Historical Developments Leading to Current Forecast Models of Annual Atlantic Hurricane Activity

J. C. Hess*
and J. B. Elsner
Department of Meteorology,
The Florida State University,
Tallahassee, Florida

Abstract

There is considerable interest in forecasting interannual hurricane activity for the Atlantic basin. Various predictors representing different components of the tropical Atlantic climate have been suggested. The choice of predictors is based on previous research into contemporaneous and lag relationships with seasonal hurricane and tropical storm frequency. Past research is divided into five distinct periods: the search for physical relationships, the use of composite charts, the use of satellite imagery and climatology of easterly waves, the emergence of recent ideas, and the development of prediction models. As an historical summary this paper describes the important research contributions in each period leading to our current understanding of yearly hurricane variability. The paper concludes by describing current methods for forecasting this variability and recommends an area for future investigations.

1. Introduction

Every year the North Atlantic Ocean is visited by a number of tropical storms and hurricanes. During the period 1950–93, year-to-year variability ranged from as few as 2 hurricanes in 1982 to as many as 12 hurricanes in 1969. Within the past decade some attempts have been made to forecast such activity months in advance (Gray 1984b; Elsner and Schmertmann 1993). The choice of predictors is based on past research into contemporaneous and lag relationships with hurricane activity. Major scientific contributions over the past century leading to current prediction models of seasonal Atlantic hurricane activity can be categorized into five distinct but overlapping chronological periods: 1) discovery of physical relationships, 2) use of composite charts, 3) use of satellite imagery and climatology of easterly waves, 4) emergence of recent ideas, and 5) development of statistical models for prediction. In what follows a justification for these groups becomes evident; however, it should be kept clear that the periods are overlapping and that although, for example, the most recent period is characterized by development of prediction models the posing of hypotheses and the use of composite charts and satellite imagery remain important in studies of season-to-season hurricane variability. Additionally it should be noted that, because the paper adopts the style of a chronology and tries to stay as close as possible to this form, the inclusion of a piece of important research may be located outside its more appropriate section.

*Current address: National Weather Service/Alaska Region, Anchorage, Alaska.
Corresponding author address: J. B. Elsner, Department of Meteorology B-161, The Florida State University, Tallahassee, FL 32306-3034.
In final form 6 April 1994.

2. Uncovering physical relationships

Fluctuation in surface pressure is an obvious candidate for explaining interannual hurricane variability. Garriott (1895) first recognized that sea level pressures (SLPs) across the Atlantic vary with abundance of hurricanes. He realized that such variations occur over extended geographical areas so that, for example, when SLP is unusually low over the Caribbean it is above normal near the British Isles (Garriott 1906). In fact, he suggested that a strengthening and northeastward movement of the Azores high promotes tropical cyclogenesis in the eastern Atlantic through an acceleration of the trade winds.

Brennan (1935) and Ray (1935) were the first to recognize that pre–hurricane season weather conditions in the Caribbean are to some extent related to disturbed weather over the same region during August and September. Based on data from the period 1903–34, Brennan (1935) noted that when rainfall is above normal and surface winds and pressures are below normal in the previous months there is an increased potential for stormy weather during the hurricane season. Seasonally lagged relationships between SLP in the Caribbean and hurricane frequency were also considered in Ray (1935). Using surface pressure data from San Juan, Puerto Rico, for the period 1899–

