Simple Empirical Models for Estimating the Increase in the Central Pressure of Tropical Cyclones after Landfall along the Coastline of the United States

PETER J. VICKERY

Applied Research Associates, Raleigh, North Carolina

(Manuscript received 12 January 2005, in final form 14 June 2005)

ABSTRACT

Modeling the increase in the central pressure of tropical cyclones following landfall plays a critical role in the estimation of the hurricane wind hazard at locations removed from the coastline. This paper describes the development of simple empirical models for estimating the rate at which tropical cyclones decay after making landfall. For storms making landfall along the Gulf of Mexico Coast and the coast of the Florida Peninsula, it is shown that the rate of storm filling is proportional to the central pressure difference and translation speed at the time of landfall and is inversely proportional to the radius to maximum winds. Along the Atlantic Coast the effect of radius to maximum winds does not play as significant a role in the rate of storm decay as compared with that seen in Florida and along the Gulf Coast. The models developed here can readily be included in any hurricane simulation model designed for estimating wind speeds in the United States.

1. Introduction

Hurricane simulation models are routinely used for developing design wind speeds in hurricane prone regions of the world, estimating losses for insurance rate purposes, or justifying the costs of improved construction practices. A key component within the hurricane simulation models is the modeling of the decay of the simulated storms after they make landfall. The modeling of the decay of the storms is critical to the accurate assessment of the hurricane wind speed risk at locations removed from the coast, up to about 200 km inland. The decay models used in hurricane simulation tools model the decay of the central pressure of the storm rather than the decay in the wind speeds as modeled, for example, in Kaplan and DeMaria (1995, 2001). Hurricane simulation computer models simulate the decay in the central pressure rather than wind speeds, since these tools employ mathematical representations of the hurricane wind field to model the magnitude of the wind speeds and wind directions given information on the key characteristics of the tropical cyclone, such as translation speed, central pressure, and radius to maximum winds. Examples of previous decay models used in hurricane simulations include the model described in Batts et al. (1980) where they model the decay of the tropical cyclone as a function of time since landfall, with a decay constant that varies with the angle at which the storm crosses the coastline. Georgiou (1985) modeled the decay of the tropical cyclones using an empirical decay model developed for four different regions of the United States, but they modeled the decay as a function of distance from the landfall point rather than as a function of time. Ho et al. (1987) present plots of tropical cyclone decay for three different regions of the United States, with the decay curves varying with storm intensity, with the result that more intense tropical cyclones (lower central pressure) decay more rapidly than the weaker tropical cyclones.

The filling models described herein represent a significant update and improvement over the filling models developed by Vickery and Twisdale (1995), which used information on hurricanes making landfall in the United States during the period 1900–91. The Vickery and Twisdale (1995) model has been used in hurricane simulation models to develop the design wind speeds given in the U.S. National Wind Loading Standard ASCE 7 (ASCE 1998, 2003), as well as the Federal Emergency Management Agency (FEMA) Hurricane Loss Estimation Model (FEMA 2003), and most re-

Corresponding author address: Peter J. Vickery, Principal Engineer, Applied Research Associates, 8540 Colonnade Center Drive, Suite 307, Raleigh, NC 27615.
E-mail: pvickery@ara.com

cently, in the development of the public Florida wind loss estimation tool (Powell et al. 2005).

The filling models described here are relatively simple statistical models suitable for use in hurricane simulation models that are designed to perform hundreds of thousands of storm simulations in relatively short periods of time. The statistically based models described here cannot model all of the physics associated with modeling the decay of the storms such as the effect of land surface water (e.g., Weixing et al. 2002), the entrainment of dry air, the effect of wind shear, interaction with frontal systems, mountainous terrain, soil moisture, etc. Even if more sophisticated filling models could be employed, the hurricane simulation models needed to make use of the more complex models must be able to simulate the variation of the additional parameters required in a more complex filling model.

2. Analysis methodology

The filling models described herein are based upon information on the central pressures of tropical cyclones at and following landfall derived from two sources. The first source, which represents the bulk of the data, uses the National Hurricane Center (NHC) best-track 6-hourly estimates of storm central pressure as given in the Hurricane Database (HURDAT; Jarvinen et al. 1984) in addition to the central pressure at landfall, usually determined from sources other than HURDAT. The most recent edition of HURDAT was used in the analysis that includes all the updates to the dataset produced to date. The updates to the HURDAT database are described in Landsea et al. (2004a, 2004b), but to date these updates have not produced any changes in the central pressures reported in the post-1926 storms, although updates may occur in the future as the HURDAT reanalysis is an ongoing project. The second data source used in the estimate of the filling of the tropical cyclones is the plots of the central pressure (normalized by the central pressure at landfall) given in Ho et al. (1987). The form of the filling model is an exponential decay function in the form

$$\Delta p(t) = \Delta p_o \exp(-at), \tag{1}$$

where $\Delta p(t)$, expressed in hectopascals (millibars, abbreviated as mb herein), is the difference between the central pressure of the storm and the far field pressure (normally taken as the pressure associated with the outermost closed isobar) t hours after landfall; Δp_o (mb) is the difference between the central pressure of the storm and the far field pressure at the time the storm makes landfall; and a is the filling constant. This form of the filling model is the same as that used by Vickery and Twisdale (1995).

Following the approach taken by Vickery and Twisdale (1995), the initial analysis of the rate of filling of storms was performed with the coastline of the United States divided into three regions: the Gulf of Mexico Coast, the Florida Peninsula, and the Atlantic Coast. This geographic regionalization is also consistent with the analyses of filling performed by Schwerdt et al. (1979) and Ho et al. (1987).

Figures 1–3 present the central pressure difference data (normalized by the central pressure difference at the time of landfall) plotted versus time after landfall and the exponential decay function derived using a simple least squares analysis, for the filling rates determined using the HURDAT central pressure data. In using the HURDAT central pressure data, a peripheral or far-field pressure of 1013 mb was assumed when computing Δp, rather than using the pressure associated with the outermost closed isobar. The use of a constant peripheral pressure of 1013 mb is a simplification but is consistent with the assumption used in most hurricane risk models, and is also consistent with that used in Ho et al. (1987), Vickery and Twisdale (1995), and Powell et al. (2005) in their estimates of Δp. A constant value 1013 mb value is used in the risk models of Georgiou (1985), Vickery et al. (2000), and Powell et al. (2005). Batts et al. (1980) use a constant peripheral pressure of 1008 mb in their modeling of the hurricane risk along the coastline of the United States. In the development of the statistical distributions of Δp used in the tropical cyclone risk models noted above, a constant peripheral pressure is used in conjunction with the HURDAT central pressures to define the statistical distributions of Δp. Thus, while the use of a constant peripheral pressure in the development of the filling models described herein is clearly a simplification, the assumption is consistent with that used in the development of tropical cyclone risk models as a whole.

A visual comparison of the modeled filling rate curves with the filling determined using the HURDAT data in the Gulf Coast data (Fig. 1) indicates that in seven cases (1945 No Name 5, 1947 No Name 4, 1970 Celia, 1980 Allen, 1983 Alicia, 1985 Danny, and 2003 Bill), the exponential model overestimates the rate of decay in the first 12–15 h; in five cases (1985 Elena, 1992 Andrew, 1995 Erin, 1980 Georges, and 2003 Claudette), the exponential model underestimates the decay. In the remaining nine cases, the model is approximately mean centered with the data. In the case of the Florida Peninsula storms (Fig. 3), the exponential decay model is approximately mean centered in all 13 cases. In the case of the Atlantic Coast landfalling storms,

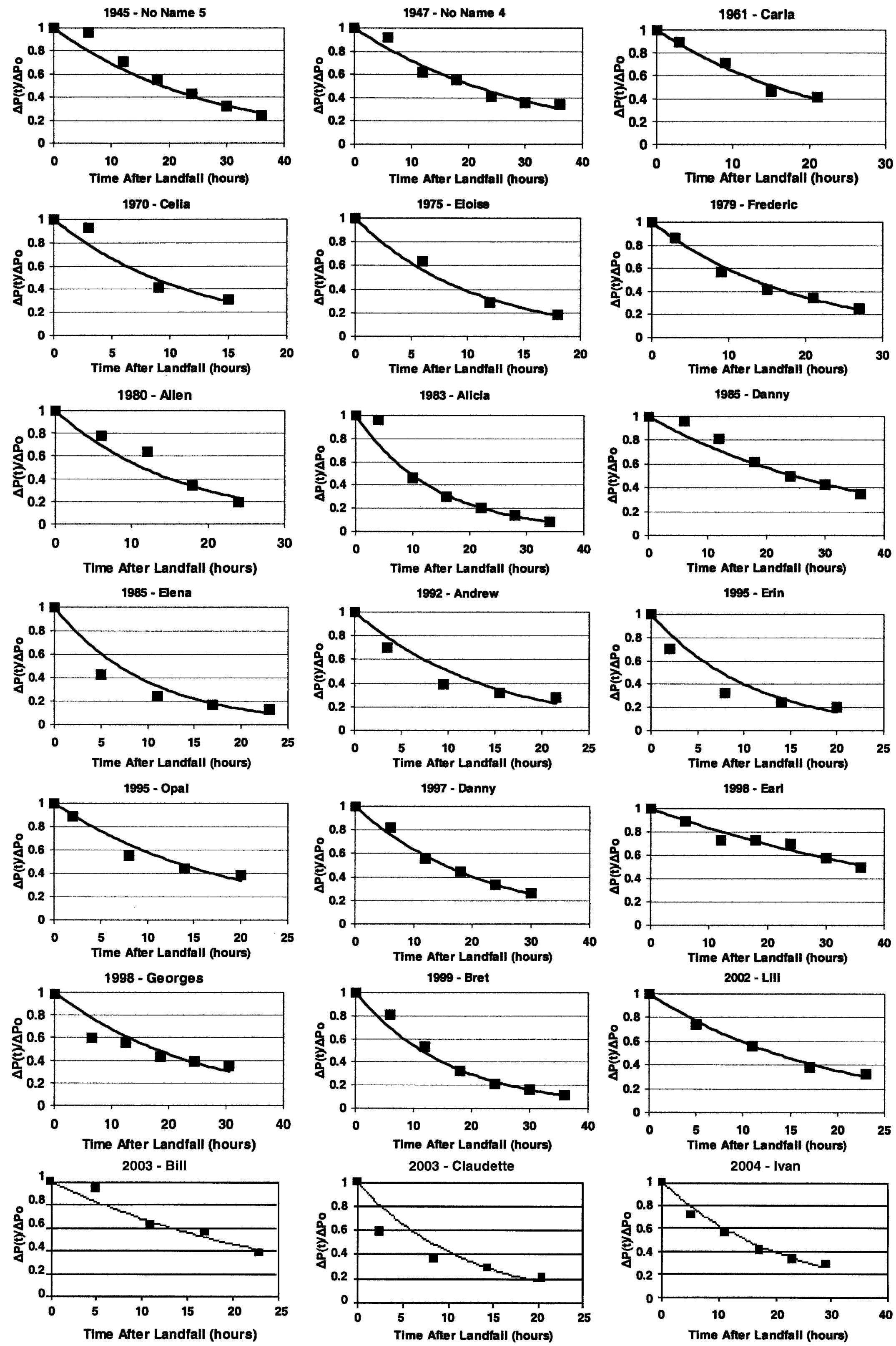

FIG. 1. Observed and fitted central pressure difference decay functions for Gulf Coast storms using HURDAT central pressure data.

