Accuracy of United States Tropical Cyclone Landfall Forecasts in the Atlantic Basin (1976–2000)

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ABSTRACT

About 13% of all Atlantic basin tropical cyclone forecasts issued from 1976 to 2000 are for landfalls along the United States coastline, and 2% more are for storms forecast to make landfall in the United States but that remain at sea. Landfall position and time forecasts are skillful at all forecast time periods and are more skillful than Atlantic basin track forecasts as a whole, but within 30 h of predicted landfall, timing errors demonstrate an early bias of 1.5–2.5 h. Landfall forecasts are most accurate for storms moving at oblique or normal angles to the coastline and slow-moving storms. During the last quarter century, after adjustment for forecast difficulty, no statistically significant improvement or degradation is noted for landfall position forecasts. Time of landfall forecasts indicate no degradation at any period and significant improvement for the 19–30-h period. The early bias and lack of improvement are consistent with a conservative or "least regret" forecast and warning strategy to account for possible storm accelerations. Landfall timing uncertainty is ~11 h at 24 and 36 h, which suggests that hurricane warnings could be disseminated about 12 h earlier (at 36 h, rather than 24 h, before predicted landfall) without substantial loss of lead time accuracy (although warning areas necessarily would be larger). Reconsideration of National Weather Service Strategic Plan and United States Weather Research Program track forecast goals is recommended in light of these results.

1. Introduction

To improve the ability to forecast natural disasters, research goals and objectives must be focused. Future tropical cyclone track forecast research (Elsberry and Marks 1999) and operational (NWS 1999) goals are based on the continuation of improvements in track forecasts during the past three decades (McAdie and Lawrence 2000; Aberson 2001). This paper concerns the ability to forecast the location and time of landfall in the less than 15% of Atlantic basin forecasts that compose landfall threats to the United States.

Regarding tropical cyclones, emergency managers and the public are primarily concerned with the location and timing of landfall. The Internet now allows them access to official (OFCL) and numerical model forecasts from which they can estimate multiple projected landfall times and positions. Though an accurate landfall location forecast is of primary importance, a case in which landfall occurs earlier than expected inhibits the ability of the public to complete storm preparations and evacuations, whereas a case in which landfall occurs later than forecast may prematurely end preparations or interfere with local economies, especially those dependent on tourism. Further, increased accuracy should allow for longer warning lead times and smaller warning areas than currently allowed, but current and projected increases in coastal population will require more time for evacuation and could therefore negate the forecast improvements. Another topic of interest to emergency managers and decision makers is the amount of time before landfall that graphical damage assessment products (Powell and Houston 1996; Powell et al. 1998; Powell 2000) and storm surge inundation forecasts (Jelesnianski et al. 1992) will have small enough errors to be useful. Such products must depict the uncertainty in the projected conditions based on a realistic assessment of the landfall position and time errors.

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McAdie and Lawrence (2000) found that average annual OFCL forecast position errors between 1970 and 1998 improved 1.0%, 1.7%, and 1.9% annually at 24, 48, and 72 h, respectively. Aberson (2001) found improvements in the ensemble of numerical guidance upon which the OFCL forecasts are based from 1976 to 1998. Although these trends are promising, neither forecast landfall position nor time error trends have been quantified. Neumann and Pelissier (1981, hereafter NP) evaluated landfall forecast position errors for the single forecast issued closest to the critical time for disseminating warnings (~24 h before landfall) for all hurricanes and tropical storms that struck the United States during 1970–79. Landfall positions were determined from the "best track," a track determined by the National Hurricane Center (NHC) after postanalysis of all available data (Jarvinen et al. 1984), and position errors were measured as distance along the coastline between the forecast and the best track landfall positions. Neither timing errors nor forecasts issued < 24 h before landfall or > 36 h before landfall were evaluated. For the 18 storms for which a ~24 h forecast was available, the mean and median errors were 72 and 58 km, respectively. Neumann and Pelissier (1981) found that the error was sensitive to the orientation of the track relative to the coastline and noted that most tracks along the Gulf of Mexico coast tended to be perpendicular to the coastline (with relatively smaller errors) and that tracks along the Atlantic coast tended to be parallel to the coastline resulting in relatively large errors.

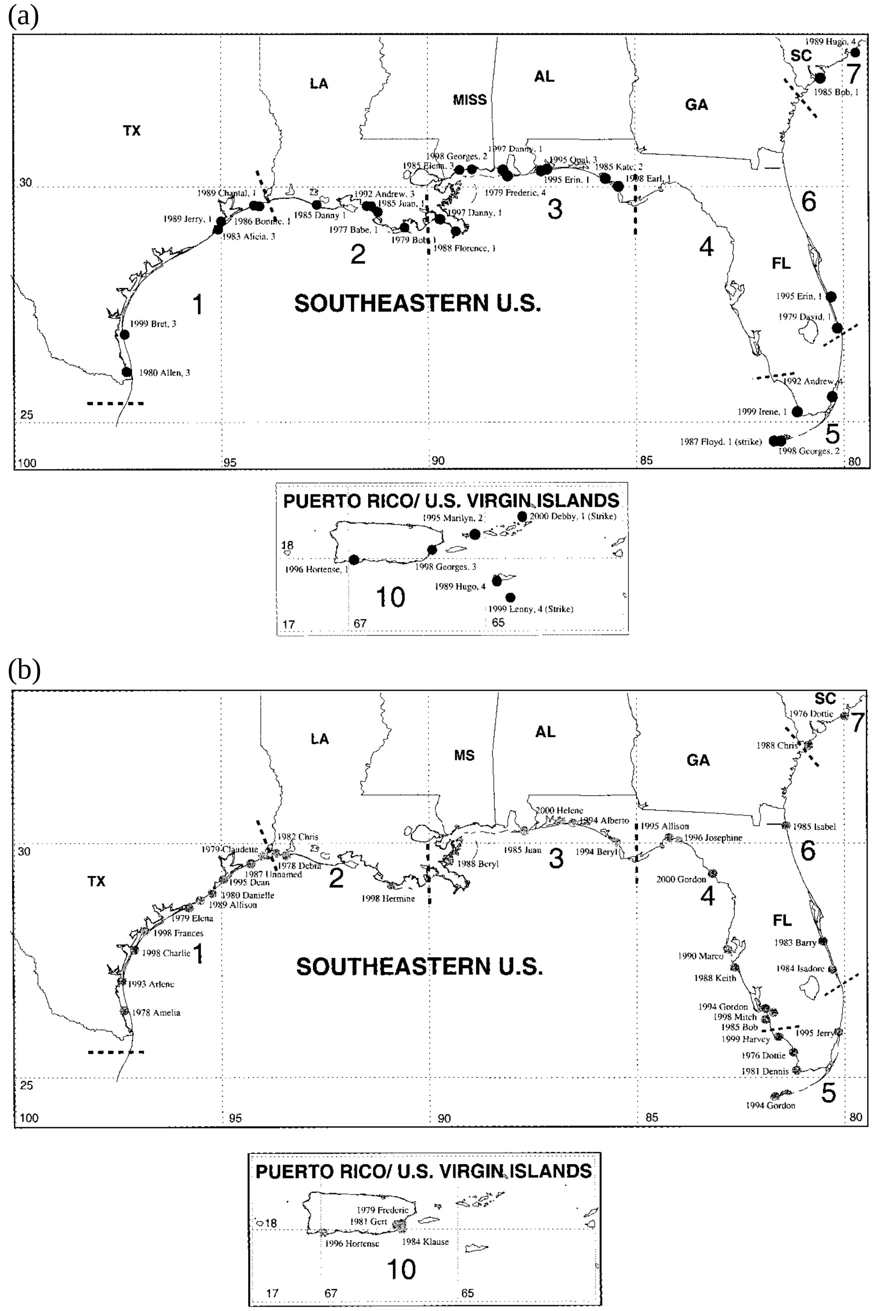

FIG. 1. Locations, year, storm name, and Saffir–Simpson category of Atlantic basin landfalling hurricanes affecting the United States from 1976 to 2000. (a) Hurricanes in the southeastern United States, (b) tropical storms in the southeastern United States.

This paper extends NP by conveying landfall forecast location and timing uncertainty as a function of forecast lead time before landfall for all Atlantic basin tropical storms and hurricanes to strike the United States during the 25-yr period between 1976 and 2000 (Fig. 1, Table A1).