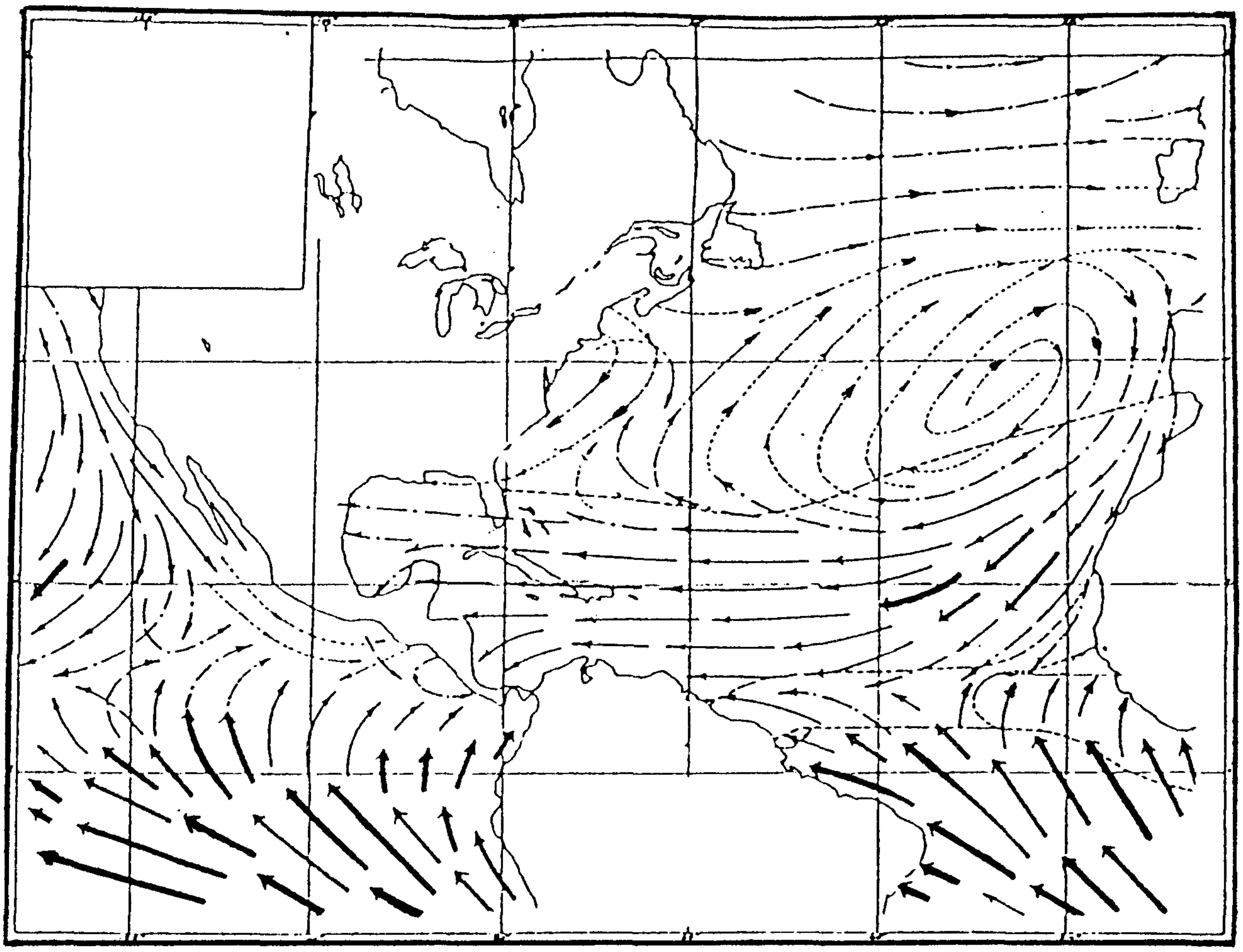

FIG. 1. Surface wind circulation over the Atlantic Ocean for the month of September, reproduced from Dunn (1940). Direction lines are based on the dominant wind computed for each 5° latitude–longitude square, and width of arrow gives a measure of the relative wind steadiness.

1933, he concluded that there is a strong inversely proportional relationship between spring–summer surface pressures and summer–fall tropical cyclone frequency in the North Atlantic. He found that a combination of May through July pressures describes the relationship best. In the same paper, he also looked at contemporaneous sea surface temperatures (SSTs) over the eastern Caribbean for the period 1920–33 and found that they are positively correlated with tropical cyclone frequency.

These early findings can partly be explained by the position of the intertropical convergence zone (ITCZ) over the Caribbean. The ITCZ is a region of lower surface pressures extending primarily east–west over the equatorial Atlantic and forming a boundary between the trade winds of both hemispheres. With the ITCZ positioned farther north over the Caribbean, lower SLPs, weaker trades, and increased convective rainfall are all concomitant over the region.

Dunn (1940) was the first to recognize the importance of easterly waves for the formation of tropical storms. He provided evidence that easterly waves often originate along the ITCZ over the eastern Atlantic. He noted that development of easterly waves along the ITCZ is enhanced when the boundary reaches its northernmost extent near 12°N and the southeast trades along the West African coast turn toward the northeast south of Cape Verde. Dunn explained that this region is favorable for disturbances of hurricane intensity to develop. The surface wind circulation over the Atlantic Ocean during September as depicted in Dunn (1940) is reproduced in Fig. 1. The southwesterly monsoon flow south of Cape Verde is clearly evident. In addition to identifying the West African coast as a preferred region for origin of tropical disturbances, Dunn (1940) noticed that the intrusion of polar air into the Tropics over the western Atlantic and the Gulf of Mexico inhibits the deepening of tropical waves.