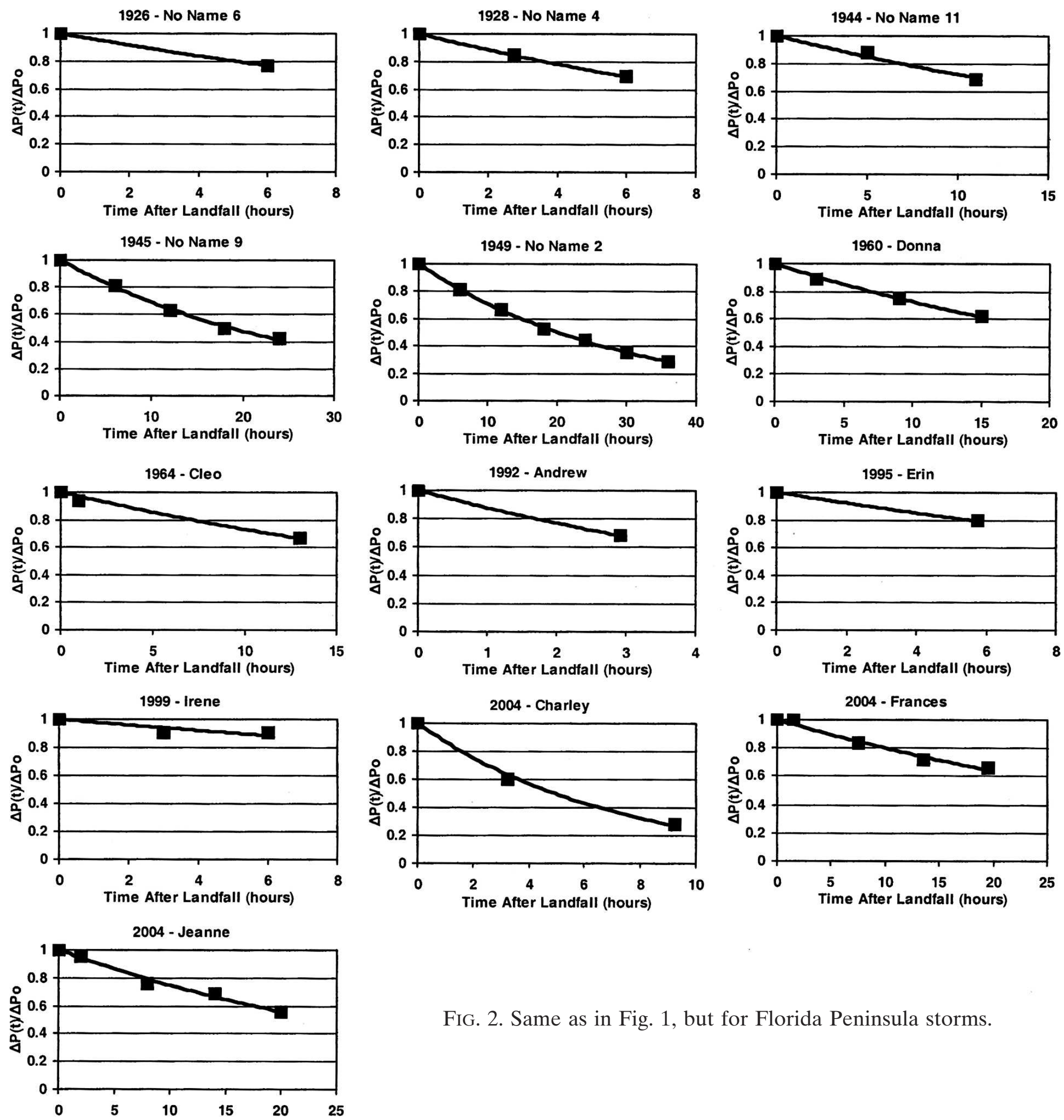

FIG. 2. Same as in Fig. 1, but for Florida Peninsula storms.

only two cases (1955 Connie and 2003 Isabel) show a clear underestimate of the rate of decay in the first 10–15 h, and only one case (1996 Bertha) shows a clear overestimate of the rate of decay, but only in the first 6–10 h after landfall. In the remaining nine cases, the model is approximately mean centered with the data.

Table 1 presents the storm landfall code, the central pressure at landfall, the landfall time, the data source used to determine the central pressure at landfall and the landfall time, the number of hours after landfall used to compute the filling rate coefficient, the number of data points used, the computed value of *a,* and the value of r^2 resulting from the regression analysis. The mean r^2 value for the individual storm exponential fits is 0.945, ranging from a low of 0.32 for the Hurricane Bertha case (Fig. 3) to a high of 1.00. The r^2 values of 1.00 are typically associated with the storms that have only two data points. Considering only storms with 3 or more data points, the mean value of r^2 is 0.942, and with 4 or more points the mean r^2 is also 0.942. The comparison of the modeled and observed decay rates shown in Figs. 1–3, coupled with the high r^2 values, indicates that modeling the decay of tropical cyclones using an exponential decay model is appropriate.

Figures 4 and 5 present the central pressure data (normalized by the central pressure at the time of landfall) plotted versus time after landfall and the exponential decay function derived using a simple least squares analysis for the filling rates determined using the Ho et al. (1987) data.

A visual comparison of the modeled filling rate curves with the filling determined using the Ho et al.

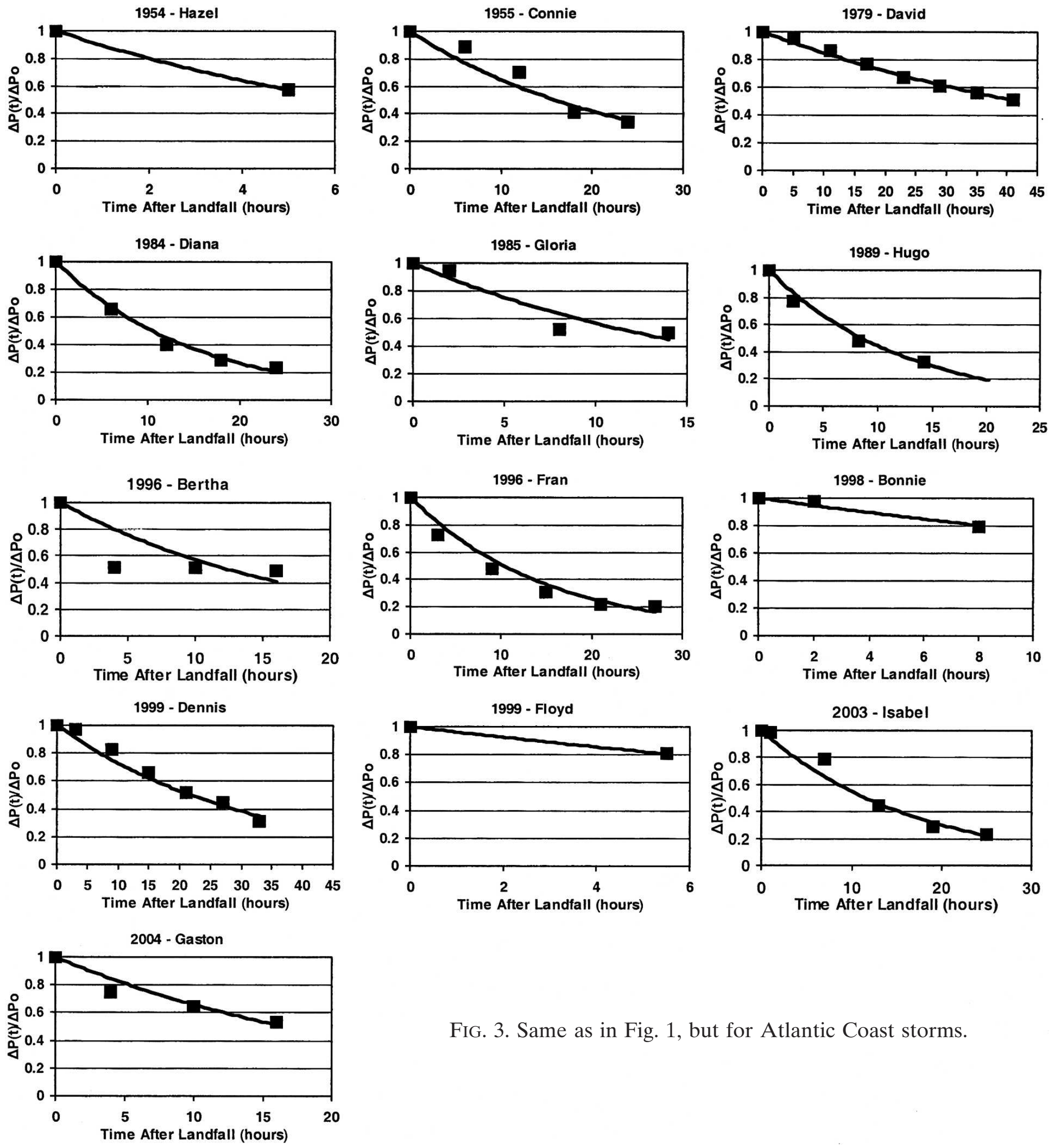

FIG. 3. Same as in Fig. 1, but for Atlantic Coast storms.

(1987) data in the Gulf Coast case (Fig. 4) indicates that in six cases (1957 Audrey, 1961 Carla, 1965 Betsey, 1970 Celia, 1980 Allen, and 1983 Alicia) the exponential model overestimates the rate of decay in the first 6–10 h after landfall. In the remaining four cases, the model is approximately mean centered. In the case of the Atlantic Coast storms (Fig. 5), the exponential decay model is approximately mean centered in all seven cases.

Table 2 presents the storm landfall code, the central pressure at landfall, the landfall time, the number of hours after landfall used to compute the filling rate coefficient, the number of data points used, the computed value of a, and the value of r^2 resulting from the regression analysis. The mean r^2 value obtained using the exponential model to fit the decay data obtained from Ho et al. (1987) is 0.953, again reinforcing the suitability of the exponential decay model to model the weakening of tropical cyclones following landfall.

Seven tropical cyclones (Hazel 1954, Carla 1962, Celia 1970, Eloise 1975, Frederic 1979, Allen 1980, and Alicia 1983) appear in both the Ho et al. (1987) data and the HURDAT data, and consequently two separate estimates of the exponential filling constants result from the regression analyses of these central pressure data. Figure 6 presents a scatterplot of the a values computed using the Ho et al. (1987) data with those derived from the HURDAT data. It is seen that in four of the cases the computed filling constants are, for prac-

TABLE 1. Landfalling storms used in filling rate analysis using HURDAT data and resulting filling rate coefficients. (Landfall codes: ATX = south Texas, BTX = central Texas, CTX = north Texas, LA = Louisiana, MS = Mississippi, AL = Alabama, AFL = northwest Florida, BFL = southwest Florida, CFL = southeast Florida, DFL = northeast Florida, GA = Georgia, SC = South Carolina, NC = North Carolina, and NY = New York.)