This paper examines the following topics: 1) the definition of landfall error, 2) the position and timing errors and skill at various times before predicted landfall for the set of landfall forecasts that verify, 3) the

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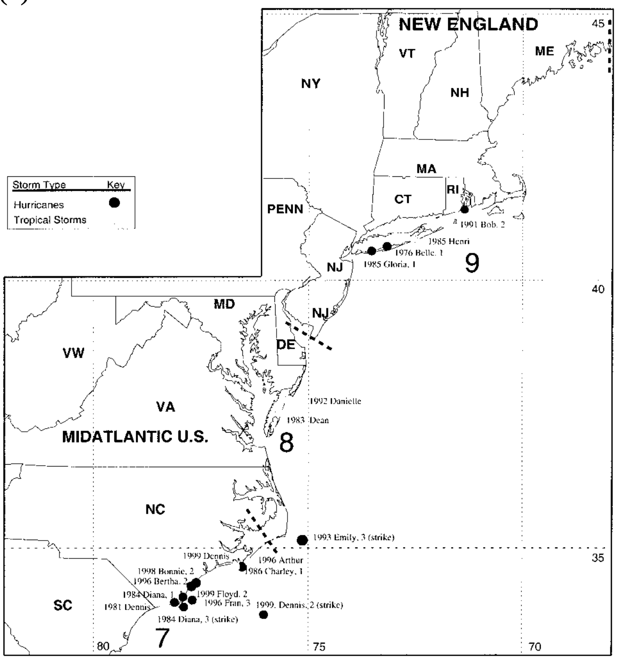

FIG. 1 *Continued.* (c) Hurricanes and tropical storms in the mid-Atlantic and New England states. See text for discussion on multiple landfalls. Bold dashed lines and large numerals denote coastal segments in Table 5.

frequency with which tropical cyclones are forecast to make landfall but fail to do so and the accuracy of these forecasts, 4) the secular trend of landfall position and time forecast accuracy, and 5) the error distribution relative to the coastline orientation, storm intensity, storm motion, and by geographic region.

2. Methods

Tropical cyclone track forecast error (FE, in km) is defined (NP) as the great circle distance between the observed (O) and forecast (F) storm location according to

$$FE = 111.11 \cos^{-1}[\sin Y_O \sin Y_F + \cos Y_O \cos Y_F \cos (X_O - X_F)], \qquad (1)$$

where the longitudes and latitudes are given by X and Y, respectively. Skill is assessed by comparing a forecast to that provided by the operational climatology and persistence (CLIPER) model forecast (Neumann 1972; Merrill 1980).

NHC issues OFCL 12-, 24-, 36-, 48-, and 72-h forecasts for all tropical cyclones in the Atlantic basin four times daily; before 1988, no 36-h OFCL forecasts were issued. CLIPER forecasts are available at the same initial and forecast times. These OFCL forecasts include a large number of cases in which the storm is forecast to remain well offshore; in only 13% of the cases is landfall predicted. The most relevant cases for warning purposes are the forecasts for which landfall was predicted, whether the landfall occurred or not. Since 1976, no landfall occurred that was not forecast.

a. Definitions of landfall error

Landfall forecast errors depend on the framework for verification. Landfall is defined as the time and location at which the storm center crosses the coastline based on NHC records, though destructive effects may occur several hours before and after the landfall time and extend several hundred kilometers from the landfall point. Observed landfall positions should be accurate to within reconnaissance requirement specifications of ±11 km (OFCM 1999). Accuracy of observed landfall times is estimated to be ±0.5 h. Using landfall of Hurricane Erin on the central Gulf of Mexico coast in 1995 as an example, four types of landfall error can be defined (Fig. 2).

1) Time and position errors between forecast and observed landfall

Time and position errors can be computed based on the forecast and observed landfall times and positions. The OFCL forecast made landfall on the Louisiana coast at 2000 UTC 3 August, 4 h after observed landfall and 231 km from the observed landfall position (Fig. 2). Definition 1 was used by NP and should be of interest to emergency managers who wish to see forecast landfall position and timing error statistics relative to the timetable of evacuation and other preparedness activities. However, this definition does not allow for the consideration of cases in which landfall was forecast but did not occur (e.g., Hurricane Felix in 1995).

2) Position error at time of landfall

A position error can be defined as the distance between the forecast and observed location at the time of landfall. At the observed time of landfall (1600 UTC 3 Aug 1995), the interpolated position of the OFCL forecast issued 0000 UTC 1 August was 160 km to the southwest of the landfall point. Definition 2 is similar to the traditional error estimates made at the specific forecast periods of 12, 24, 36, 48, and 72 h,

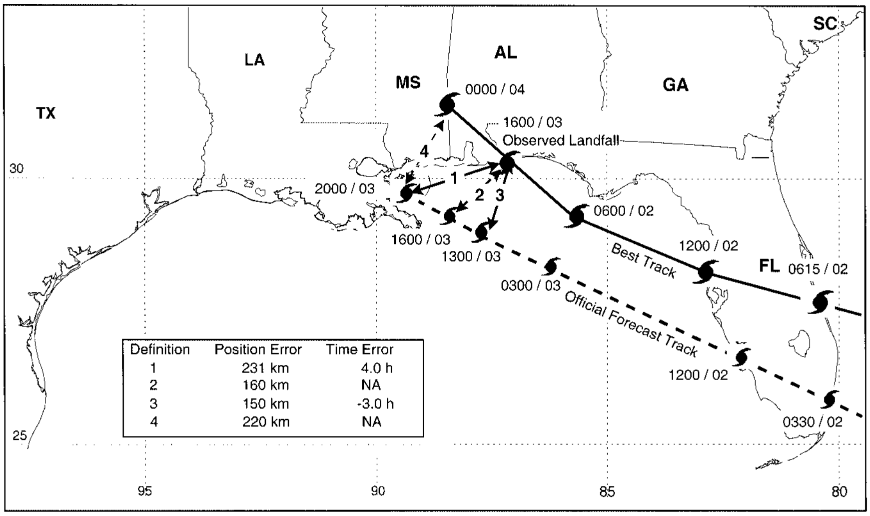

FIG. 2. Landfall forecast error definitions for Hurricane Erin's landfall near Pensacola, FL. Official forecast was issued 0000 UTC 1 Aug 1995 (64 h before actual landfall and 68 h before forecast landfall). Numbers beside track positions indicate time UTC/date.

but is applied through interpolation of the forecast track and does not allow for the calculation of timing error.

3) TIME AND POSITION OF CLOSEST APPROACH TO THE LANDFALL POINT

The time and position of the closest approach of the interpolated forecast track to the observed landfall point can define another error measure. In Fig. 2, the 1300 UTC interpolated position of the OFCL forecast was the closest to the observed landfall point, 150 km away. Definition 3 allows for the inclusion of forecasts that never make landfall. However, there is no a priori knowledge of the closest approach point.

4) POSITION ERROR AT TIME OF FORECAST LANDFALL

The position error between the observed and forecast locations of the storm at the interpolated forecast landfall time can also be computed. For Erin (Fig. 2), at the time the OFCL forecast predicted landfall on the Louisiana coast (2000 UTC 3 Aug 1995), the actual storm position was already well inland, 220 km away. Definition 4 may be of interest to forecasters who wish to assess the position errors of landfall forecasts. This definition ignores timing errors (except as an alongtrack error component) and also does not allow for consideration of potential cases in which landfall occurred but was not forecast. However, this definition does include cases where landfall was forecast but did not occur.

b. Procedure

OFCL Atlantic basin forecasts for 1976–2000 were examined for all hurricane and tropical storm predictions crossing the coastline of the mainland United States, Puerto Rico, and the United States Virgin Islands (USVI). Tropical depression landfalls were not considered. Definition 1 was chosen since observed landfall positions and times are ingrained in the minds of the affected public and are found readily in NHC poststorm reports. The error is defined as the time and position difference between the forecast (F) and observed (O) landfall using Eq. (1) for position and

$$\mathrm{TE} = T_{\mathrm{F}} - T_{\mathrm{O}} \tag{2}$$

for timing error, where T is the landfall time.

OFCL and CLIPER forecast tracks are interpolated to 0.5-h resolution with cubic b splines. The interpolated positions are considered to be as accurate at those of the landfall locations (11 km, 0.5 h). Landfall is considered to be forecast if the interpolated OFCL center position crossed or came within 75 km of the coastline. This method yielded several candidate landfalls for some forecasts. Candidates compose landfall forecasts just outside of the United States borders, positions where a storm that had previously made landfall recrossed the coastline to go out to sea, or positions within 75 km of the coast for a time before crossing the coast. For example, a forecast track parallel to the coast might contain several positions qualifying as landfall; the closest position to the coast is selected. If several positions are at nearly the same distance from the coast, the earliest is selected.

Some storms did not make landfall but passed close enough (one maximum wind radius to the left or two to the right of the storm center) to land to satisfy the NHC definition of a "strike." Hurricane Floyd 1987 in the Florida Keys, the first approach to the Carolina coastline of Hurricane Diana 1984 and of Hurricane Dennis 1999, Hurricane Emily 1993 in North Carolina, and Hurricane Lenny 1999 in the USVI are considered strikes. These cases are included in the landfall database by defining the strike point as the storm center position at the time of closest approach to land by interpolation of the best track (they are indicated as strikes in Table A1).