It was Riehl and colleagues during the late 1940s and early 1950s who were the first to stress the importance of a meridional separation of midlatitude westerlies from tropical easterlies for tropical cyclone strengthening (see, e.g., Riehl and Shafer 1944; Riehl and Burgner 1950). These studies mentioned that although initial storm development may be enhanced by a north–south shear of the horizontal winds, intensification of the storm requires a deep layer of easterlies with little or no vertical shear of horizontal winds.

The association between seasonal tropical cyclone frequency and large-scale SLP fluctuations is revisited in Namias and Dunn (1955). They were in agreement with Garriott (1906) that increased Atlantic hurricane activity occurs when the Azores high extends northeastward into Europe but suggested that the reason for this association was a penetration of midlatitude cyclonic vorticity into the Tropics rather than simply a freshening of the trades. The cyclonic vorticity is associated with a meridionally aligned trough along the Spanish and African coasts near Cape Verde. Further, Dunn (1956) noted that disturbances in the easterlies originating over Africa pass through this trough before becoming hurricanes. Comparing this idea with the reference to midlatitude–tropical interaction made by Dunn (1940) suggests a possible contradiction with regard to whether midlatitude disturbances inhibit or promote tropical cyclogenesis. It is currently understood that strong vertical shear of horizontal winds often associated with midlatitude disturbances will inhibit deep convection and limit tropical cyclogenesis. In contrast, it is also recognized that midlatitude disturbances can provide a source of low-level cyclonic vorticity important for initiation of tropical cyclone development.

Dunn and Miller (1960) were also in agreement with much of the earlier works when they noted that persistent SLP anomalies in portions of the tropical Atlantic have a strong influence on hurricane frequency. Specifically, when the Azores high shifts northeastward, the Bermuda high is weakened and hurricane frequency is increased over much of the tropical Atlantic, including the Caribbean.

It was Riehl (1956) who first mentioned the influence of midlatitude troughs on hurricane frequency. He demonstrated that a large-amplitude trough in the westerlies extending well into the Tropics can fracture with the southern portion, retrograding into the development of a tropical cyclone. Concerning the possibility of a seasonally lagged relationship, he comments that there is some tendency for seasonal hurricane numbers to be low if, in late spring, the subtropical anticyclone has above-average strength with east–west elongation. Riehl (1956) as well as Miller (1958) mention the importance of the strength and positioning of the upper-level anticyclone and its associated divergence pattern for tropical cyclone intensification.

3. Use of composite charts

An important paper in the history of interannual hurricane forecasting was written by Namias in 1955. Namias believed geographic areas favorable for tropical cyclone genesis can be prescribed by the long-period mean flow aloft (Namias 1955). He tested this idea by constructing and comparing 700-mb composite charts between years of extreme tropical cyclone activity. Although his initial study concentrated on the annual vulnerability of a limited area along the northeastern coast of the United States to hurricane activity, the work was significant because the methodology of compositing circulation maps inspired much future work.

It was Ballenzweig (1959) who applied this type of compositing technique to the entire Atlantic basin. Since more than three-fourths of all tropical cyclones form in August, September, and October, Ballenzweig based his composite approach on this season. Using data from the period 1933–55, he contrasts two composite height charts: one for the five years with the greatest number of tropical cyclones, and one for the five years with the least number of storms. These two charts are reproduced in Fig. 2.

The maximum tropical cyclone incidence chart shows a positive 700-mb anomaly stretching across the entire Atlantic at about 40°N. Negative anomalies are located over Iceland and over the subtropical Atlantic and Caribbean. The minimum tropical cyclone incidence chart shows the same positive anomaly at 700 mb, only smaller and shifted to the south around 30°N. Negative anomalies stretch from the Great Lakes to the central Atlantic and are located over the British Isles. It can be concluded that a northward displacement of westerlies forces a northward shift of subtropical anticyclones with their attendant zone of deep easterlies enlarging the area favorable for tropical cyclone formation. Although later studies using better data have failed to find useful seasonal relationships at the 700-mb level, possibly due to averaging over an entire season, this early use of compositing was a forerunner to more recent work in which compositing is used to elucidate important hurricane relationships on the monthly and seasonal timescales.