Year and name	Landfall code	Central pressure (mb)	Landfall time (UTC)	Landfall source	Hours	a	N	r^2
Florida Peninsula								
1926—No Name 6	HR CFL 4	931	9/17/1926 1200	HURDAT, Mitchell (1926)	6.0	0.0439	2	1.0000
1928—No Name 4	HR CFL 4	929	9/17/1928 0900	HURDAT, Mitchell (1928)	6.0	0.0616	3	1.0000
1944—No Name 11	HR BFL 3	949	10/19/1944 1700	HURDAT, Ho et al. (1987)	11.0	0.0327	3	0.9762
1945—No Name 9	HR CFL 3	951	9/16/1945 0000	HURDAT, Ho et al. (1987)	24.0	0.0372	5	0.9970
1949—No Name 2	HR CFL 3	954	8/27/1949 0000	HURDAT, Ho et al. (1987)	36.0	0.0346	7	0.9995
1960—Donna	HR BFL 4	942	9/10/1960 1500	Miller (1964)	15.0	0.0323	4	0.9958
1964—Cleo	HR CFL 2	968	8/27/1964 1700	HURDAT, Ho et al. (1987)	13.0	0.0314	3	0.9849
1992—Andrew	HR CFL 5	922	8/24/1992 0905	NHC preliminary report	2.9	0.1314	2	1.0000
1995—Erin	HR CFL 1	984	9/2/1995 0615	NHC preliminary report	5.8	0.0403	2	1.0000
1999—Irene	HR BFL 1	982	9/15/1999 1930	HRD wind analysis	6.0	0.0204	3	0.7000
2004—Charley	HR BFL 4	941	8/13/2004 2045	NHC preliminary report	11.0	0.1407	3	0.9954
2004—Frances	HR CFL 2	960	9/5/2004 0430	NHC preliminary report	25.5	0.0225	5	0.9801
2004—Jeanne	HR CFL 3	950	9/26/2004 0400	NHC preliminary report	20.0	0.0292	6	0.9902
Gulf Coast								
1945—No Name 5	HR BTX 2	966	8/27/1945 1800	HURDAT, Ho et al. (1987)	36.0	0.0373	7	0.9658
1947—No Name 4	HR LA 3	966	8/27/1949 0000	HURDAT, Ho et al. (1987)	36.0	0.0330	7	0.9959
1961—Carla	HR BTX 4	931	9/12/1960 0300	HURDAT, Ho et al. (1987)	21.0	0.0443	5	0.9729
1970—Celia	HR ATX 3	945	8/4/1970 0300	HURDAT, Ho et al. (1987)	15.0	0.0820	4	0.9475
1975—Eloise	HR AFL 3	955	9/23/1975 1200	Hebert (1976)	18.0	0.0958	4	0.9856
1979—Frederic	HR AL 3	946	9/13/1979 0300	HURDAT, Ho et al. (1987)	27.0	0.0526	6	0.9863
1980—Allen	HR ATX 3	945	8/10/1980 0600	NHC preliminary report	24.0	0.0613	5	0.9310
1983—Alicia	HR CTX 3	962	8/18/1983 1600	HURDAT, Ho et al. (1987)	34.0	0.0728	7	0.9864
1985—Danny	HR LA 1	987	11/21/1985 2230	NHC preliminary report	36.0	0.0281	6	0.9653
1985—Elena	HR AL 3	959	9/2/1985 1145	HURDAT	23.0	0.1010	5	0.8863
1992—Andrew	HR LA 3	956	8/26/1992 0830	NHC preliminary report	21.5	0.0689	5	0.8718
1995—Erin	HR AFL 2	973	8/3/1995 1600	NHC preliminary report	20.0	0.0921	5	0.8654
1995—Opal	HR AFL 3	942	10/4/1995 2200	NHC preliminary report	20.0	0.0542	5	0.9369
1997—Danny	HR AL 1	986	7/19/1997 1800	NHC preliminary report	30.0	0.0453	6	0.9950
1998—Earl	HR AFL 1	987	9/3/1998 0600	NHC preliminary report	36.0	0.0184	7	0.9536
1998—Georges	HR MS 2	964	9/28/1998 1130	NHC preliminary report	30.5	0.0396	6	0.8834
1999—Bret	HR ATX 3	951	8/23/1999 0000	NHC preliminary report	36.0	0.0610	7	0.9893
2002—Lili	HR LA 1	963	10/3/2002 1300	NHC preliminary report	23.0	0.0524	5	0.9866
2003—Bill	N/A (LA)	997	9/30/2003 1900	NHC preliminary report	23.0	0.0392	5	0.9482
2003—Claudette	HR BTX 1	979	7/15/2003 1530	NHC preliminary report	20.5	0.0854	5	0.8722
2004—Ivan	HR MS 3	946	9/16/2004 0650	NHC preliminary report	29.2	0.0470	6	0.9716
Atlantic Coast								
1954—Hazel	HR NC 4	938	10/15/1954 1900	HURDAT, Ho et al. (1987)	5.0	0.1113	2	1.0000
1955—Connie	HR NC 3	969	8/13/1955 0000	HURDAT, Ho et al. (1987)	24.0	0.0434	5	0.9307
1979—David	HR GA 2	970	9/4/1979 1900	HURDAT, Ho et al. (1987)	35.0	0.0165	8	0.9924
1984—Diana	HR NC 2	978	9/13/1984 0600	HURDAT, Ho et al. (1987)	24.0	0.0662	5	0.9782
1985—Gloria	HR NY 3	961	9/27/1995 1600	NHC preliminary report	14.0	0.0571	4	0.8714
1989—Hugo	HR SC 4	934	9/22/1989 0345	Powell et al. (1991)	14.3	0.0813	4	0.9841
1996—Bertha	HR NC 2	974	7/12/1996 2000	NHC preliminary report	16.0	0.0561	4	0.3216
1996—Fran	HR NC 3	954	9/6/1996 0300	NHC preliminary report	27.0	0.0675	6	0.9411
1998—Bonnie	HR NC 2	964	8/27/1998 0400	NHC preliminary report	8.0	0.0275	3	0.9608
1999—Dennis	N/A (NC)	984	9/4/1999 2100	NHC preliminary report	33.0	0.0320	7	0.9701
1999—Floyd	HR NC 2	956	9/16/1999 0630	NHC preliminary report	5.5	0.0309	2	1.0000
2003—Isabel	HR NC 2	957	9/18/2003 1700	NHC preliminary report	25.0	0.0602	6	0.9760

tical purposes, identical. However, for the other three cases, the rate of decay computed using the HURDAT central pressure data is higher (more rapid filling) than that computed using the Ho et al. (1987) data. The most significant difference between the filling constants computed using the two different datasets is seen in the case of Hurricane Hazel, where the decay constant estimated using the HURDAT data is almost double that

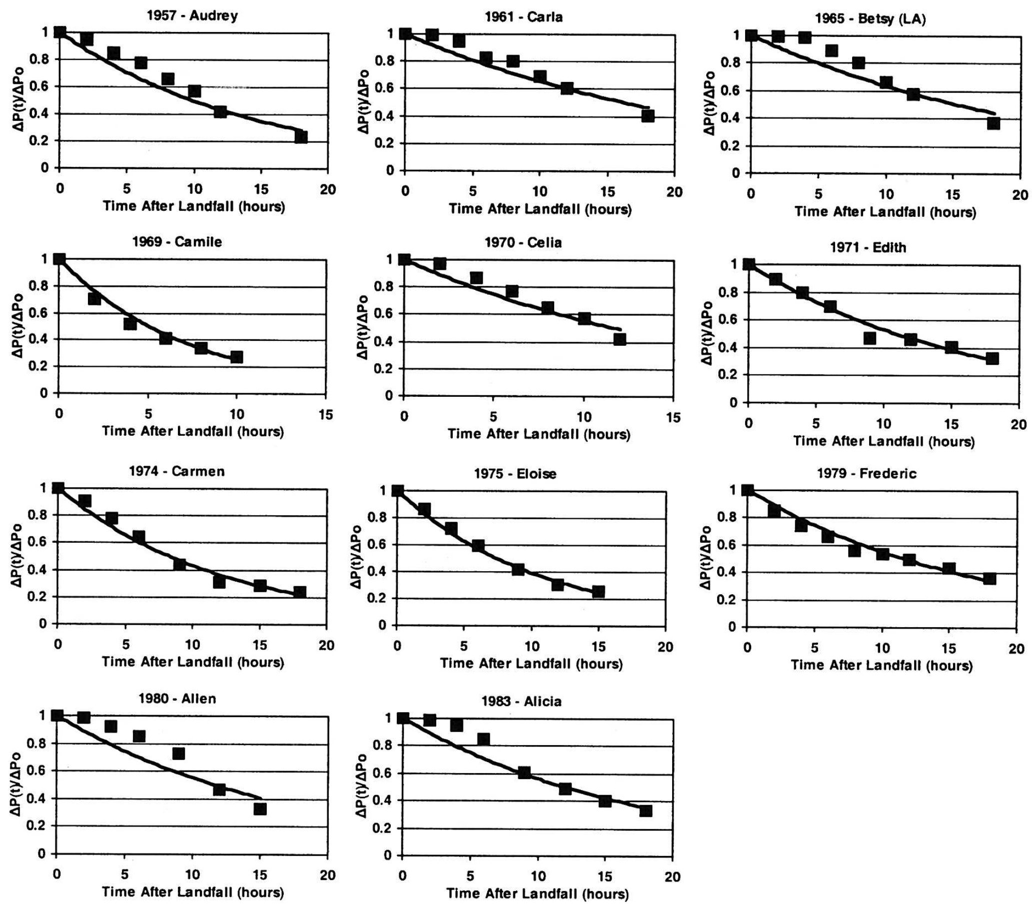

FIG. 4. Observed and fitted central pressure difference decay functions for Gulf Coast storms using central pressure data from Ho et al. (1987).

estimated using the Ho et al. (1987) data. The reason for the significant difference in the filling rate of Hurricane Hazel resulting from the two sets of data is not understood. In the case of Hurricanes Alicia and Celia, the HURDAT-estimated filling constants are 26% and 40% higher, respectively. In subsequent analyses of the filling of tropical cyclones, the average value of the filling constants computed from the two sets of data has been used.

A scatterplot of the errors (modeled central pressure minus observed central pressure) is given in Fig. 7, with the error presented as a function of time since landfall associated with the use of the exponential decay model to describe the rate of decay of the tropical cyclones after landfall, broken out by region. The errors shown in Fig. 7 are approximately mean centered, about a mean of zero, with no trend for the mean value of the error to deviate from zero as time since landfall increases. The distribution of the errors given in Fig. 7 reinforce the suitability of an exponential model for modeling the rate of increase in the central pressure of a tropical cyclone after landfall, as no bias in the estimates of the pressures arises from the use of the model. Table 3 presents the numerical values of the mean and standard deviation of the error as a function of time since landfall for each of the three regions.

3. Analysis of filling rate coefficients

The initial analysis of the filling rate constants given in Table 1 followed the approach used in Vickery and Twisdale (1995), where the exponential filling constant, a, was modeled as a linear function of the central pressure difference of the tropical cyclone at the time of landfall. Following the suggestions of Kaplan and DeMaria (2001), in the analysis of the filling constants for tropical cyclones making landfall along the Atlantic Coast, the analysis was extended by separating the Atlantic Coast into two regions (in addition to the all–Atlantic Coast region), where storms making landfall in the New England area were treated separately, leaving a New England Coast region and a Mid-Atlantic Coast

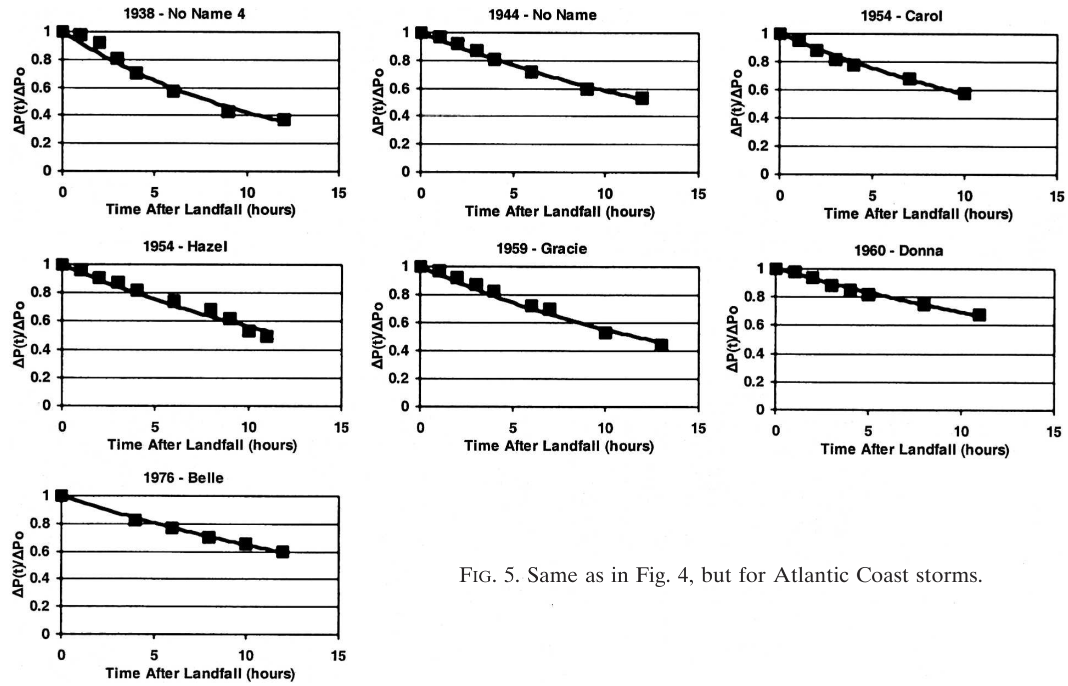

FIG. 5. Same as in Fig. 4, but for Atlantic Coast storms.

region. As in Kaplan and DeMaria (2001), the New England region includes all storms making landfall on Long Island and north of Long Island. Using this model, the filling constant a is modeled as

$$a = a_0 + a_1 \Delta p_o, \quad (2)$$

where the constants a_0 and a_1 are determined using a standard linear regression analysis. Figure 8 shows the values of the decay constant, a, plotted versus Δp_o for the five different geographic regions. Also shown in Fig. 8 are the three linear models given in Vickery and Twisdale (1995), for the Gulf Coast, Florida Peninsula, and the Atlantic Coast cases. In the Gulf Coast case, it is readily seen that the linear relationship between a and Δp_o is very similar to that given in Vickery and Twisdale (1995), but the r^2 value of 0.27 resulting from

TABLE 2. Same as in Table 1, but using Ho et al. (1987) data.