Landfalls are considered to be independent if they are separated by more than 24 h. When multiple landfalls occurred within a 24-h period, the most significant landfall is chosen subjectively. For example, the Hurricane David 1979 landfall at Palm Beach, Florida, is used instead of that at Savannah, Georgia; the Hurricane Gloria 1985 landfall at Long Island, New York, is chosen over that at the Outer Banks, North Carolina; the Hurricane Hugo 1989 landfall at St. Croix, U.S. Virgin Islands, is selected over the one at Fajardo, Puerto Rico; the Hurricane Bob 1991 landfall in Newport, Rhode Island, is picked over the earlier strike at Cape Hatteras, North Carolina, and the previous and subsequent landfalls at Block Island, Rhode Island, and Rockland, Maine, respectively; and the Hurricane Marilyn 1995 landfall at St. Thomas, U.S. Virgin Islands, is chosen over that at St. Croix. Forecasts associated with a storm that makes landfall following an approach close enough to qualify as a strike (Diana 1984 and Dennis 1999) are evaluated for initial forecast times after each strike.

For island landfall forecast verification in Puerto Rico and the USVI, the absence of a long, continuous coastline requires a different criterion for choosing forecast landfall positions. The location of the closest approach of the forecast track to the island nearest the actual landfall is chosen (definition 3).

1) Special cases

In their investigation, NP recognized three special cases: 1) "surprise" storms that made landfall though predicted to remain offshore, 2) short-lived storms that made landfall within 24 h of development, and 3) "near-miss" storms that remained offshore despite being predicted to make landfall. For the 1976–2000 period, no surprise storms and several short-lived storms (Table A1) were found. Short-lived storms are included in this study.

Near-miss storms are of special concern to emergency managers since landfall forecasts might require initiation of costly evacuation and other storm preparation activities. As discussed by NP, since these storms do not make landfall, the time and position errors are indeterminate. Emergency managers should know the probability that a forecast of landfall will verify, and the error characteristics of those that do not. Forecast errors of near-miss storms are evaluated separately using definition 4.

2) Forecast lead time

The initial position of OFCL forecasts is the storm position 3 h before the forecast issuance time. Hence, a 0900 UTC forecast contains forecast positions 12, 24, 36, 48, and 72 h from the 0600 UTC position. Occasionally, "special" advisories are issued after the normal issuance times to correct wind radii, intensity, or position estimates. All OFCL forecasts are assumed to have been issued at their regular times. Forecast lead time is defined as the period from the advisory *issuance* to the time the forecast track makes landfall. Forecast advisories issued at or shortly after landfall may contain prelandfall initial positions; only forecasts issued before landfall are included in this study.

3) Forecast skill

Skill is assessed by comparison of OFCL forecasts with those from CLIPER (Neumann 1972; Merrill 1980). Relative error is

$$RE = 100(OE - CE)/CE, \quad (3)$$

where OE represents the OFCL forecast landfall error and CE is the operational CLIPER landfall forecast error for forecasts issued at the same initial time. Unfortunately, about 8% of CLIPER forecasts initialized at the same time as the OFCL forecasts of landfall did not come close enough to land to satisfy the landfall or strike criteria. To obtain a homogeneous dataset, the CLIPER location and time of closest approach to land for these cases is used (definition 3), provided the forecast is within 500 km of land.

3. Results

Table 1 shows the total and annual averages of Atlantic basin tropical storms and hurricanes making landfall in the United States and of OFCL forecasts issued for these cases from 1976 to 2000. The landfall forecasts include 31 that were issued for Barry (1983), Anita (1977), Gilbert (1988), and Beryl (2000), all of which approached the southern Texas coast before making landfall in northern Mexico. Near-miss storms compose 104 forecasts with 9 of these not verifiable according to definition 4 due to dissipation before landfall. The majority (55%) of landfall forecasts are for Gulf of Mexico storms; 32% are for East Coast storms; and 12% are for those threatening Puerto Rico and the USVI.

a. Landfall forecast position and time errors

The number of landfall forecasts issued for each 6-h period within 48 h of predicted landfall is 50–75. Beyond 48 h prior to forecast landfall, only ~30 forecasts are available for each 6-h period. To allow for sample sizes for statistical analysis, position and time errors are collected into bins surrounding 3 (0–6 h), 12 (7–18 h), 24 (19–30 h), 36 (31–42 h), 48 (42–54 h), and 63 (55–72 h) h before predicted landfall. Table 2 shows the mean position and timing errors for each of these periods.

Position (Fig. 3a) and time (Fig. 3b) errors decrease as the predicted time of landfall approaches. Though large errors are expected at long forecast lead times, those at short forecast lead times are troublesome, especially in the critical 24–36-h period when watches and warnings are being formulated (Sheets 1990). Examination of position forecast outliers indicates that the most problematic forecasts were for Hurricanes Belle 1976 and Floyd 1999 along the East Coast, and Hurricanes Elena 1985 and Earl 1998 in

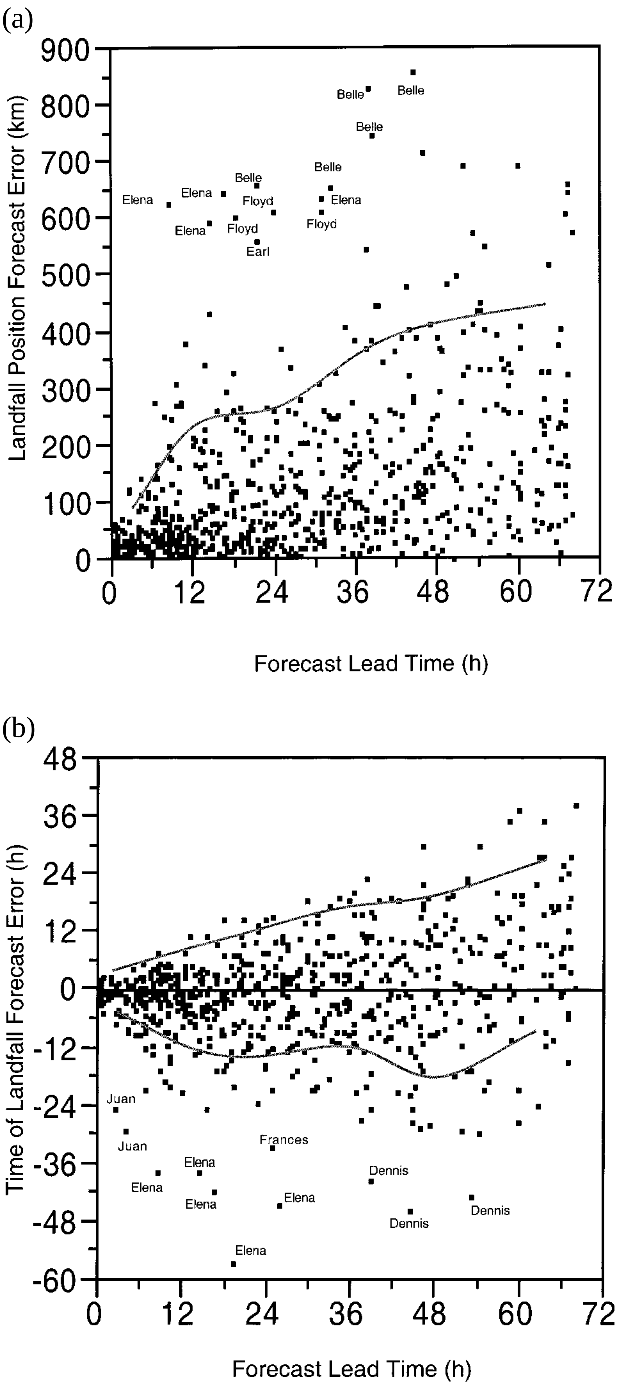

FIG. 3. (a) Landfall distance error (km) and (b) landfall time error, as a function of forecast lead time (h). Solid lines represent 90% (position and time) and 10% (time) quantiles. Storm names of outliers are noted. Dennis refers to the 1999 landfall of the tropical storm rather than the previous strike.

TABLE 1. Numbers of Atlantic basin tropical cyclones, U.S. landfalls, near-miss storms, and forecasts for 1976–2000. A near miss is a forecast of landfall that does not verify.

	Total	Average per year
Storms		
Tropical cyclones in basin	245	10
Tropical cyclones making landfall in the United States	79	3
Hurricane landfalls*	47	2
Tropical storm landfalls*	45	2
Near-miss storms	23	1
Forecasts		
Forecasts issued	5473	219
Nonlandfall forecasts issued	4674	187
Landfall forecasts issued	799	32
Verifying landfall forecasts*,**	695	28
Verifying hurricane landfall forecasts*,**	432	17
Verifying tropical storm landfall forecasts*,**	263	11
Near-miss forecasts	104	4

*See text (section 2b) for details on multiple landfalls and strikes. See appendix for details on individual U.S. landfalls.
**Includes forecasts of landfalls for the U.S. coast that verified along the Mexican coast.

TABLE 2. U.S. OFCL forecast landfall position and time errors and near-miss forecast errors for 1976–2000. ABS signifies the mean of the absolute value of the time errors.