Additionally, Ballenzweig (1959) discussed the possible midlatitude influences on annual tropical cyclone activity as seen from his composite charts. He noted that weaker-than-normal westerlies in the Atlantic south of about 45°N are probably symptomatic of occasional northward penetration of the easterlies. When coupled with strengthened westerlies to the north, the result is a strong north–south shear of the horizontal wind in middle latitudes. More active westerlies support the equatorward penetration of midlatitude frontal systems. Low-level vorticity associated with such fronts often provides the necessary organization for initiation and development of tropical cyclones, particularly in an environment of deep easterlies (Riehl and Burgner 1950).

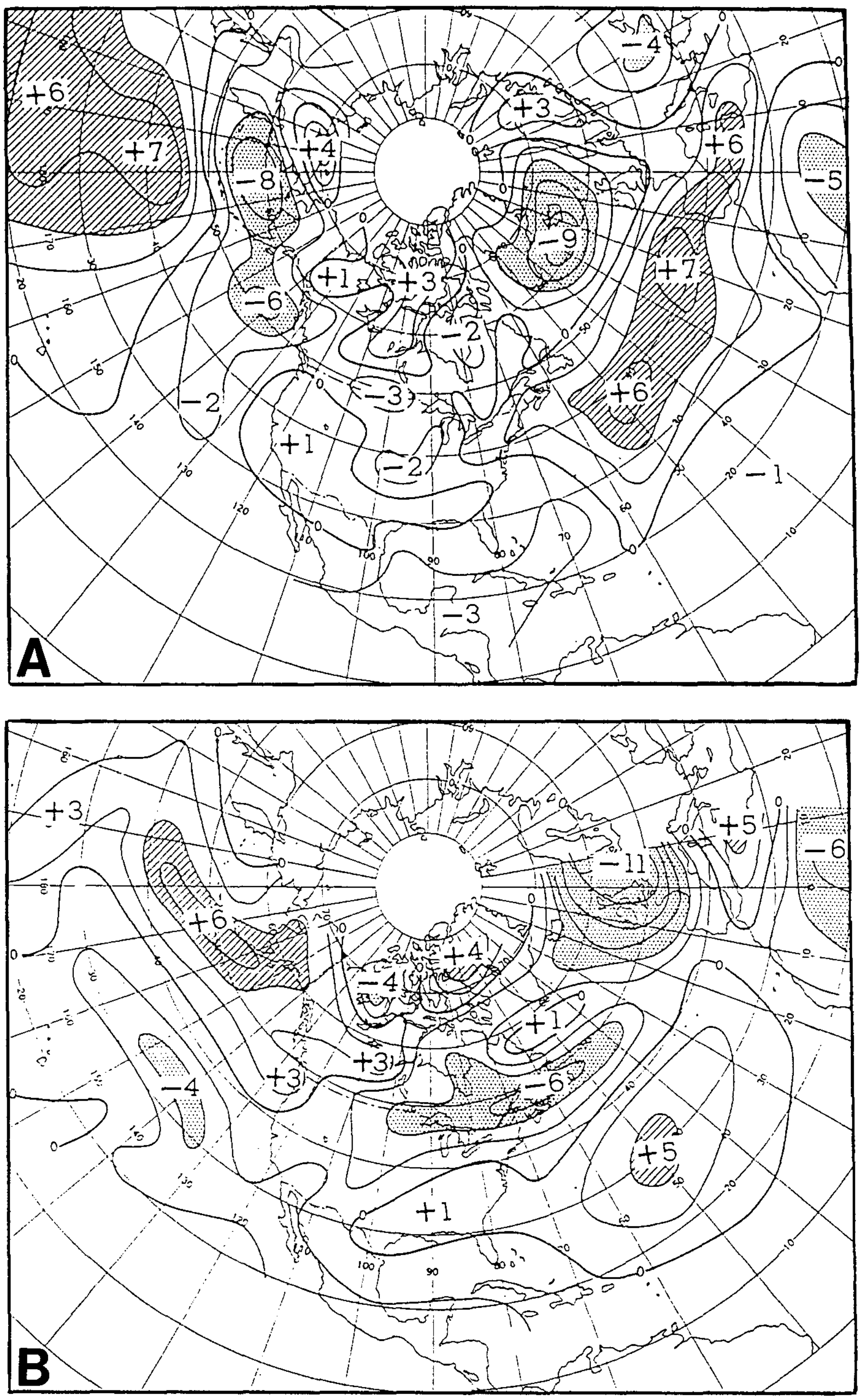

Fig. 2. Composite charts of the average departures from normal of the 700-hPa height (in tens of feet) for (a) the five seasons (August through October) of maximum tropical cyclone incidence and (b) the five seasons of minimum tropical cyclone incidence in the North Atlantic. Reproduced from Ballenzweig (1959).

4. Satellite imagery and climatology of easterly waves

As noted above, tropical cyclone formation from easterly waves was an idea that had been accepted for many years, but with the advent of the satellite imagery it was possible for the first time to see precisely where and how formation of these waves occurred. One of the first problems encountered was the large amount of benign convective activity seen in the tropical imagery. Guidelines were quickly set for determining which tropical disturbances warranted constant satellite monitoring and which could be ignored. Indeed, from the satellite perspective it was considerably easier to develop an accurate climatology of easterly waves. As an example, for the 25-yr period 1967–91 there was an average of 59 easterly waves per year (Avila and Pasch 1992). Satellite imagery further revealed that much of this easterly wave activity originated over West Africa.

It was also learned that nearly half the waves leaving the African coast dissipate before they make it east of the Lesser Antilles. A few reasons are discussed by Simpson et al. (1969), centering on the greater likelihood of midlatitude westerlies intruding into the Caribbean and reducing the depth of the easterlies over this region. Further, early hurricane studies from satellite imagery showed no strong relationship between the number of African waves per year and the number of hurricanes that form during the hurricane season.