Year and name	Landfall code	Central pressure (mb)	Hours after landfall	a	N	r^2
Gulf Coast						
1957—Audrey	HR CTX 4	945	18	0.0702	8	0.9216
1961—Carla	HR BTX 4	931	18	0.0425	8	0.9092
1965—Betsy (LA)	HR LA 3	948	18	0.0450	8	0.8681
1969—Camille	HR MS 5	909	10	0.1375	6	0.9701
1970—Celia	HR ATX 4	945	12	0.0590	7	0.9123
1971—Edith	HR LA 2	978	18	0.0636	8	0.9636
1974—Carmen	HR LA 3	936	18	0.0841	8	0.9757
1975—Eloise	HR AFL 3	955	15	0.0936	7	0.9942
1979—Frederic	HR AL 3	946	18	0.0594	9	0.9665
1980—Allen	HR ATX 3	945	15	0.0594	7	0.8419
1983—Alicia	HR CTX 3	962	18	0.0577	8	0.9391
Atlantic Coast						
1938—No Name 4	HR NY 3	943	12	0.0862	8	0.9786
1944—No Name	HR NC 3	955	12	0.0538	8	0.9933
1954—Carol	HR NY 3	961	10	0.0561	7	0.9906
1954—Hazel	HR NC 4	938	11	0.0573	10	0.9623
1959—Gracie	HR SC 3	951	13	0.0595	9	0.9772
1960—Donna	HR NY 3	961	11	0.0368	8	0.9879
1976—Belle	HR NY 1	982	12	0.0435	6	0.9964

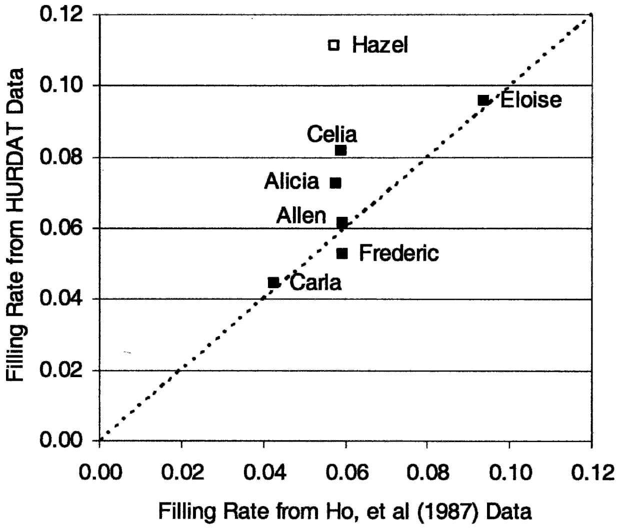

FIG. 6. Comparison of filling coefficients derived from HURDAT data with filling coefficients derived from Ho et al. (1987) data.

the current analysis is much higher than the r^2 value of 0.07 reported in Vickery and Twisdale (1995). In the case of the Florida Peninsula storms it is clear that a simple model describing a as a linear function of Δp_o is not a good choice, even though the r^2 value of 0.3194 is greater than that produced in the Gulf Coast storm case. The linear model yields negative values of the filling constant for storms having central pressure differences of 20 mb or less, which is clearly not possible. The linear decay model of Vickery and Twisdale (1995) shown in Fig. 8 is seen to pass through the bulk of the data exhibiting slower filling but grossly underestimates the filling rates of the two outlying storms (Hurricane Andrew in 1992 and Hurricane Charley in 2004).

In the case of the Atlantic Coast storms, the new regression model yields a higher slope and lower intercept than the Vickery and Twisdale (1995) model, but both lines pass through a point near the centroid of the data. The new model will weaken the more intense storms more rapidly than will the model of Vickery and Twisdale (1995). The r^2 value for the new model of 0.37 is notably greater than the value of 0.16 given in Vickery and Twisdale (1995). The r^2 values associated with the Mid-Atlantic and New England regression analyses are 0.42 and 0.55, respectively, again notably higher than the r^2 values evident in the Vickery and Twisdale (1995) results (for the entire Atlantic Coast). The improvement in the r^2 values in this study for Gulf and Atlantic Coast tropical cyclones relative to those given in Vickery and Twisdale (1995) results from a combination of the following:

(i) The new study uses only storms with published values of Δp_o rather than interpolating between the post- and prelandfall land values of Δp to estimate Δp_o, as was used in Vickery and Twisdale (1995). This resulted in the use of only tropical cyclones having values of Δp_o greater than 16 mb in this study versus all tropical cyclones with data after landfall in Vickery and Twisdale (1995).

(ii) The addition of more filling data from storms making landfall after 1991, and the inclusion of the Ho et al. storms that yield values of the filling coefficient a that fall closer to the mean of the model.

In the Florida Peninsula case, the failure of this simple linear model to adequately model the variation of the filling constant prompted a reexamination of the parameters needed to adequately explain the variation in the rate of filling of these Florida Peninsula storms. The failure of the linear model to adequately model the variation of the filling constant is associated with two outlying storms: Hurricane Andrew (1992) and Hurricane Charley (2004). The most obvious major difference between these two storms and the remaining 11 storms was that these two storms were associated with storms with small radius to maximum winds (RMW). Thus, the first model variation involved the introduction of RMW in addition to Δp_o based on the premise that smaller storms would tend to decay more rapidly than larger storms since a relatively larger portion of the core of the storm is removed from the energy source more rapidly than in the case of a larger storm. The notion that the filling rate of storms decreased as the percentage of the storms underlying circulation that was over water increased is qualitatively discussed in Malkin (1959) and noted again in Kaplan and DeMaria (1995). In this case the filling constant a is modeled as

$$a = a_0 + a_1(\Delta p_o/\mathrm{RMW}). \tag{3}$$

A second model variation involved the introduction of the translation speed in addition to RMW and Δp_o as a means to quantify how rapidly the core of the storm is initially removed from its energy source. In this case, the filling constant a is modeled as

$$a = a_0 + a_1(\Delta p_o c/\mathrm{RMW}), \tag{4}$$

where c is the translation speed of the storm at the time of landfall.

Table 4 presents the values of the RMW and translation speed for all of the tropical cyclones used in the filling rate study. In all cases, the value of the translation speed has been computed using the HURDAT best-track positions using a central difference approach. The translation speed at each 6-h position of

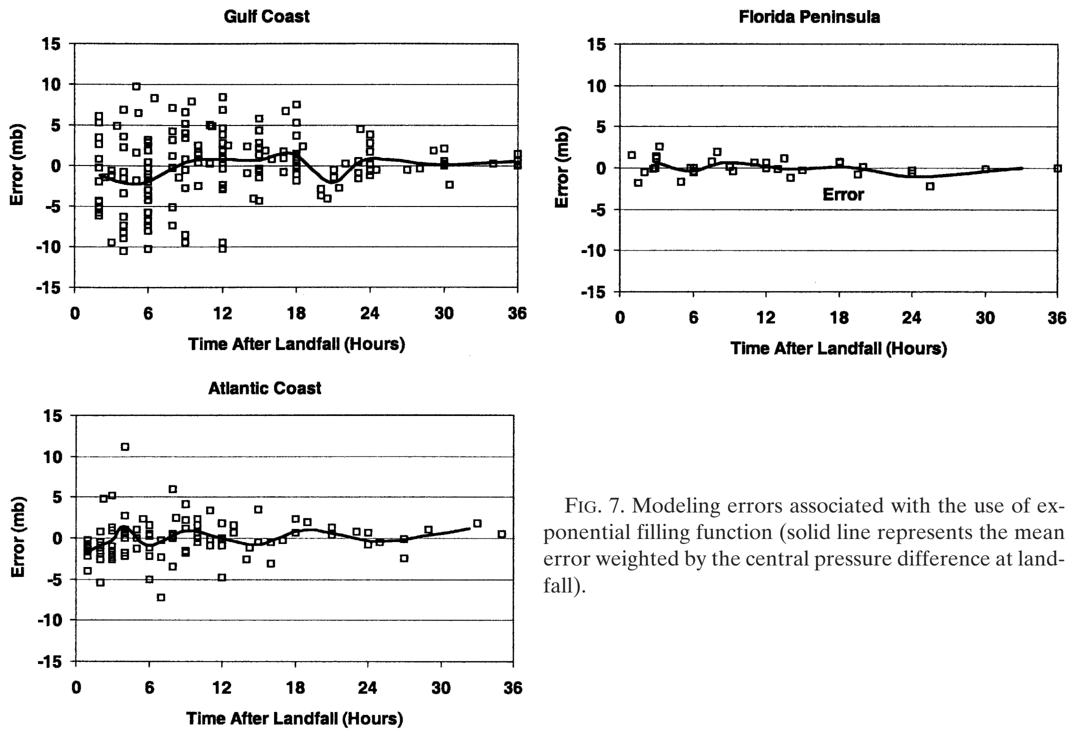

FIG. 7. Modeling errors associated with the use of exponential filling function (solid line represents the mean error weighted by the central pressure difference at landfall).

the NHC best track was computed by dividing the distance traveled from the position 6 h prior to the current position to the current position, plus the distance traveled from the current position to the position 6 h hence by the 12-h period. The translation speed at landfall was computed through linear interpolation of the translation speeds computed at each of the six of our best track points, to the location where the best track crossed the smoothed coastline.

The values of the RMW were obtained from a variety of sources, with the dominant sources being Ho et al. (1987) and the wind analyses performed by the Hurricane Research Division (HRD), the majority of which are available on the HRD Web site (www.aoml.noaa.gov/hrd/). Other sources for RMW include poststorm wind field analyses such as those described in Vickery et al. (2000), and lower-tropospheric (700 mb primarily) aircraft data.

Figures 9 and 10 show the values of the decay constant, a, plotted versus Δp_o/RMW and $\Delta p_o c$/RMW, respectively, for the five different geographic regions. Table 5 summarizes the resulting values of the slopes (a_1), intercepts (a_0), r^2, and standard deviation of the errors for all model types. For each region examined, the largest value of r^2 is given in boldface in Table 5.

The introduction of the RMW into the linear model

TABLE 3. Errors in modeled and observed central pressures as a function of time after landfall using exponential decay function. Values in parentheses are computed using the absolute value of the error.

