometer heights, averaging times, and exposures using the procedures described by Powell et al. (1996).

Results showed that the winds in the northern model decayed more (less) rapidly than those of the southern model, when the winds just after landfall were greater (less) than 33 kt. It is hypothesized that this faster rate of decay is due to the higher terrain near the coast for the northern sample and to the more hostile environmental conditions (e.g., higher vertical wind shear). The slower decay rate when the winds fall below 33 kt in the northern model might be due to the availability of a baroclinic energy source as the storms undergo extratropical transition.

Several applications of the southern decay model were described by Kaplan and DeMaria (1995), including a method to estimate the maximum inland penetration of winds, given the storm speed and intensity at landfall, and a method for generating a wind ''swath'' for an individual storm. These same applications could also be applied to the northern decay model. Maps of the maximum inland penetration of winds using the northern and southern models have been developed for use in the HURREVAC program. The HURREVAC software was developed by FEMA for use by the emergency management community and also includes maps of hurricane-induced storm surge along the entire U.S. coastline. As was illustrated by the 1938 New England hurricane (Tannehill 1938), even the northern storms discussed in this study can produce substantial damage and loss of life from the combined effect of storm surge and heavy precipitation.

Additional research will be required to evaluate further the accuracy of both the northern and southern versions of the decay model. This additional research is particularly important for the northern version of the decay model, which was developed and evaluated for a relatively small sample size. It would also be worthwhile to compare the results of the decay model with more sophisticated three-dimensional numerical weather prediction models such as the GFDL model (Kurihara et al. 1995). The availability of high-resolution landfall datasets such as those that Marks et al. (1998) are planning to collect might help to accomplish these goals.

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