Forecast lead time range (h)	No. of forecasts	Position mean error (km)	Position error std dev (km)	Time mean error (h)	Time error std dev (h)	Time error ABS (h)	Near-miss mean position error (km)	No. of forecasts
0–6	87	38	33	–1.4	4.8	2.6	20	1
7–18	179	98	109	–2.6	8.0	5.5	199	14
19–30	129	122	122	–1.6	10.9	7.8	227	21
31–42	119	164	156	–0.1	11.1	8.8	295	22
43–54	93	199	167	–0.5	14.7	11.5	385	16
55–72	88	221	162	6.8	14.5	12.6	739	21

the Gulf of Mexico. The most accurate 90% of forecasts (Fig. 3a) with lead times of 3, 12, 24, 36, and 48 h have errors of less than 75, 170, 250, 350, and 450 km, respectively.

For forecast lead times within 48 h, a number of outliers have time of landfall errors larger than the forecast lead time. Storms with large early biases include erratically moving storms in the Gulf of Mexico [Hurricanes Juan (1985) and Elena (1985), and Tropical Storm Frances (1998)] and in the Atlantic [Hurricane Dennis (1999)].

Perhaps the most significant result is the early time of landfall forecast bias at the short forecast lead times. Mean absolute landfall time errors are < 8 h within 30 h of landfall with a 1.5–2.5-h early bias (Table 2), which suggests a tendency toward conservative or "least regret" (Sheets 1984) forecasts that allow the public slightly more preparation time than forecast. For the 0–6-, 7–18-, and 55–72-h periods the bias estimates were significantly different from zero (< 5% chance of a zero bias using the *t* test). At 19–30 h, there is a 9% probability of a zero bias. At the remaining forecast lead times, the bias estimates are not significantly different from zero.

Mean position errors in the 19–30- and 31–42-h periods are 120–170 km, and the standard deviations are nearly as large. This and the 11-h standard deviations in the times of landfall forecasts in the 19–30- and 31–42-h periods encompassing the critical warning and watch periods underscore the difficulty in completing the evacuation of coastal areas requiring more than 24 h to evacuate. At very short times before landfall, landfall position and time errors are small. Landfall position errors of less than a typical radius of maximum wind (i.e., < 50 km) are small enough that it may be possible to introduce real-time damage assessment products projected along a forecast track with uncertainty bands in the cross-track direction.

b. *Near misses*

Near misses (Table 3) occurred when the storm forecast to make landfall remained at sea or dissipated before reaching land. Some near misses were for storms that made landfall and then continued out to sea and threatened to landfall elsewhere but remained at sea [e.g., Debby (2000)]. Other near misses threatened coastal areas without making landfall and then continued on to make landfall elsewhere [e.g., Gloria (1985)]. An average of one storm per year is forecast to make landfall but remains at sea. In these cases, position and time errors from definition 1 do not apply, so position errors are determined by the difference between the forecast landfall position and the actual location of the storm at the time of forecast landfall (landfall error definition 4) in Table 2. These errors are comparable to or larger than mean position errors from 1970 to 1998 for the entire Atlantic basin (McAdie and Lawrence 2000). Near misses can be particularly troublesome for emergency managers since, though they remain offshore, they can produce coastal erosion, wave damage, and deaths due to

Table 3. Landfall forecasts and warnings issued for each near-miss storm.

Year	Storm	Landfall forecasts issued	Threatened area	Hurricane warnings issued?	Hurricane watches issued?	Tropical storm or gale warnings issued?	Tropical storm watches issued?
Hurricanes							
1978	Ella	4	Mid-Atlantic states	No	Yes	No	No
1985	Gloria	4	USVI	Yes	Yes	No	No
1985	Kate	3	South FL	Yes	Yes	Yes	No
1989	Dean	1	PR/USVI	Yes	Yes	No	No
1995	Felix	9	Mid-Atlantic states	Yes	Yes	Yes	No
1995	Luis	6	PR/USVI	Yes	Yes	Yes	No
1996	Edouard	10	New England	Yes	Yes	Yes	No
1996	Hortense	10	PR/USVI	Yes	Yes	Yes	Yes
1996	Lili	4	FL Keys	No	No	Yes	No
1999	Jose	7	PR/USVI	Yes	Yes	Yes	No
2000	Debby*	3	South FL	No	No	No	No
Tropical storms							
1978	Juliet	1	SE United States	No	No	No	No
1979	Henri	3	Gulf coast	No	No	Yes	No
1980	Jeanne	10	TX/LA	No	Yes	Yes	No
1982	Alberto	5	South FL	Yes	Yes	Yes	No
1984	Arthur	2	PR/USVI	No	No	No	No
1984	Isidore	1	SE United States	No	No	Yes	No
1986	Andrew*	3	Mid-Atlantic states	No	No	Yes	No
1992	Earl	1	SE United States	No	No	No	Yes
1995	Sebastien	3	PR/USVI	No	No	No	Yes
1999	Irene	9	Mid-Atlantic states	Yes	Yes	Yes	Yes
1999	Katrina*	5	FL Gulf coast	No	No	No	No

*Some forecasts could not be verified due to storm dissipation.

drowning without producing damaging winds on the coast. They can also approach close enough to the coast that tropical storm or hurricane conditions are expected, thus requiring watches and warnings. During 1976–2000, all but four near-miss storms (Table 3) approached close enough to require warnings. Unfortunately, there is no way of determining a priori whether a given forecast of landfall will be a near miss.

c. *Landfall forecast skill*

To provide a larger sample size for more accurate estimates of relative error, landfall forecasts are placed into four forecast lead time period bins [9 (0–18 h), 24 (19–30 h), 48 (31–54 h), and 63 (55–72 h) h before predicted landfall]. Skill determined from mean OFCL and CLIPER landfall forecast errors for each time period, and skill for Atlantic basin track forecasts (1970–99 and 1996) are shown in Fig. 4. Skillful forecasts are indicated by negative relative error. Landfall position forecasts are skillful (< 5% chance of zero skill by *t* test) at all time periods. Landfall position forecasts are most skillful in the 55–72-h period before forecast landfall. Skill assessment for time of landfall forecasts is based on absolute value of the time error. Times of landfall forecasts are skillful at all but the 55–72-h period. Times of landfall forecasts are most skillful 19–54 h before predicted landfall, and are nearly as skillful at short lead times. In general, the skill of landfall position forecasts is 5%–10% higher than for Atlantic basin position forecasts, although basinwide forecasts in 1996 (the most accurate season on record) showed greater skill beyond 24 h than the landfall subset.

d. *Trends in landfall forecast accuracy*

Atlantic basin OFCL forecast position accuracy has improved 1%–2% per year from 1970 to 1998 (McAdie and Lawrence 2000). Consistent with this improvement, Aberson (2001) has documented improvement in the operational suite of track forecast models in the Atlantic basin from 1976 to 1998.

To account for the possibility that a trend may be hidden by difficulty in forecasting individual cases early or late in the period, an adjusted error (Neumann 1981; McAdie and Lawrence 2000) is calculated based on annual mean OFCL and CLIPER landfall position and time errors. As described in McAdie and Lawrence (2000), an expected annual mean error is computed based on a weighted (by number of forecasts in a given year) fit of annual mean OFCL to CLIPER errors. For each of the four forecast lead time periods, each year's mean forecast error is adjusted for difficulty by subtracting the expected error from the OFCL and then adding the mean error for the period of record. Weighted linear least squares fits of annual mean adjusted position and time errors are evaluated for a secular improvement trend (Fig. 5). Annual mean adjusted errors lower than the mean for the entire period of record represent skillful forecasts.

A significant improvement trend (according to the F test at the 95% level) is indicated only for time of landfall forecasts in the 19–30-h period. Position errors show an improvement trend in the 31–54-h period but the fit fails significance testing at the 95% level (the trend is significant at 90%). No forecast periods show evidence of any significant degradation. Unfortunately, in the 55–72-h period (Figs. 5g,h), CLIPER landfall forecasts exist in only 13 of the 25 years.

e. *Effect of track orientation relative to the coastline, motion, and intensity*

Since prediction of the location and timing of landfall is more difficult for storms moving parallel to the coastline than for those moving perpendicular to it, each landfall is categorized according to the orientation of the track relative to the smoothed coastline

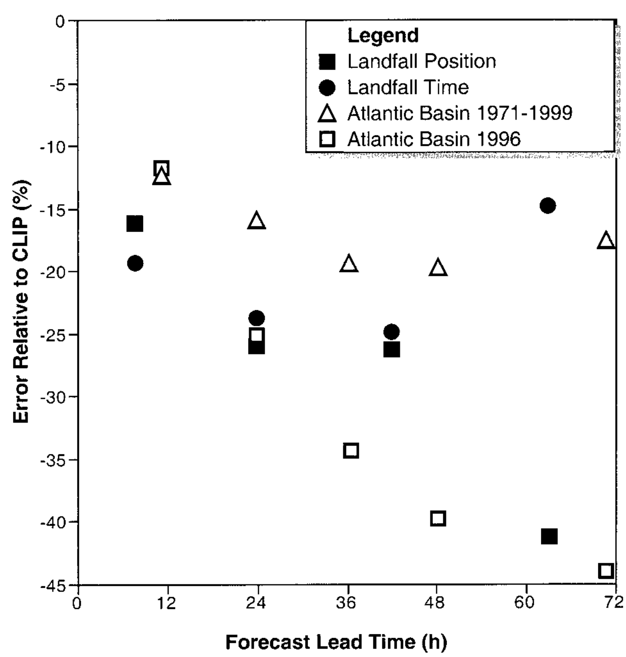

FIG. 4. Landfall relative position (filled squares) and time (circles) errors as a function of forecast lead time. Negative relative error indicates skill. Atlantic basin track forecast skill for 1971–99 (open triangles) and 1996 (open squares) is also plotted.