Gulf Coast				Florida Peninsula				Atlantic Coast			
Hours	N	Mean (mb)	Std dev (mb)	Hours	N	Mean (mb)	Std dev (mb)	Hours	N	Mean (mb)	Std dev (mb)
2.0	14	−1.16 (3.74)	4.21 (2.02)	2.8	6	0.75 (0.97)	1.18 (0.97)	1.0	7	−1.63 (1.63)	1.23 (1.23)
4.0	19	−2.10 (5.14)	5.95 (3.48)	5.8	7	−0.38 (0.40)	0.62 (0.61)	2.0	9	−0.97 (2.19)	2.75 (1.79)
6.0	21	−2.03 (4.47)	5.04 (2.95)	8.4	4	0.58 (0.79)	0.99 (0.78)	3.0	8	−0.25 (2.11)	2.63 (1.39)
9.0	24	0.35 (3.74)	4.72 (2.80)	12.0	4	0.28 (0.35)	0.41 (0.33)	4.0	9	1.43 (2.33)	3.94 (3.43)
11.9	23	0.80 (3.25)	4.41 (3.02)	13.9	4	−0.09 (0.65)	0.93 (0.56)	6.0	14	−0.95 (1.83)	2.59 (2.02)
14.9	15	0.60 (2.27)	2.82 (1.69)	18.9	4	0.17 (0.59)	0.72 (0.31)	9.0	17	0.94 (1.81)	0.85 (0.85)
17.7	21	1.44 (1.89)	2.48 (2.14)	24.5	3	−1.01 (1.01)	0.99 (0.99)	11.9	10	0.05 (1.42)	2.14 (1.53)
20.9	7	−2.16 (2.23)	1.62 (1.50)	33.0	2	−0.06 (0.06)	0.06 (0.06)	15.0	6	−0.74 (1.88)	0.84 (0.84)
23.7	12	0.75 (1.55)	2.02 (1.44)					19.0	6	1.06 (1.14)	1.67 (1.67)
29.5	10	0.18 (0.84)	1.25 (0.91)					25.0	6	−0.41 (0.89)	1.67 (1.67)
35.7	6	0.49 (0.50)	0.50 (0.49)					32.3	3	1.12 (1.12)	0.61 (0.61)

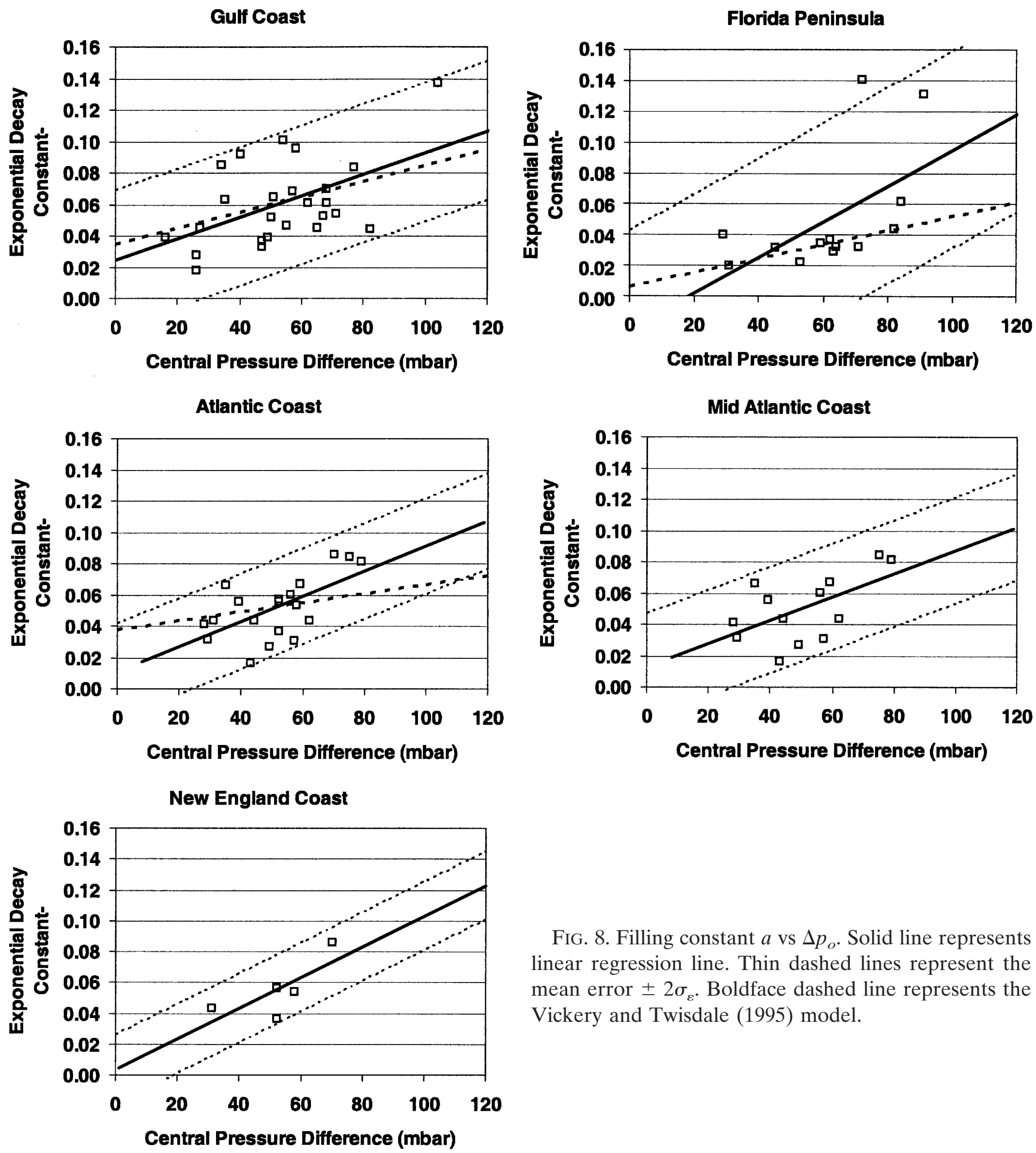

FIG. 8. Filling constant a vs Δp_o. Solid line represents linear regression line. Thin dashed lines represent the mean error $\pm\ 2\sigma_\varepsilon$. Boldface dashed line represents the Vickery and Twisdale (1995) model.

for defining the variation of the filling constant is seen to increase the value of r^2 for Gulf Coast, Florida, and Mid-Atlantic storms relative to the model defining the filling constant as a function of Δp_o alone. The introduction of the translation speed into the model is seen to increase the r^2 in all cases (relative to the Δp_o/RMW model), and yields the largest value of r^2 in all cases except for storms making landfall along the New England Coast. It should be noted, however, that the range in the RMW (factor of 2.5) for the storms used to define the rate of filling in the New England area is much less than that seen in the case of Florida (factor of 10), or the Gulf Coast (factor of 8), suggesting that the RMW effect may exist but is not evident because of the limited range of RMW in the storm dataset.

Analysis of model errors

The errors associated with the use of the filling models described above were estimated at 3-h increments and are given in Figs. 11–15. Errors have been computed for the three models proposed herein. Errors associated with applying the models of Vickery and Twisdale (1995) to the new storm dataset are also computed and presented. Model estimates of the central pressure of each storm as a function of time after landfall were computed using the Δp_o, RMW and translation speed data given in Tables 1, 2, and 4, coupled with the re-

TABLE 4. Translation speed and RMW values used in filling rate analysis. "Recon" indicates aircraft reconnaissance.

Year and name	Translation speed ($m\,s^{-1}$)	RMW (km)	RMW source
Florida Peninsula			
1926—No Name 6	5.7	35	Ho et al. (1987)
1928—No Name 4	5.7	52	Ho et al. (1987)
1944—No Name 11	8.1	54	Ho et al. (1987)
1945—No Name 9	6.4	22	Ho et al. (1987)
1949—No Name 2	6.4	43	Ho et al. (1987)
1960—Donna	5.1	33	Ho et al. (1987)
1964—Cleo	4.6	13	Ho et al. (1987)
1992—Andrew	8.8	19	Powell et al. (1996), wind analysis
1995—Erin	7.4	100	HRD
1999—Irene	5.2	74	HRD
2004—Charley	11.0	10	HRD, wind analysis
2004—Frances	3.0	70	HRD, wind analysis
2004—Jeanne	5.2	65	HRD, wind analysis
Gulf Coast			
1945—No Name 5	2.4	33	Ho et al. (1987)
1947—No Name 4	8.6	43	Ho et al. (1987)
1957—Audrey	7.3	37	Ho et al. (1987)
1961—Carla	3.7	56	Ho et al. (1987)
1969—Camille	7.2	15	Ho et al. (1987)
1970—Celia	7.3	17	Ho et al. (1987)
1971—Edith	8.6	28	Ho et al. (1987)
1974—Carmen	4.6	19	Ho et al. (1987)
1975—Eloise	12.5	26	Ho et al. (1987)
1979—Frederic	6.6	35	Recon data, wind analysis
1980—Allen	3.8	74	Ho et al. (1987)
1983—Alicia	4.1	55	Ho et al. (1987)
1985—Danny	1.0	60	Recon data
1985—Elena	7.6	22	Recon data, wind analysis
1992—Andrew	4.9	33	M. D. Powell (2004, personal communication)
1995—Erin	5.7	42	HRD, wind analysis
1995—Opal	11.1	90	HRD, wind analysis
1997—Danny	5.6	28	HRD
1998—Earl	7.9	119	HRD
1998—Georges	2.2	56	HRD
1999—Bret	2.7	17	HRD
2002—Lili	6.7	19	HRD
2003—Bill	6.4	94	HRD
2003—Claudette	5.8	39	HRD
2004—Ivan	8.0	60	HRD, wind analysis
Atlantic Coast			
1938—No Name 4	19.5	83	Ho et al. (1987)
1944—No Name	15.4	54	Ho et al. (1987)
1954—Carol	15.9	41	Ho et al. (1987)
1954—Hazel	18.5	46	Ho et al. (1987)
1955—Connie	5.0	41	Ho et al. (1987)
1959—Gracie	6.8	48	Ho et al. (1987)
1960—Donna	17.4	89	Ho et al. (1987)
1976—Belle	10.0	37	Ho et al. (1987)
1979—David	5.9	65	Recon data
1984—Diana	1.9	30	Recon data
1985—Gloria	19.8	100	Recon data
1989—Hugo	12.2	40	Powell et al. (1991), wind analysis
1996—Bertha	7.7	70	HRD, wind analysis
1996—Fran	7.9	85	HRD, wind analysis
1998—Bonnie	2.7	72	HRD, wind analysis
1999—Dennis	4.3	41	HRD
1999—Floyd	11.2	57	HRD
2003—Isabel	9.3	90	HRD, wind analysis
2004—Gaston	3.9	43	HRD (11 h prior to landfall)