With the aid of satellite imagery it became possible to more easily distinguish tropical cyclogenesis as a result of tropical disturbances, such as easterly waves from cyclogenesis resulting from baroclinic disturbances. Using satellite data, Frank (1970) noted that newly formed tropical cyclones that have latent heat as their primary energy source often result from tropical-type depressions such as disturbances along the ITCZ or easterly waves, whereas young tropical cyclones driven only partially by latent heat are most likely a result of baroclinic disturbances such as old frontal systems or cutoff upper-level lows. In fact, around 64% of all hurricanes in a season on average can be traced to an African easterly wave (Avila and Pasch 1992). Further, Avila (1991) pointed out that virtually all eastern North Pacific tropical cyclogenesis can be traced to an easterly wave having traversed Central America. Further, the importance of easterly waves as precursors to tropical cyclogenesis is unique to the North Atlantic and the eastern North Pacific.

Although the exact relationship remains uncertain, it is speculated that both the QBO and El Niño events are related to yearly Atlantic hurricane numbers through vertical shear of the horizontal winds in the tropical cyclogenesis regions of the Atlantic.

5. Recent ideas

With larger datasets and increased availability of computers many of the aforementioned physical associations with yearly hurricane and tropical storm activity discovered earlier in the century were subjected to rigorous statistical testing. Several new relationships were also discovered. For example, Shapiro (1982) demonstrated statistically significant relationships between Atlantic hurricane frequency and both SSTs and SLPs over portions of the Atlantic basin. More recently, however, using better data, Raper (1993) suggested that these correlations with SSTs are somewhat weak and inhomogeneous despite the well-known fact that warm SSTs are a necessary ingredient for tropical cyclogenesis. With regard to SLPs it is noted that although they are marginally useful for seasonal predictions (Shapiro 1982), a physical basis as to why this is the case requires further study. Additionally, Gray (1984a) uncovered significant relationships with parameters associated with the quasi-biennial oscillation (QBO) as well as with positive SST anomalies in the eastern and central Pacific Ocean connected to El Niño events. Shapiro (1989) also suggested a statistically significant relationship between the QBO and Atlantic tropical cyclone activity with the 30-mb zonal wind leading storm activity by as much as three months.