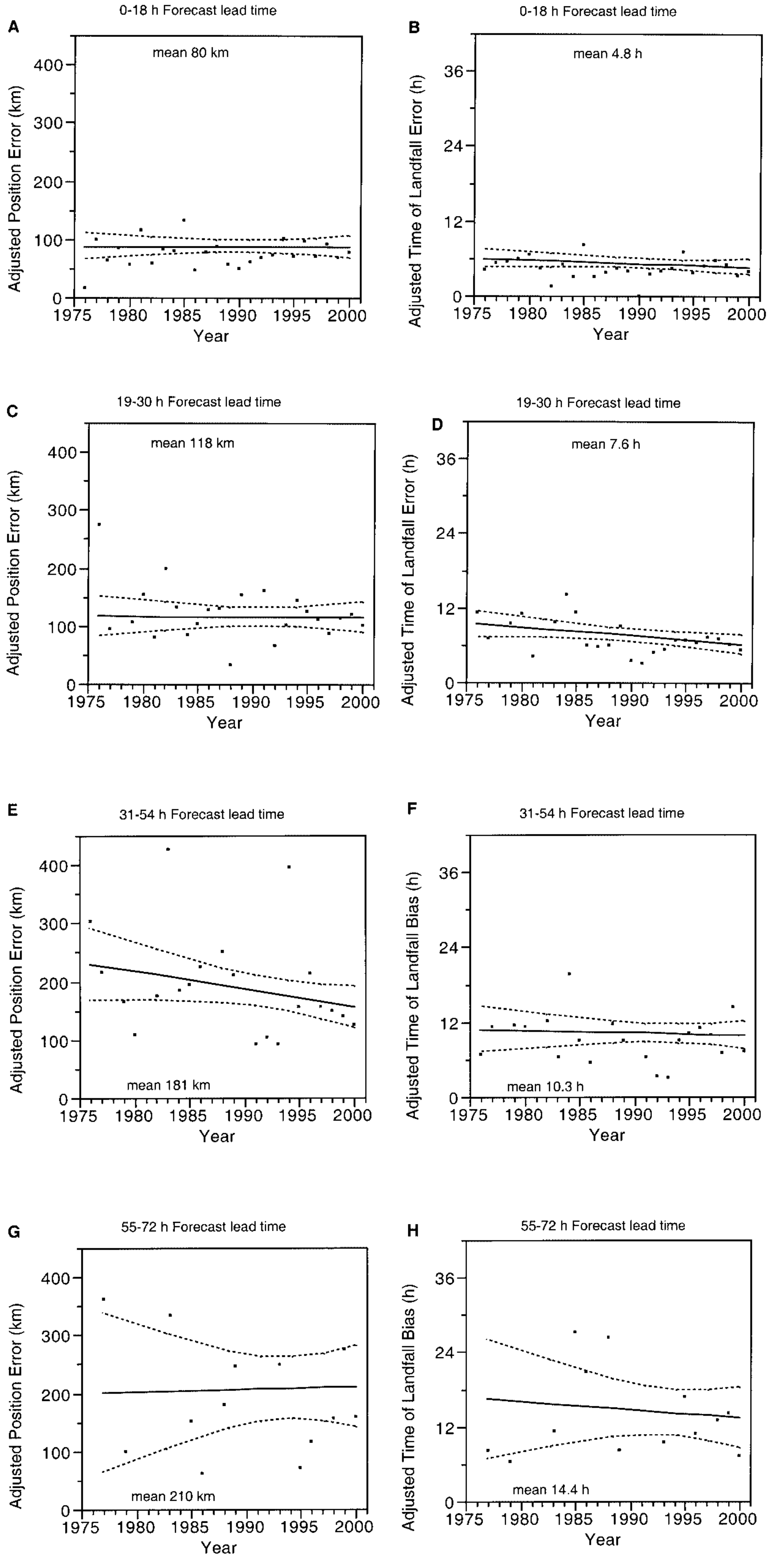

FIG. 5. Annual mean adjusted landfall position errors, and time of landfall (absolute value) errors in each time period before predicted landfall: (a),(b) 0–18; (c),(d) 19–30; (e),(f), 31–54; and (g),(h) 55–72 h. Weighted least squares fits (solid lines) and 95% confidence bands on the fits (dashed lines) are also shown. Mean landfall position and time errors for the 25-yr period are indicated in each plot.

before landfall. Tracks are classified as normal (moving at an angle of 45°–90° compared to a smoothed coastline) or parallel (moving at an angle < 45° compared to the coastline). Within 30 h of predicted landfall (Table 4), position errors are 15%–50% larger for tracks parallel to the coastline than for perpendicular ones. Within 55 h of predicted landfall, track forecasts parallel to the coastline have larger time errors, larger early biases, and larger standard deviations in the forecast position and time of landfall than perpendicular ones.

The data are divided into forecasts for slow- and fast-moving storms relative to the median observed speed at the time of landfall (5.2 m s^{-1}). Within 55 h of predicted landfall, slow-moving storms have 10%–50% smaller mean distance errors, much smaller standard deviations, and a later time of landfall bias than fast movers.

Storms are also categorized by intensity at the time of landfall according to the hurricane disaster potential or Saffir–Simpson (SS) scale (*Weatherwise* 1974; Saffir 1975). Errors for weak (tropical storm and SS category 1 at landfall) and strong (SS categories 2–4 at landfall) storms are shown in Table 4. Within 55 h of predicted landfall mean position errors are slightly smaller for strong storms than for weak ones. OFCL errors and those of many objective forecast techniques are generally smaller for strong storms than for weak ones (Aberson

TABLE 4. Landfall position and time errors by track orientation, intensity, and storm motion.

		Normal	Parallel	Strong	Weak	Fast	Slow
0–18-h period before predicted landfall							
	No. of cases	137	129	82	184	137	129
Position error	Mean (km)	63	95	76	80	96	60
	Std dev (km)	74	112	117	84	117	60
Time error	Mean (h)	–1.9	–2.5	–2.8	–1.9	–2.3	–2.0
	Std dev (h)	5.9	8.2	8.2	6.6	7.2	7.0
Absolute value time error	Mean (h)	4.2	4.9	4.6	4.5	4.1	5.0
19–30-h period before predicted landfall							
		Normal	Parallel	Strong	Weak	Fast	Slow
	No. of cases	77	52	46	83	58	71
Position error	Mean (km)	114	134	109	129	145	103
	Std dev (km)	98	150	128	119	150	90
Time error	Mean (h)	–0.9	–2.6	–3.5	–0.6	–2.7	–0.8
	Std dev (h)	9.3	13.0	12.2	10.0	12.5	9.4
Absolute value time error	Mean (h)	7.2	8.7	7.9	7.8	8.0	7.7
31–54-h period before predicted landfall							
		Normal	Parallel	Strong	Weak	Fast	Slow
	No. of cases	107	105	87	125	108	104
Position error	Mean (km)	188	171	166	188	191	167
	Std dev (km)	138	183	163	161	181	139
Time error	Mean (h)	3.7	–4.3	–2.6	1.4	-0.6	0.1
	Std dev (h)	11.5	12.8	10.0	14.2	10.6	14.7
Absolute value time error	Mean (h)	9.7	10.2	8.1	11.3	8.7	11.3

and DeMaria 1994; Marchok et al. 2000). Strong storms tend toward earlier landfall time forecasts than weak ones at all time periods.

f. Errors relative to the coastline

Position and time biases [left (right) and early (late)] are shown in Fig. 6 with axes signifying coastline (x) and time (y) biases, and with centroid coordinates (x,y) listed for each time. Early (late) bias landfall forecasts have negative (positive) values, and forecasts of landfall to the left (right) of the observed position have negative (positive) values. For the 0–18-h period before forecast landfall (Fig. 6a) a left-side, early bias is apparent, and some of the forecast outliers included predictions of landfall 24–36 h early. For the 19–30-h period before forecast landfall (Fig. 6b), a left, slight early bias is also shown. At 31–54 h before forecast landfall (Fig. 6c), no time bias is evident, but the left bias is relatively large. At 55–72 h (Fig. 6d), the left bias is large, and a late timing bias is indicated. The tendency toward a left-side coastal bias at all forecast periods is associated with the difficulty of forecasting recurvature, and an early bias for the time periods < 30 h before forecast landfall is associated with least regret forecasts to account for possible storm accelerations.

g. Errors in specific regions

To display the errors and biases so that they may be most useful for hurricane forecasters and local disaster management officials, the coastline is divided into segments of roughly 5° latitude, from Texas to Maine, and an additional area for Puerto Rico and the USVI (numbered coastal segments are shown in Fig. 1). Mean forecast time of landfall (absolute value) and landfall position errors are calculated in each coastal segment containing seven or more forecasts (Table 5). Coastal segments containing mean time of landfall and left–right position forecast errors with < 10% probability of zero values (based on the *t* test) are also listed in Table 5. Each sample is relatively small so a single forecast can greatly influence the mean errors. For example, the north-central Gulf of Mexico (segment 3) has mean position errors twice as large as adjacent coastal areas due to relatively large forecast errors for Hurricane Elena 1985.