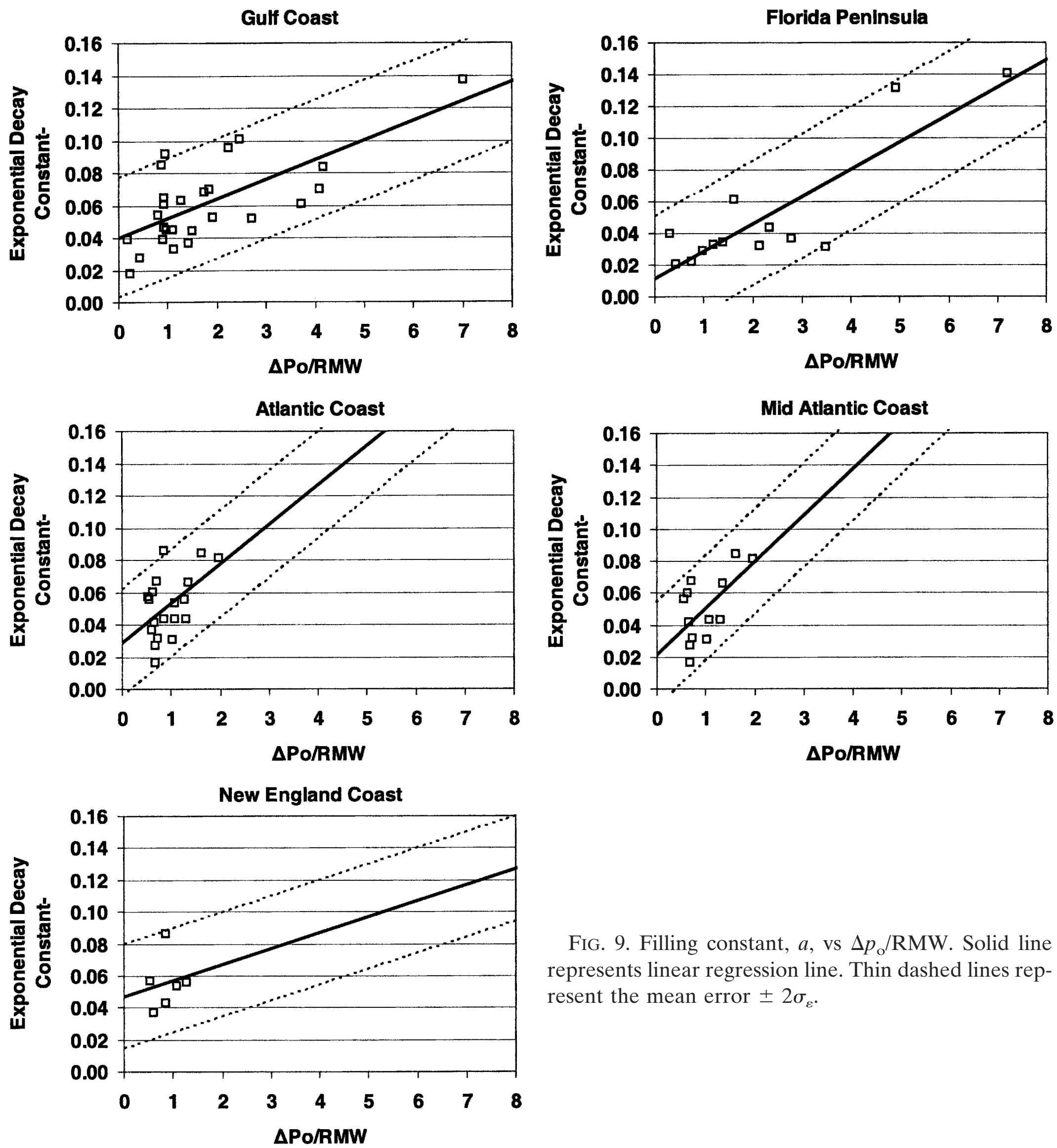

FIG. 9. Filling constant, a, vs Δp_o/RMW. Solid line represents linear regression line. Thin dashed lines represent the mean error $\pm$ $2\sigma_\varepsilon$.

gression equation parameters given in Table 5. Since the storms make landfall at random times between the 6-h HURDAT positions, in the error analysis, estimates of values of the central pressures at 3-hourly increments following landfall were computed through interpolation of the HURDAT 6-hourly data, or the pressure data from Ho et al. (1987). Computing the errors at the constant 3-h time increment following landfall ensures there are a sufficient number of samples at each time to produce estimates of the mean and standard deviation of the errors in order to examine trends in the error statistics as a function of time after landfall. The interpolation of the observed pressure data was performed with the central pressure in logarithmic space and time in linear space. Also shown in Figs. 11–15 are the errors computed at the actual times after landfall that the observations were taken. These data are presented to demonstrate that the error analyses produced using the interpolated data did not produce any appreciable bias in the results. The error ε is defined as the observed central pressure minus the modeled central pressure; thus a negative error indicates that the predicted model is overestimating the true decay of the storm (or underestimating the magnitude of the central pressure difference, i.e., modeling a weaker storm). The mean and standard deviations of the errors are tabulated as a function of time after landfall in Table 6. The errors in the estimate of the central pressures shown in Figs. 11–15 and presented in Table 6 include both the errors associated with the inability of the exponential decay

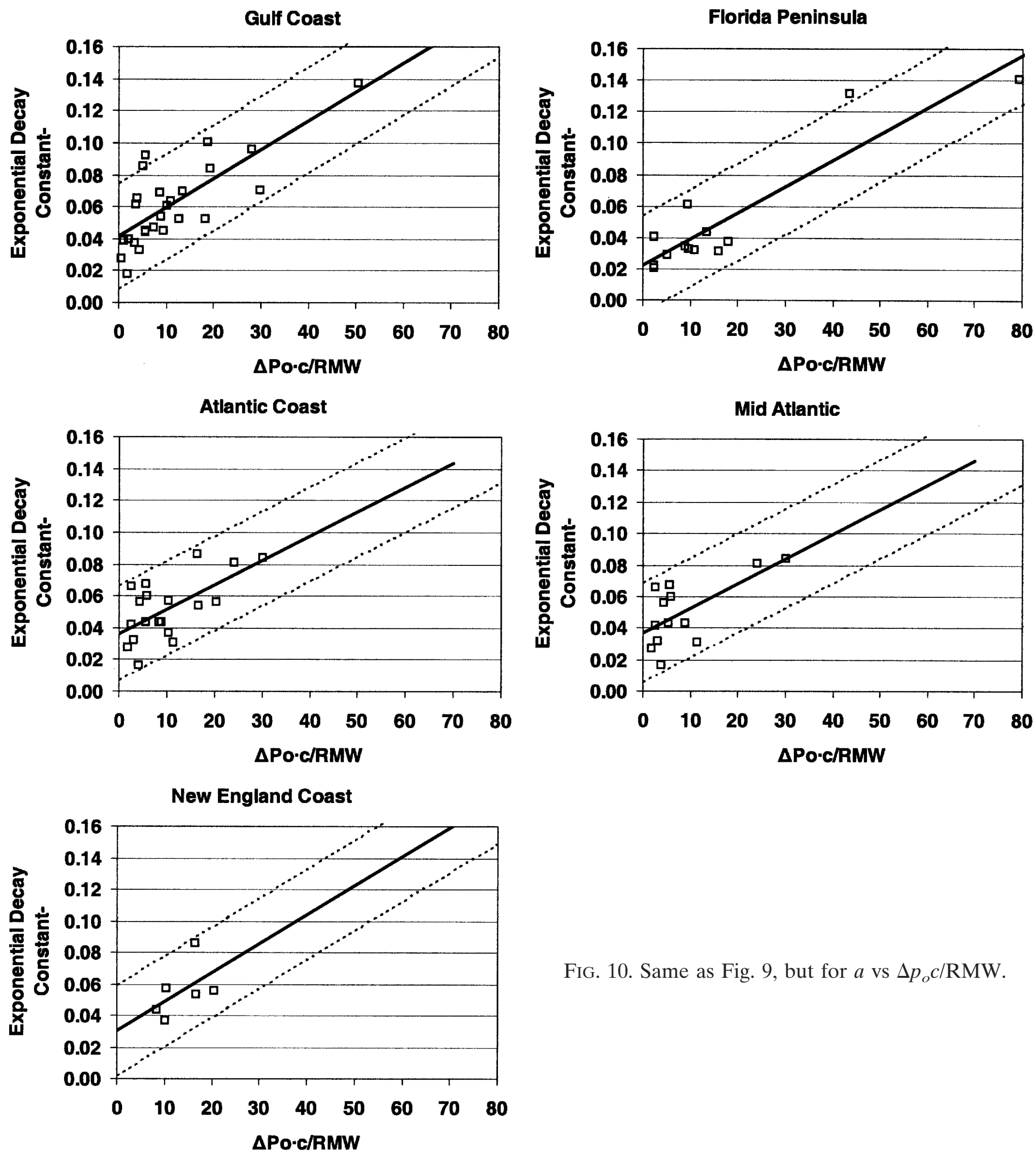

FIG. 10. Same as Fig. 9, but for a vs $\Delta p_o c$/RMW.

model to precisely model the decay of the storms (recall the errors given in Table 3) in addition to the error associated with the modeling of the decay exponent itself (i.e., regression model errors). Thus, a perfect model relating the decay constant to the storm characteristics could yield errors no lower than those given in Table 3.

In the case of the Gulf Coast storms it is seen in Fig.

TABLE 5. Decay constant a, regression parameters (RMW, km; translation speed c, m s^{-1}; and Δp_o, mb; a_0 is the intercept and a_1 is the slope). The largest value of r^2 for each region is in boldface.

		$a = a_0 + a_1 \Delta p_o$				$a = a_0 + a_1 \Delta p_o$/RMW				$a = a_0 + a_1 \Delta p_o c$/RMW			
Landfall region	N	a_1	a_0	r^2	σ_ε	a_1	a_0	r^2	σ_ε	a_1	a_0	r^2	σ_ε
Gulf Coast	26	0.00068	0.0244	0.2683	0.0225	0.0120	0.0400	0.4839	0.0189	0.00181	0.0414	**0.5884**	0.0169
Florida Peninsula	13	0.00116	−0.0213	0.3149	0.0325	0.0172	0.0115	0.7442	0.0120	0.00167	0.0225	**0.8378**	0.0158
Atlantic Coast	19	0.00080	0.0110	0.3660	0.0156	0.0245	0.0286	0.2499	0.0170	0.00153	0.0364	**0.3921**	0.0153
Mid-Atlantic Coast	13	0.00074	0.0128	0.3212	0.0174	0.0290	0.0213	0.3776	0.0166	0.00156	0.0370	**0.4206**	0.0161
New England Coast	6	0.00099	0.0034	**0.5471**	0.0114	0.0100	0.0470	0.0287	0.0167	0.00184	0.0304	0.2621	0.0146

TABLE 6. Errors in modeled and observed central pressures as a function of time after landfall (RMW, km; translation speed c, m s^{-1}; and Δp_o, mb; a is the decay constant, a_0 is the intercept, and a_1 is the slope describing the relationship between a and the independent variable). Values in parentheses are computed using the absolute value of the error.