The QBO represents an oscillation of stratospheric zonal winds with a period of approximately 26 months. The largest amplitude of the oscillation is found in the Tropics, where the winds fluctuate between strong easterlies and weak easterlies (or even weak westerlies). El Niño events refer to the aperiodic warming of ocean waters over the equatorial eastern and central Pacific. Such warmings occur roughly every three to seven years, changing the pattern of deep convection over this region and affecting global weather patterns including the upper-level tropical wind field (Arkin 1982). In fact, Shapiro (1987) showed that intraseasonal variability of tropical winds (combined upper and lower level) over the Atlantic basin are strongly correlated with the El Niño and can be used as indicators of Atlantic tropical storm frequency both contemporaneously and with a few month's lead. The relationship between Atlantic tropical cyclone formation and El Niño events is further substantiated using a low-resolution general circulation model (Wu and Lau 1992). Although the exact relationship remains uncertain, it is speculated that both the QBO and El Niño events are related to yearly Atlantic hurricane numbers through vertical shear of the horizontal winds in the tropical cyclogenesis regions of the Atlantic. For example, it appears that when the QBO is in its westerly (anomaly) phase vertical shear of horizontal winds is reduced and tropical cyclogenesis is less inhibited.

The influence of upper-level midlatitude troughs on tropical cyclogenesis beginning with Miller (1958), Colo and Nightingale (1963), Fett (1966), Erickson (1967), Yanai (1968), and Ramage (1974) continues to be an active area of research. Sadler (1978), studying tropical cyclones in the western Pacific, noted that a major factor controlling the rarity of tropical cyclogenesis is the random coincidence of surface depressions and favorable upper-tropospheric, large-scale outflow of heat and mass. Studying the case of Hurricane Elena in the Atlantic, Molinaro and Vollaro (1989) noted a rapid intensification of the storm simultaneous with the passing of a middle-latitude trough to the north. Current thinking as to upper-level causal mechanisms for tropical cyclogenesis centers on eddy flux convergence of angular momentum from the storm environment (Pfeffer and Challa 1992; DeMaria et al. 1993). Knowledge of such contemporaneous relationships is of limited use in forecasting seasonal numbers; however, such information can guide the search for lagged (predictive) associations.

Although it was known since at least the time of Dunn (1940) that easterly waves moving off the coast of West Africa are responsible for at least a portion of the yearly Atlantic hurricane variability, no direct connection between West African rainfall and seasonal hurricane activity was made until Gray (1990). Gray (1990) noted that the annual frequency of the strongest Atlantic hurricanes was greater during the period 1947–69, when rainfall in the western Sahel was plentiful, and during the period 1970–87, when drought conditions prevailed and the number of strong hurricanes was considerably less. He suggested that these interdecadal changes are linked to long-period changes in global-scale oceanic thermohaline processes. Warm SST anomalies in the North Atlantic driven by a combination of a warm Gulf Stream and a cold, salty subsidence current at high latitudes can, on the timescale of a decade or so, reverse and become cold anomalies as fresh (less dense) water from melting ice inhibits the high-latitude oceanic subsidence (Street-Perrott and Perrott 1990). Cold North Atlantic SST anomalies are associated with an equatorward displacement of the monsoon trough, resulting in drought conditions over the Sahel. Dry conditions in the Sahel tend to increase the north-to-south thermal gradient in the lower troposphere that intensifies the midlevel (3 to 4 km) easterly jet over West Africa. A stronger jet more quickly advances the prehurricane cloud clusters, diminishing their chances for sustained organization (Gray 1990). Landsea and Gray (1992), using a detrended analysis, showed that the association between western Sahel rainfall and Atlantic hurricane frequency is strong even on the annual timescale.

6. Development of statistical prediction models

With contemporaneous correlations well established researchers began focusing on statistically significant lagged relations with hurricane activity and the potential for predictions. Gray and colleagues led the way in this effort. In Gray (1984b) the first prediction model was developed for the purpose of forecasting seasonal Atlantic hurricane activity. The forecast model was based on three predictors, including phase of the stratospheric QBO, occurrence and strength of El Niño, and mean SLP anomalies over the Caribbean Basin. Model development was based on a 33-yr data sample from 1950–82. Models developed included seasonal numbers of 1) hurricanes, 2) tropical storms plus hurricanes, and 3) hurricane days. The models were rule-based formulas whereby the average number over the dataset was specified as a constant and correction factors (adjustment terms) were added or subtracted depending on whether the magnitude and/or sign of the independent variable was favorable or unfavorable for tropical cyclone development. For example, the number of hurricanes and tropical storms expected in a particular year was expressed as