Only a few coastal segments satisfied the *t*-test criterion for listing time and position biases. For the 0–18-h period, a left-side bias is indicated for the Carolinas and an early time bias is noted for the eastern Gulf of Mexico, New England, and Puerto Rico–USVI coastal segments. At 19–30 h, an early bias is noted in Puerto Rico–USVI. The 31–54-h period has an early and left bias in Puerto Rico–USVI, a right bias in Texas, and a left bias in south Florida, the Carolinas, and mid-Atlantic states. A late bias is suggested for Texas and the north-central Gulf of Mexico through south Florida for the 55–72-h period, with a left-side bias for the Carolinas and Puerto Rico–USVI.

Some insight into position biases may be gained from a study of Atlantic basin spatial errors for OFCL and numerical model forecasts conducted by Marchok et al. (2000). They found larger errors for the mid-Atlantic to New England states than in the southern states and Puerto Rico–Virgin Islands at 12–48 h, which is likely due to difficulty in predicting recurvature. Large 48–72-h errors were documented in the western Gulf of Mexico with a west and southwest (left) bias along the Gulf coast.

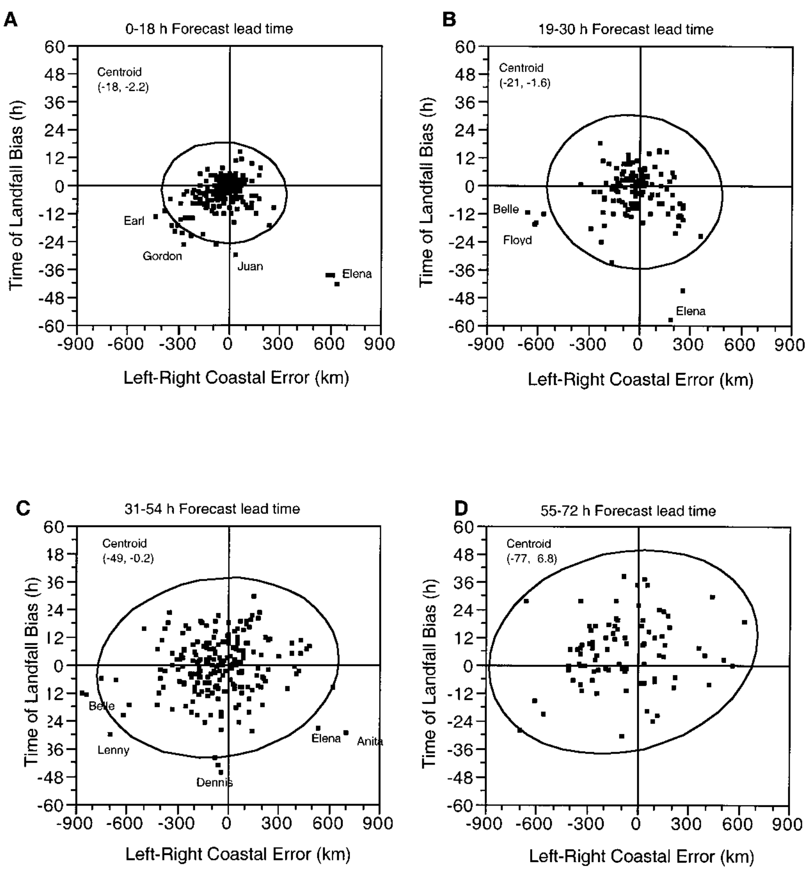

FIG. 6. Time of landfall vs landfall position bias along the coastline: (a) 0–18, (b) 19–30, (c) 31–54, and (d) 55–72 h. Outliers are identified and centroid coordinates (km, h) are shown. Dennis refers to the 1999 landfall of the tropical storm. Ellipses represent 99% probability curves for a bivariate normal distribution.

4. Conclusions and discussion

Following an approach first used by Neumann and Pelissier (1981), landfall forecast position and timing errors in the United States are compiled for the 1976–2000 seasons from 695 landfall forecasts in the Atlantic basin. In a given year, an average of 10 named storms form, with 3 making landfall in the United States and one "near-miss" case.

Conclusions are as follows:

- A small percentage of landfall forecasts (~13%) qualify as near misses (i.e., landfall was predicted but did not occur). All but one of

TABLE 5. Landfall errors and biases by coastal segment. Coastal segment numbers are shown in Fig. 1. Coastal segments with less than seven forecasts in a given period are not listed. Left/right coastal bias is the mean of the distance errors to the left or right of the landfall position. Only significant left/right coastal and time biases (<10% chance of zero mean by *t* test) are listed.

Forecast period (h)	Coastal segment	1	2	3	4	5	6	7	8	9	10
0–18	No. of forecasts	32	28	50	17	34	9	46	8	13	29
	Mean position error (km)	58	46	109	60	94	62	88	71	100	55
	Left/right coastal bias (km)	—	—	—	—	–69	—	–50	—	—	—
	Time bias (h)	—	–3.2	–4.3	–1.6	—	—	—	—	–3.6	–2.1
	Absolute value time error (h)	3.9	4.8	6.8	2.4	5.0	2.9	4.1	3.7	4.5	3.4
19–30	No. of forecasts	25	12	21	7	17	7	15	—	—	16
	Position error (km)	133	77	130	76	102	176	140	—	—	105
	Left/right coastal bias (km)	—	—	—	—	—	—	—	—	—	—
	Time bias (h)	—	—	—	—	—	—	—	—	—	–4.3
	Absolute value time error (h)	10.2	5.0	11.0	4.6	4.9	7.5	8.1	—	—	7.6
31–54	No. of forecasts	38	15	36	13	24	—	33	10	10	28
	Position error (km)	242	85	190	77	161	—	150	144	367	173
	Left/right coastal bias (km)	85	—	—	—	–109	—	–73	–123	—	–137
	Time bias (h)	—	—	—	—	—	—	—	—	—	–5.0
	Absolute value time error (h)	10.3	7.8	9.8	8.3	7.6	—	13.7	6.7	8.9	10.9
55–72	No. of forecasts	16	—	19	—	10	—	21	—	—	12
	Position error (km)	316	—	187	—	193	—	233	—	—	212
	Left/right coastal bias (km)	—	—	—	—	—	—	–143	—	—	–200
	Time bias (h)	5.3	—	11.6	—	—	—	—	—	—	—
	Absolute value time error (h)	8.7	—	18.3	—	11.3	—	12.5	—	—	9.4

the near-miss hurricanes included the issuance of a hurricane warning, and about a third of the tropical storm near misses included issuance of tropical storm or hurricane warnings.

- Landfall position and time forecasts are skillful at all time periods before landfall and demonstrate skill levels 5%–10% higher than Atlantic basin track forecasts.
- Standard deviations of the landfall timing errors suggest uncertainties of 11 h at 24–36 h before predicted landfall decreasing to 8 and 5 h at 12 and 3 h, respectively.
- Time of landfall forecasts show an early bias of 1.5–2.5 h within 30 h of predicted landfall, consistent with conservative forecasts to account for the possibilities of storm acceleration.
- No significant improvement or degradation is indicated for landfall position forecasts at any lead time period during the 1976–2000 period.
- Times of landfall forecasts issued in the 19–30-h period before predicted landfall show significant improvement (2% per year).
- Within 55 h of predicted landfall, storms moving parallel to the coastline before landfall have 15%–40% larger average landfall position errors, earlier time error biases, and ~1 h larger timing errors than those storms moving normal to the coastline.
- Slow-moving (< 5.2 m s^{-1}) storms have 10%–40% smaller distance errors than fast-moving ones.

a. *Why have landfall forecasts not improved?*

One possible explanation for the lack of improvement may be the impact of a conservative "least regret" warning policy on the forecast process. Landfall forecasts issued within 30 h of predicted landfall compose most of the early and left bias forecasts (Fig. 6, Table 5) and show an early bias for high-error (parallel, fast) and low-error (normal, slow) forecasts (Table 4), which suggests that a conservative warning policy plays a role.