Hours after landfall	N	Vickery and Twisdale (1995)		$a = a_0 + a_1\Delta p_o$		$a = a_0 + a_1\Delta p_o$/RMW		$a = a_0 + a_1\Delta p_o c$/RMW	
		Mean	Std dev	Mean	Std dev	Mean	Std dev	Mean	Std dev
Gulf Coast									
3	32	−1.90 (5.17)	6.33 (4.02)	−2.14 (5.22)	6.28 (4.00)	−1.63 (4.45)	5.32 (3.26)	−1.72 (4.19)	5.09 (3.29)
6	32	−2.10 (6.90)	8.46 (5.19)	−2.47 (7.02)	8.44 (5.17)	−1.57 (5.89)	6.95 (3.87)	−1.69 (5.25)	6.33 (3.81)
9	32	−1.27 (7.27)	9.00 (5.30)	−1.69 (7.38)	9.11 (5.44)	−0.51 (5.77)	7.02 (3.91)	−0.61 (5.01)	6.23 (3.65)
12	31	−1.44 (6.26)	7.68 (4.54)	−1.74 (6.56)	8.02 (4.80)	−0.04 (5.00)	6.08 (3.33)	−0.03 (4.39)	5.28 (2.82)
18	27	−2.36 (5.28)	6.15 (3.83)	−2.54 (5.47)	6.50 (4.23)	−0.40 (4.00)	4.90 (2.74)	−0.05 (3.47)	4.33 (2.50)
24	11	−4.70 (5.22)	4.38 (3.68)	−4.55 (5.20)	4.36 (3.46)	−2.99 (5.31)	5.09 (2.15)	−2.00 (5.14)	5.64 (2.67)
30	8	−4.79 (5.35)	4.36 (3.52)	−4.29 (5.00)	4.28 (3.28)	−4.24 (5.47)	4.24 (2.10)	−3.00 (4.55)	4.74 (3.01)
36	5	−5.91 (5.91)	3.53 (3.53)	−5.47 (5.46)	3.31 (3.31)	−5.86 (5.86)	2.27 (2.27)	−4.71 (4.82)	4.25 (4.09)
Florida									
3	12	1.78 (2.66)	5.67 (5.40)	−0.79 (3.99)	5.65 (3.82)	−0.34 (2.06)	2.68 (1.41)	−0.27 (1.37)	2.01 (1.43)
6	11	2.45 (3.52)	7.62 (7.14)	−2.47 (5.70)	7.24 (4.84)	−1.33 (3.04)	4.32 (3.22)	−1.00 (2.68)	3.65 (2.55)
9	8	3.35 (4.90)	10.74 (10.04)	−2.16 (7.21)	9.70 (6.33)	−2.88 (3.70)	4.82 (4.14)	−2.54 (2.68)	2.24 (2.05)
12	6	−0.93 (2.35)	2.64 (1.17)	−7.12 (7.13)	4.99 (4.96)	−4.94 (5.00)	5.41 (5.35)	−3.35 (3.35)	2.51 (2.51)
18	4	−1.35 (3.24)	3.39 (3.39)	−8.69 (8.69)	3.39 (3.39)	−2.81 (2.97)	3.39 (3.39)	−2.97 (2.97)	3.39 (3.39)
24	3	−1.83 (2.97)	4.65 (3.66)	−9.05 (9.05)	3.05 (3.05)	−5.15 (5.14)	5.38 (5.38)	−4.90 (4.90)	3.24 (3.24)
Atlantic									
3	20	0.33 (3.37)	4.25 (2.49)	0.11 (3.28)	4.01 (2.20)	0.36 (3.14)	4.10 (2.56)	0.11 (3.06)	4.06 (2.58)
6	18	0.21 (4.43)	5.25 (3.08)	0.05 (4.41)	5.30 (2.68)	0.44 (4.44)	5.96 (3.73)	0.22 (4.63)	5.72 (3.11)
9	17	0.58 (4.72)	6.06 (3.67)	0.39 (4.52)	5.47 (2.89)	0.82 (4.80)	6.62 (4.48)	0.44 (5.25)	6.40 (3.45)
12	14	0.62 (4.53)	6.02 (3.81)	0.74 (3.74)	4.97 (3.20)	1.17 (5.04)	6.64 (4.26)	1.41 (4.84)	5.87 (3.37)
18	9	1.17 (5.56)	7.09 (4.12)	−1.19 (5.23)	7.26 (4.84)	−1.82 (6.44)	8.04 (4.65)	−0.40 (6.38)	8.12 (4.51)
24	6	−2.36 (5.02)	7.20 (5.32)	−1.12 (4.13)	6.78 (5.20)	−1.23 (5.93)	7.77 (4.47)	0.41 (5.79)	7.67 (4.34)
30	2	−10.00 (10.00)	8.78 (8.78)	−7.63 (7.63)	9.93 (9.93)	−9.08 (9.09)	7.59 (7.60)	−8.07 (8.07)	7.82 (7.82)
Mid-Atlantic									
3	14	0.46 (4.28)	5.04 (2.43)	0.72 (4.12)	4.81 (2.32)	0.57 (3.90)	4.83 (2.71)	0.26 (3.93)	4.82 (2.58)
6	11	−0.48 (5.22)	6.13 (2.85)	0.17 (5.10)	5.92 (2.60)	−0.06 (4.78)	6.05 (3.42)	−0.20 (5.30)	6.36 (3.14)
9	11	−0.16 (5.14)	6.37 (3.40)	0.67 (5.09)	5.92 (2.66)	0.20 (4.96)	6.48 (3.87)	0.00 (5.62)	6.94 (3.67)
12	10	0.03 (5.18)	6.63 (3.75)	1.37 (4.88)	5.83 (3.10)	0.93 (5.23)	6.82 (4.14)	1.25 (5.27)	6.48 (3.58)
18	6	−0.85 (5.74)	7.95 (4.95)	1.28 (5.78)	7.47 (4.20)	1.59 (6.89)	8.91 (5.05)	1.64 (6.93)	8.48 (4.18)
24	6	−2.36 (5.02)	7.20 (5.32)	−0.18 (4.50)	6.82 (4.73)	0.11 (6.17)	8.06 (4.39)	0.13 (5.73)	7.64 (4.36)
30	2	−10.00 (10.00)	8.78 (8.78)	−7.03 (7.03)	9.57 (9.57)	−7.83 (7.84)	7.17 (7.18)	−8.29 (8.30)	7.88 (7.88)
New England									
3	6	0.01 (1.25)	1.54 (0.71)	−0.50 (1.33)	1.47 (0.58)	−0.21 (1.35)	1.62 (0.72)	−0.34 (0.92)	1.26 (0.83)
6	6	1.58 (2.84)	4.29 (3.42)	0.75 (2.53)	3.17 (1.74)	1.19 (3.33)	4.87 (3.48)	1.00 (3.24)	4.43 (2.88)
9	6	1.94 (3.96)	5.75 (4.33)	0.94 (3.41)	4.45 (2.63)	1.45 (4.57)	6.47 (4.40)	1.23 (4.44)	5.95 (3.68)
12	4	2.10 (2.93)	4.62 (3.97)	0.78 (2.18)	2.64 (1.20)	1.79 (3.99)	5.82 (4.10)	1.70 (3.49)	4.70 (3.12)

11 that both the mean error and the standard deviation of the error continually decrease as the model changes from the Vickery and Twisdale (1995) model, to the Δp_o model, to the Δp_o/RMW and finally to the $\Delta p_o c$/RMW model. In the Gulf Coast case, it is clear that the decay of the tropical cyclones is best modeled using the model in the form of Eq. (4).

In the case of the Florida Peninsula storms (Fig. 12), the Vickery and Twisdale (1995) model models the bulk of the data well but significantly underestimates the decay rate of Hurricane Charley. Hurricane Andrew does not appear in Fig. 12 as it reentered the Gulf of Mexico after being over land for less than 3 h. The Δp_o model performs poorly, significantly underestimating the decay of Hurricane Charley, but overestimating the decay by about 10 mb of the bulk of the data after the storms have been over land for about 12 h. The $\Delta p_o c$/RMW model yields the lowest mean error, although a small 2–4-mb bias toward overestimating the decay is evident after about 12 h. As in the case of the Gulf Coast storms, it is clear that the decay of the tropical cyclones is best modeled using an equation in the form of Eq. (4).

In the case of the Atlantic and Mid-Atlantic storms

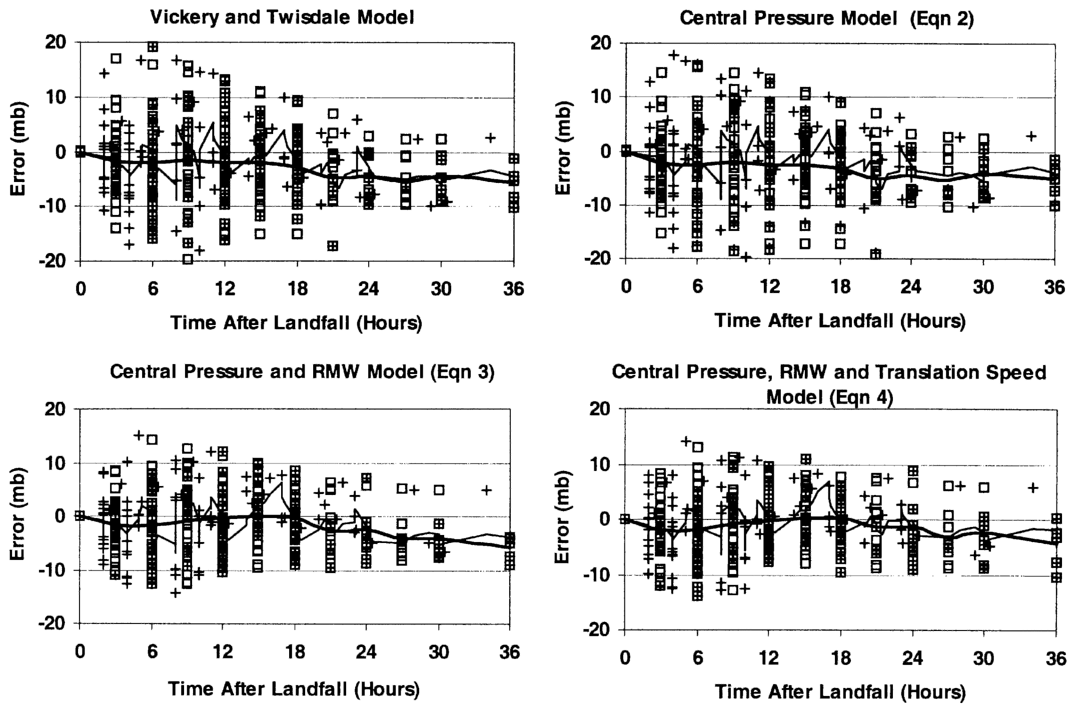

FIG. 11. Error in the estimated central pressure vs time after landfall for Gulf Coast storms. Squares represent errors computed at 3-h positions. Thick solid line represents the mean 3-h error. Plus marks (+) indicates error at original time. Thin solid line represents the 5-point moving average of original time errors.

(Figs. 13 and 14), the selection of the best model is not as clear as in the case of the Gulf Coast and Florida Peninsula storms. All the models produce similar mean errors as a function of time since landfall, and all have a mean error near zero, except for near 30 h after landfall where all models overestimate the filling of the one storm, Hurricane David in 1979. Note that the filling of Hurricane David, an unusually slow filling storm, is the outlier that appears below the zero error line in each figure.

In the New England case, although there are only six storms used to develop the model, the errors plotted in Fig. 15 suggest that the model in the form of Eq. (2) (i.e., filling constant modeled as a function of Δp_o alone) best describes the relationship between the filling constant and the tropical cyclone characteristics. It is also noteworthy that a statistically significant difference between the filling rate constant slopes and intercepts for the New England filling rate model (filling computed as a function of Δp_o alone) and neither the Gulf of Mexico nor Mid-Atlantic filling constants were observed, suggesting that the pressure filling of the New England storms is not statistically different, in direct contrast to the observations of Kaplan and DeMaria (2001). It is possible that this conflicting conclusion is brought about by the fact that Kaplan and DeMaria model the weakening of the tropical cyclones by examining the reduction in the wind speeds directly. The wind speeds in the cyclones are dependent on more than the central pressure difference alone, also being a function of a combination of the RMW and a pressure profile parameter (e.g., Holland 1980), both of which vary as a storm weakens, and the translation speed of the storm, and thus it is not surprising that differences in the characteristics of storm filling are seen when comparing filling defined by wind speed or filling defined by central pressure.

Furthermore, in the case of the New England storms, in most instances the tropical cyclones are weakening before they make landfall as they have traveled over colder waters north of North Carolina. It is also likely that in most of the six cases used to model the filling of the New England storms, these storms have become extratropical (Hart and Evans 2001) or are in the extratropical transition phase. For transitioning or extratropical storms the overall relationship between central pressure and wind speed in these storms is different than for most of the purely tropical storm cases, owing primarily to the fact that these are transitioning storms and as a result generally have lower pressure gradients,

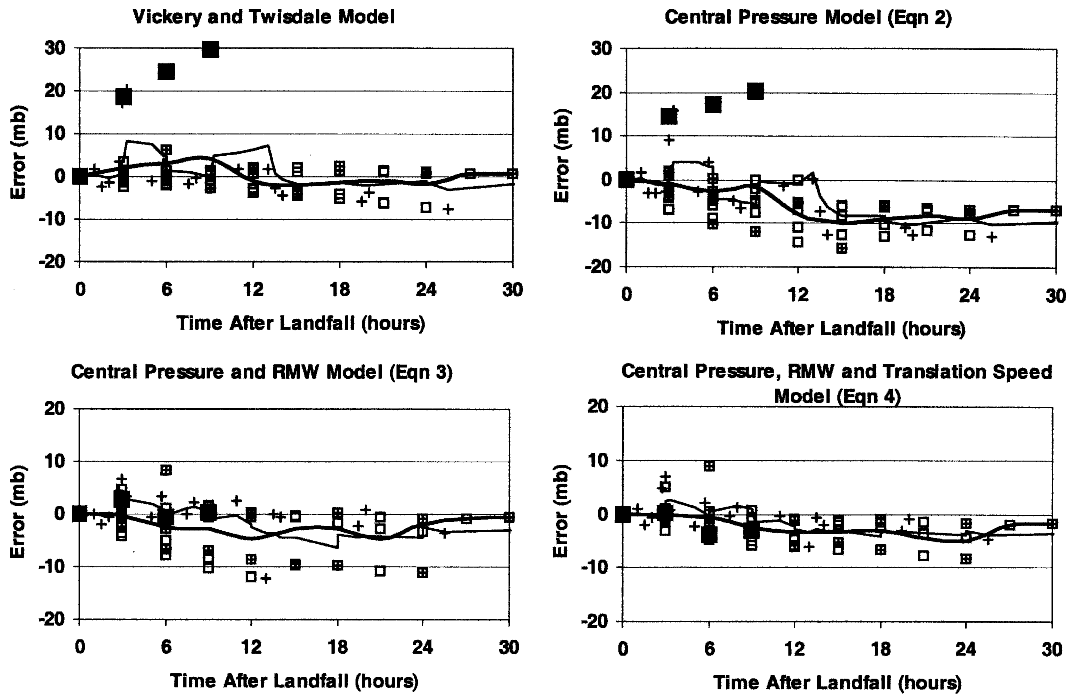

FIG. 12. Same as in Fig. 11, but for Florida Peninsula storms. Filled squares represent Hurricane Charley.