$$\text{\# of hurricanes and tropical storms} = \text{avg season} + \text{QBO} + \text{EN} + \text{SLPA}, \quad (1)$$

where QBO is the 30-mb equatorial wind direction correction factor [if westerly, add 1.5; if easterly, subtract 1.5 and set to zero if zonal wind direction is in changeover phase from east to west (or vice versa) anomaly during the season], EN is the El Niño influence (if present, subtract 2 for a moderate event, 4 for a strong event; otherwise add 0.7), and SLPA is the average sea level pressure anomaly from stations over the Caribbean Basin (add 1 or 2 if SLPA is < -0.4 mb or < -0.8 mb, respectively; subtract 1 or 2 if SLPA is between $+0.4$ and $+0.8$ mb or $> +0.8$ mb, respectively; make no correction for SLPA between -0.4 and $+0.4$ mb).

In-sample hindcast skill (over the 33-yr period) as measured by the correlation coefficient for the three models ranged from 0.82 for all storms (hurricanes and tropical storms) to 0.68 for hurricane days. An estimation of out-of-sample error, an error more relevant to actual forecast situations, was modest but still respectable especially when, in Gray's words, "one considers that little or no previous skill existed for this type of forecast."

Based on the work outlined in Gray (1984b), and beginning with the 1984 hurricane season, Gray et al. began making actual forecasts of Atlantic hurricane activity. The original forecast in 1984 was issued on 24 May, before the official start of hurricane season (1 June), and then updated on 30 July, just prior to the start of the most active portion of the season (1 August). Forecasts were made for four categories of activity, including numbers of hurricanes, named storms, hurricane days, and named storm days. Seasonal forecasts as defined by these four categories have been issued by Gray et al. every year following. In 1987 a fifth category, described as hurricane destruction potential and defined as the square of a hurricane's maximum wind speed for each 6-h period of existence, was added as an additional dependent variable to the suite of forecasts. An objective summary of these early forecasts and their verification is given in Hastenrath (1990), who commented that performance was quite remarkable.

More recently additional modifications and extensions have changed the original forecast procedure. For example, following the evaluation of the influence of West African rainfall on Atlantic hurricane activity, the forecast procedure was modified to include the categories of intense hurricanes and intense hurricane days. Intense or major hurricanes are storms reaching at least three on the Saffir–Simpson hurricane scale (Simpson 1974). It was Frank and Clark (1977) who first noted that the majority of tropical Atlantic weather disturbances that develop into intense hurricanes originate from West Africa. Since these disturbances remain over warm tropical waters for a lengthy period of time compared with disturbances having origins farther west, they have more time to develop into intense hurricanes. Further, since the strength and organization of these West African disturbances are intimately linked to seasonal rainfall conditions over the western Sahel, with July rainfall as a good indicator of August and September precipitation (Bunting et al. 1975), improvements in forecasting seasonal hurricane activity became possible. Figure 3 is reproduced from Gray (1990) and shows tracks of the strongest hurricanes over the period 1947–89 divided into the ten wettest and ten driest years in the western Sahel.