Another possibility is deficiencies in numerical models or observations. Reynolds et al. (1994) and Zhu et al. (1996) indicated that, in the midlatitudes, most synoptic-scale errors in global numerical weather prediction models are not due primarily to model deficiencies, and that the largest forecast improvements are likely to be achieved by decreasing the analysis error by improving observing systems, data assimilation methods, and by targeting observations. The rawinsonde network may have deteriorated in the Caribbean and Central America during the past 25 years but successful recent National Oceanic and Atmospheric Administration (NOAA) Hurricane Field Program adaptive observing experiments have led to an operational program of synoptic surveillance of the environment surrounding tropical cyclones. Burpee et al. (1996) and Aberson and Franklin (1999) documented 16%–30% improvement in 12–60-h forecasts for storms within 72 h of potential landfall when synoptic dropwindsonde observations were assimilated into the models. Hence, a sampling strategy of enhanced and targeted observations, and improvements in assimilation of these data into numerical models, in storms close to the North American network may lead to improved landfall forecasts.

b. Landfall errors and warning area

Since the landfall position forecasts are skillful, warning areas based on the uncertainty of the landfall position forecast should be considered (Neumann 1975). Neumann (1975) considered the size of the warning area to be comparable to the width of a typical damage swath (~140 km) plus 1.5–2.0 standard deviations of the landfall forecast error on each side, leaving a 5%–15% chance of experiencing damaging winds outside the area. For example, using results in Table 2 with 2.0 standard deviations, at 24 h the warning area would correspond to 620 km (with a 5% chance of being exceeded), comparable to the mean Atlantic basin hurricane warning area of 650–750 km determined by Jarrell and DeMaria (1999) from 1967 to 1997. To be more certain (say, to 99% probability) of all damaging winds being within the warning area, the area would need to be 3.0 standard deviations of the error on each side of the swath, an 860-km length of coastline. This implies that the current warning areas are ~200 km smaller than what could be objectively estimated certainly, which suggests an inherent value in the warnings. If we use the estimate of $35 million per 100 km of coastline for preparation costs (OFCM 1997), the savings is ~$70 million per warning episode.

Another possible application of landfall position and time error statistics would be for improvements to landfall strike probability (Sheets 1984, 1990). Though the landfall error statistics would be more relevant than the general basin errors currently used, the sample size is too small to fit frequency distribution models capable of resolving spatial and seasonal variability (e.g., Crutcher et al. 1982). For 1976–2000 only 129 landfall forecasts are available for the 19–30-h forecast lead time period compared to > 4000 24-h position forecasts for the entire Atlantic basin.

c. Discussion of United States Weather Research Program goals

Recently, the USWRP Hurricane Landfall Workshop (Elsberry and Marks 1999) and the United States Weather Research Program (USWRP) implementation plan (http://mrd3.nssl.ucar.edu/USWRP/USWRP_Vision.html) listed potential forecast goals that might be achievable given successful tropical cyclone research and transfer of results to operational forecasting. USWRP track forecast goals include 1) reducing landfall track and intensity forecast errors by 20%, 2) increasing warning lead time to and beyond 24 h with 95% confidence without increasing the present 3:1 ratio of area warned to area experiencing damaging winds, and 3) making skillful (compared to persistence) forecasts of onset of gale and hurricane force winds out to 48 h with 95% confidence. These goals now have operational implications since the 2000–05 strategic plan for the National Weather Service (NWS 1999) seeks to link its improvement goals to scientific and technological advancements. In particular, the strategic plan performance measure seeks to "increase the average lead time for hurricane landfall forecasts (warnings) from 19 h (1998) to beyond 24 h with no increase in warned area." In addition to the USWRP goals and NWS strategic plan, another goal-related document has interpreted the improvement in Atlantic basin forecast accuracy to apply to landfall forecasts. A report on effective disaster warnings by the Working Group on Natural Disaster Information Systems (Subcommittee on Natural Disaster Reduction 2000) states that, "Prediction of hurricane landfalls is improving. . . . For the next four-year period, forecasts for land-falling storms should improve an additional 20% due to the use of better models and data. . . ." Since these goals are related to landfall forecast issues, our findings should prompt renewed discussion of forecast goals.

USWRP goal 1 (reduction of landfall track errors by 20%) is a formidable goal since no discernable improvement is indicated during the past 25 years. A goal of 20% reduction in basinwide position forecast errors would be a reasonable alternative.

A portion of USWRP goal 2 and the NWS strategic objective (to increase warning lead time) may be supported by these findings. Emergency managers base most of their preparedness activities on the time of onset of gale force (17 m s^{-1}) winds, which average about 10 h before landfall based on the median landfall storm motion of 5.2 m s^{-1} and an average radius of gale force winds of 204 km (Jarrell and DeMaria 1999). Locations with offshore flow experience the onset of gale force winds several hours after locations with onshore flow. Landfall timing uncertainty is ~11 h from 24–36 h before predicted landfall. However, the 24–36-h landfall forecast location uncertainty combined with urgency brought on by high coastal population density and long evacuation lead times would require a corresponding increase in warning area. Advanced warning lead time would require reeducating users of warning products. Increased warning areas would raise overwarning costs, although the size of the warning area could be decreased as the location and time of landfall becomes more certain (Jarrell and DeMaria 1999). Considering the lack of a significant improvement trend in landfall forecasts issued within 30 h of predicted landfall, goals to decrease the overwarning ratio or keep the warning area constant while increasing lead time may not be realistic. A goal of advancing warning lead time beyond 24 h and sequentially reducing the size of the warning area by 10% within 12 h of the predicted time of landfall might be an alternative to consider.

USWRP goal 3 (skillful forecasts of gale and hurricane wind onset) is partially addressed by the landfall position and timing forecast error statistics. The forecast of the onset of gale and hurricane force winds is both a track and wind field forecast problem. Skillful times of landfall forecasts are documented at all forecast lead time periods suggesting that wind field forecasting is the remaining problem. Unfortunately, forecasts of the maximum wind (intensity) show little skill (OFCM 1997), efforts to verify gale and hurricane force wind radii forecasts are just beginning (Houston et al. 1998), and numerical models do not yet provide wind radii forecast guidance. USWRP goal 3 may be appropriate after development of an operational wind radii forecast verification system.

Landfall position forecasts have not improved significantly during the past quarter century despite dramatic basinwide improvements in track forecasting. The objective model guidance should be investigated for trends in the accuracy of landfall forecasts, though this is made difficult by the relatively short period of record for individual models. Aberson (2001) has shown that the current suite of operational model track guidance encompasses the actual track nearly 95% of the time within 48 h of the initial time. Therefore, the ensemble could be used to objectively determine the limits of coastal warnings based on the expected reliability of the models in individual cases.

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Appendix: U.S. tropical cyclone landfalls for the Atlantic basin: 1976–2000

OFCL landfall positions, times, maximum sustained winds, and minimum sea level pressures of storms in this study (Table A1) are based on data contained in Atlantic basin seasonal summary articles published in *Monthly Weather Review* or in NHC reports prepared on each storm. If specific location, time, and intensity are not available from these sources, the best track (HURDAT) database (Jarvinen et al. 1984) is consulted. For information purposes, Table A1 also includes supplemental information on alternative estimates of the maximum sustained surface wind speed in hurricanes making landfall determined from published sources, and real-time or retrospective wind analyses conducted by the NOAA Hurricane Research Division (available online at www.aoml.noaa.gov/hrd).

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TABLE A1. U.S. tropical cyclone landfalls for the Atlantic basin 1976–2000 for hurricanes and tropical storms. Maximum sustained wind speeds (MWS) are NHC official estimates, except for hurricanes (*) alternative estimates or fastest-mile (~40 s mean) winds based on published reports (see citation index), or (**) estimates for marine exposure from HRD's real-time wind analysis (http://www.aoml.noaa.gov/hrd). Short-lived storms that made landfall within 24 h of genesis are indicated by (S). See text for details on strikes and multiple (M) landfalls within a 24-h period. SS refers to Saffir–Simpson category; P is minimum sea level pressure at landfall.