for the same central pressure difference, and the maximum wind is more strongly affected by the faster translation speeds associated with the more northerly storms. These differences in storm characteristics tends to support the assumption that the conflicting conclusions regarding the filling of New England storms versus other storms obtained from this and previous pressure-filling studies is a result of one set of models at-

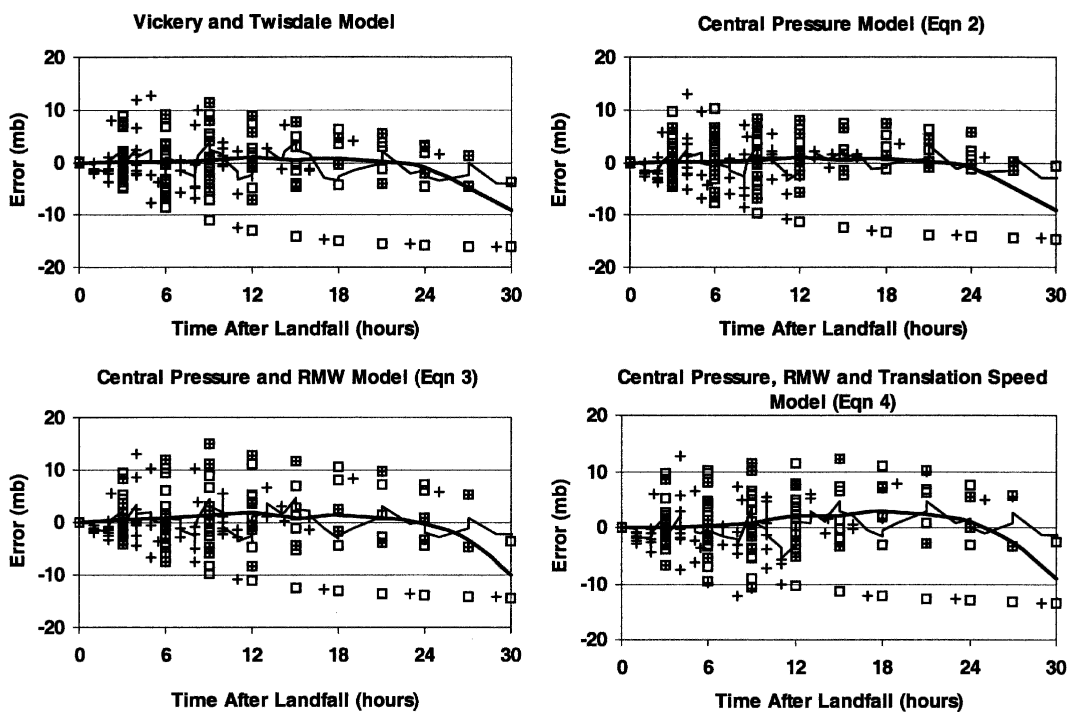

FIG. 13. Same as in Fig. 11, but for Atlantic Coast storms.

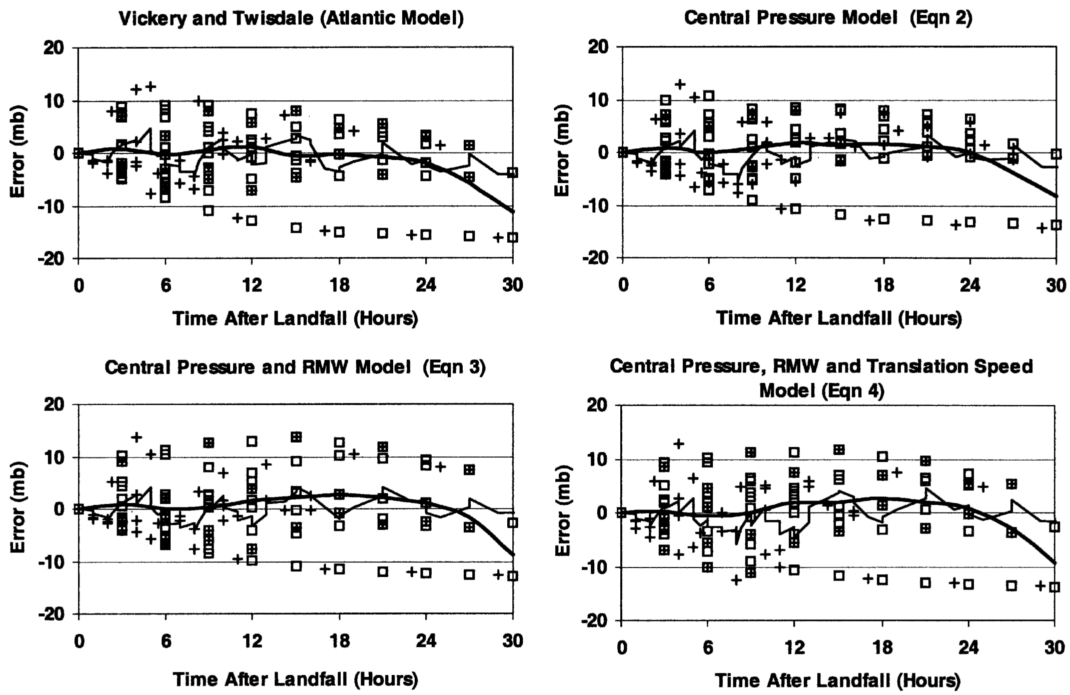

FIG. 14. Same as in Fig. 11, but for Mid-Atlantic storms.

tempting to explain the reduction in wind speed and the other modeling the increase in central pressure. For these reasons alone, even though a statistically significant difference between the New England filling and the Gulf and Atlantic filling does not appear, it is felt that the New England storms should be separated from the other cases with the filling modeled as a function of Δp_o alone.

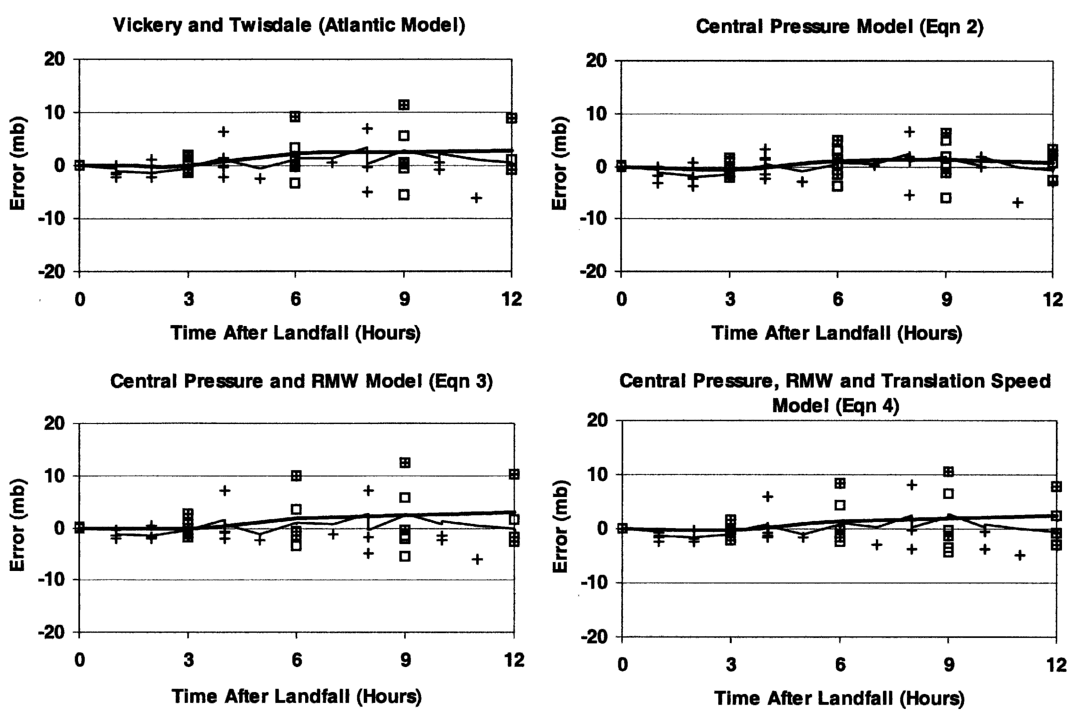

FIG. 15. Same as in Fig. 11, but for New England storms.

4. Selection of models for hurricane hazard analysis

Within in a hurricane simulation model, when a modeled hurricane makes landfall the filling of the storm is modeled through the selection of a filling coefficient using one of the linear models discussed above. The filling coefficient used in the simulation uses the mean value associated with the characteristics of the storm at the time of landfall plus an error term sampled from a normally distributed error with a mean of zero and a standard deviation equal to the error σ_ε from Table 5. With the requirement to sample an error term taken into account, it is advantageous to select a model where the range of the mean $\pm 2\sigma_\varepsilon$ is not, or is unlikely to be, negative. With this in mind, the models chosen for implementation in a hurricane hazard model are as follows:

$$\text{Gulf Coast: } a = 0.0413 + 0.0018 \times (\Delta p_o c/\text{RMW});\ \sigma_\varepsilon = 0.0169,$$

$$\text{Florida Peninsula Coast: } a = 0.0225 + 0.0017 \times (\Delta p_o c/\text{RMW});\ \sigma_\varepsilon = 0.0158,$$

$$\text{Mid-Atlantic Coast: } a = 0.0364 + 0.0016 \times (\Delta p_o c/\text{RMW});\ \sigma_\varepsilon = 0.0161, \quad \text{and}$$

$$\text{New England Coast: } a = 0.0034 + 0.0010\Delta p_o;\ \sigma_\varepsilon = 0.0114.$$

When implemented, the minimum allowable value of a sampled filling coefficient is set at 0.015, with the sampled error constrained to lie within $\pm 3\sigma_\varepsilon$.

5. Summary and conclusions

New simple empirical filling models to model the decay of tropical cyclones after landfall have been developed to update the models given in Vickery and Twisdale (1995). The empirical filling models are modeled in the form of an exponential decay model to represent the reduction in the central pressure difference as a function of time since landfall. The magnitude of the filling constant used in the exponential decay function is modeled as a function of key readily defined characteristics of a tropical cyclone at the time of landfall. For storms making landfall along the Gulf Coast of the United States and the Florida Peninsula, the reduction in the central pressure difference following landfall is well modeled with the decay constant modeled as a function of $\Delta p_o c$/RMW. Along the Mid-Atlantic Coast, the reduction in the central pressure difference following landfall is adequately modeled with the decay constant modeled either as a function of $\Delta p_o c$/RMW or as a function of Δp_o alone. Along the New England Coast, the reduction in the central pressure difference following landfall is adequately modeled with the decay constant modeled as a function of Δp_o. The new models significantly improve the r^2 values of the filling models relative to those described in Vickery and Twisdale (1995), particularly for storms making landfall along the Gulf Coast.

Acknowledgments. The work that provided the basis for this publication was supported by funding under a contract with the Federal Emergency Management Agency. The substance and findings of that work are dedicated to the public. The author is solely responsible for the accuracy of the statements and interpretations contained in this publication.

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