Hurricanes

Year	Storm	SS Category	Location	Month	Day	Time (UTC)	Lat (°)	Long (°)	MWS (kt)	Citation	P (hPa)
1976	Belle	1	Jones Beach, NY	8	10	0500	40.7	73.3	60, 78*	1	983
1977	Babe (S)	1	Morgan City, LA	9	5	0600	29.5	91.2	65		955
1979	Bob (S)	1	Grand Isle, LA	7	11	1200	29.1	90.6	65		986
1979	David (M)	1	Palm Beach, FL	9	3	1600	27.0	80.2	80		974
1979	Frederic	4	Dauphin Island, AL	9	13	0300	30.3	88.2	126, 97*, 93*	2	946
1980	Allen	3	Brownsville, TX	8	10	0600	26.1	97.2	100		945
1983	Alicia	3	Galveston, TX	8	18	0700	29.1	95.1	100, 81* 76*	3	962
1984	Diana strike	3	Cape Fear, NC	9	12	0300	33.9	77.7	100, 100*	4	950
1984	Diana	1	Cape Fear, NC	9	13	0700	33.9	78.0	80, 68*	4	979
1985	Bob	1	Beaufort, SC	7	25	0300	32.2	80.5	65		1003
1985	Danny	1	Lake Charles, LA	8	15	1630	29.6	92.7	80		959
1985	Elena	3	Biloxi, MS	9	2	1300	30.4	89.2	110, 83*	5	959
1985	Gloria (M)	1	Long Island, NY	9	27	1600	40.6	73.3	75		961
1985	Juan	1	Morgan City, LA	10	29	1200	29.6	91.3	65		974
1985	Kate	2	Panama City, FL	11	21	2230	30.0	85.4	85		967
1986	Bonnie	1	Port Arthur, TX	6	26	1200	29.6	94.2	75		990
1986	Charley	1	Cape Lookout, NC	8	17	1400	34.7	76.5	65		990
1987	Floyd strike	1	Key West, FL	10	12	1700	24.6	81.8	65		993
1988	Florence	1	Boothville, LA	9	10	0200	29.1	89.3	70		984
1989	Chantal	1	High Island, TX	8	1	1300	29.6	94.4	70		986
1989	Hugo (M)	4	St. Croix, USVI	9	18	0600	17.7	64.8	120, 110*	6	940
1989	Hugo	4	Sullivan's Island, SC	9	22	0400	32.8	79.8	120, 114*	7	934
1989	Jerry	1	Galveston Island, TX	10	16	0030	29.2	95.0	75		983
1991	Bob (M)	2	Newport, RI	8	19	1800	41.4	71.4	85, 87*	8	964
1992	Andrew	4	Homestead, FL	8	24	0905	25.5	80.3	125, 128*	9	922
1992	Andrew	3	Point Chevreuil, LA	8	26	0830	29.6	91.5	105, 101*	10	956
1993	Emily strike	3	Cape Hatteras, NC	8	31	2100	35.2	75.1	100, 101*11		961
1995	Erin	1	Vero Beach, FL	8	2	0615	27.7	80.3	75, 55**		984
1995	Erin	1	Pensacola Beach, FL	8	3	1600	30.3	87.2	75, 79.5*	12	973
1995	Marilyn (M)	2	St. Thomas, USVI	9	16	0438	18.3	65.1	95, 89*, 89*	13	952
1995	Opal	3	Pensacola, FL	10	4	2200	30.3	87.1	100, 89*	12	942
1996	Bertha	2	Wrightsville/Topsail, NC	7	12	2000	34.3	77.8	90, 85*	14	974
1996	Fran	3	Cape Fear, NC	9	6	0030	33.9	78.1	100, 95*	14	954
1996	Hortense	1	Guanica, PR	9	10	0600	18.0	66.9	70, 60**		989
1997	Danny	1	Empire, LA	7	18	0900	29.3	89.7	65, 67**		989
1997	Danny	1	Fort Morgan, AL	7	19	1000	30.2	88.1	70, 62**		984
1998	Bonnie	2	Wilmington, NC	8	27	0330	34.4	77.7	95, 82**		964
1998	Earl	1	Panama City, FL	9	3	0600	30.1	85.7	70, 64**		987
1998	Georges	3	Fajardo, PR	9	21	2200	18.1	65.8	100, 80**		968
1998	Georges	2	Key West, FL	9	25	1530	24.5	81.8	90, 85**		981
1998	Georges	2	Biloxi, MS	9	28	1130	30.4	88.9	90, 76**		964
1999	Bret	3	Padre Island, TX	8	23	0000	26.9	97.4	100, 90**		951
1999	Dennis strike	2	Cape Lookout, NC	8	30	1330	33.7	76.0	85, 78**		965
1999	Floyd	2	Cape Fear, NC	9	16	0630	33.8	78.0	90, 83**		956
1999	Irene	1	Cape Sable, FL	10	15	2000	25.3	81.1	70, 61**		987
1999	Lenny strike	4	St. Croix, USVI	11	17	1800	17.4	64.8	135, 125**		933
2000	Debby strike	1	St. Johns, USVI	8	22	1500	18.5	64.4	65, 60**		994

TABLE A1. *Continued.*

Tropical storms

Year	Storm	Location	Month	Day	Time (UTC)	Lat (°)	Long (°)	MWS (kt)	P (hPa)
1976	Dottie (S)	Southwest, FL	8	19	1330	25.5	81.3	35	1004
1976	Dottie	Charleston, SC	8	20	2200	32.7	80.0	35	1005
1978	Amelia (S)	Corpus Christi, TX	7	31	0000	26.4	97.4	45	1005
1978	Debra (S)	Port Arthur, TX	8	29	0000	29.5	93.5	50	1002
1979	Claudette	Cameron, LA	7	24	1615	29.8	94.0	45	997
1979	Elena	Matagorda, TX	9	1	1200	28.5	95.8	35	1004
1979	Frederic	Humacao, PR	9	4	1200	18.1	65.8	45	1004
1980	Danielle (S)	Galveston, TX	9	6	0000	29.4	94.9	40	1004
1981	Dennis	Southwest FL	8	17	0600	25.2	81.2	36	999
1981	Dennis	Southport, NC	8	20	0400	33.9	78.4	48	999
1981	Gert	Eastern PR	9	8	1900	18.2	65.9	50	1002
1982	Chris	Port Arthur, TX	9	11	1200	29.8	93.8	55	994
1983	Barry	Melbourne, FL	8	25	1100	27.9	80.6	30	1013
1983	Dean	Eastern Shore, VA	9	30	1200	37.5	75.8	40	1010
1984	Isidore	Jupiter, FL	9	27	1800	27.3	80.5	45	1001
1984	Klaus	Eastern PR	11	7	0600	18.0	65.8	45	998
1985	Bob (S)	Ft. Myers, FL	7	23	1400	26.4	81.9	40	1005
1985	Henri	Long Island, NY	9	24	2100	40.8	72.5	35	1006
1985	Isabel	Jacksonville, FL	10	10	2100	30.6	81.4	35	1008
1985	Juan	Valparaiso, FL	10	31	1800	30.3	87.7	55	982
1987	Unnamed (S)	Beaumont, TX	8	10	0600	29.6	94.5	40	1009
1988	Beryl	Slidell, LA	8	9	0600	29.6	89.5	45	1001
1988	Chris	Savanna, GA	8	28	1500	32.0	80.9	40	1005
1988	Keith	Tampa, FL	11	23	0700	27.3	82.6	55	995
1989	Allison (S)	Freeport, LA	5	26	1300	28.7	95.7	40	1002
1990	Marco	Bradenton Beach, FL	10	11	1200	27.5	82.8	50	994
1992	Danielle	Delmarva, VA	9	25	2200	37.8	75.5	55	1007
1993	Arlene (S)	Padre Island, TX	6	20	0900	27.1	97.4	35	1001
1994	Alberto	Destin, FL	7	3	1500	30.4	86.5	55	993
1994	Beryl	Panama City, FL	8	16	0000	30.0	85.6	50	1000
1994	Gordon	Key West, FL	11	15	1300	24.6	81.7	45	999
1994	Gordon	Ft. Myers, FL	11	16	1300	26.6	81.9	45	996
1995	Allison	St. Marks, FL	6	5	1500	30.1	84.2	55	991
1995	Dean (S)	Freeport, TX	7	31	0200	29.2	95.3	40	999
1995	Jerry	Jupiter, FL	10	23	1800	27.0	80.2	35	1006
1996	Josephine	Apalachee Bay, FL	10	8	0330	30.0	83.9	60	981
1996	Arthur	Cape Lookout, NC	6	20	0000	34.7	76.4	35	1005
1998	Charlie (S)	Port Aransas, TX	8	22	1000	27.8	97.1	40	1000
1998	Frances	Corpus Christi, TX	9	11	0600	28.2	96.9	45	990
1998	Hermine (S)	Cocodrie, LA	9	20	0500	29.1	90.9	35	1000
1998	Mitch	Naples, FL	11	5	1100	26.2	81.9	55	989
1999	Dennis	Cape Lookout, NC	9	4	2100	34.8	76.5	60	984
1999	Harvey	Everglades City, FL	9	21	1700	25.9	81.7	50	999
2000	Gordon	Cedar Key, FL	9	18	0300	29.3	83.2	55	992
2000	Helene	Fort Walton, FL	9	22	1200	30.5	86.6	35	1006

Citation key
1 SethuRaman (1979)
2 Powell (1982); Reinhold and Mehta (1981)
3 Marshall (1984); Powell (1987)
4 NRC (1986)
5 NRC (1991)
6 NRC (1994)
7 NRC (1994); Powell et al. (1991)
8 Houston and Powell (1993)
9 Powell and Houston (1996)
10 Ramsay et al. (2001)
11 Burpee et al. (1994)
12 Powell and Houston (1998)
13 Powell and Houston (1998); Marshall (1997)
14 Houston et al. (1997)

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