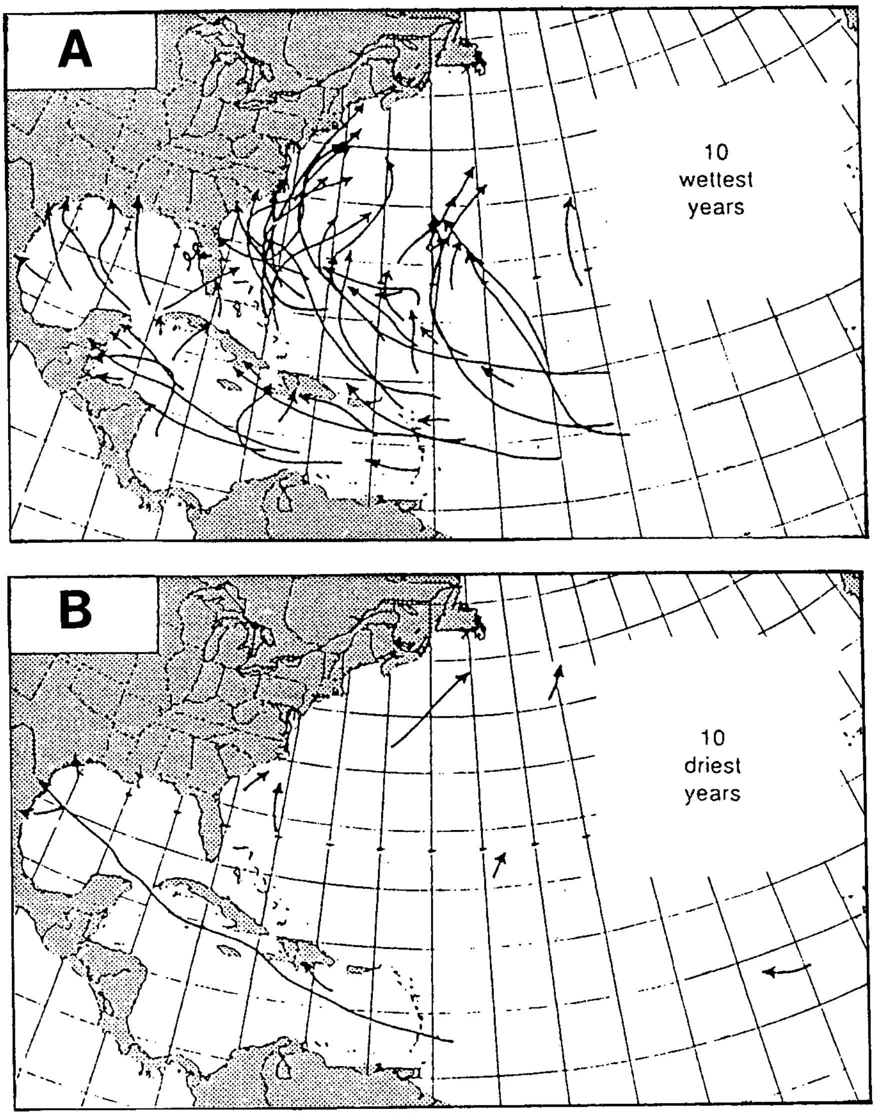

FIG. 3. Comparison of intense hurricanes tracks over the period 1947 through 1989 for (a) the ten wettest years versus (b) the ten driest years over the western Sahel. Reproduced from Gray (1990).

Additionally, it became possible to make longer-lead (up to 11 months) forecasts based on this relationship since West African rainfall during the hurricane season appears to be related to the strength of the West African monsoon (as indicated by rainfall in the Gulf of Guinea) in the previous year (Landsea and Gray 1992). Further, following the work in Gray et al. (1992), the rule-based prediction algorithms were changed to multiple linear regression models. Using the method of least absolute deviation (LAD) regression, forecast models were estimated for seven categories of hurricane activity, including annual numbers of named storms, named storm days, hurricanes, hurricane days, intense hurricanes, intense hurricane days, and hurricane destruction potential.

Currently, seasonal forecasts are made at three times during the year, by 1 December (Gray et al. 1992), by 1 June (Gray et al. 1994), and by 1 August (Gray et al. 1993). The predictors used in each of the forecast models are displayed in Table 1. In the table, RG -1 is the observed rainfall in the Gulf of Guinea from the previous year during August to November, except in the 1 December forecast, where it is the current year; RS-1 is the observed rainfall in the western Sahel from the previous year during August to September, except in the 1 December forecast, where it is the current year; RS is the observed rainfall in the western Sahel during June–July just prior to the 1

TABLE 1. Predictors currently used in Gray et al.'s various forecast models. A description of the variables is given in the text.

Predictors	Forecast made by 1 December	1 June	1 August
RG-1	*	*	*
RS-1	*	*	
RS			*
ΔP		*	
ΔT		*	
U50	*	*	*
U30	*	*	*
IU50–U30I	*	*	*
ZWA		*	*
SLPA		*	*
SSTA		*	*
ΔSSTA		*	
SOI		*	*
ΔSOI		*	

August forecast; ΔP and ΔT are West African February to May surface pressure and temperature gradients, respectively; U50 and U30 are extrapolated values of the QBO of the zonal wind for the coming September at 30 and 50 mb; IU50–U30I is the magnitude of the vertical wind shear between these two levels in September near 10°N; SLPA is June–July anomalies of sea level pressures at selected stations in the Caribbean Basin; ZWA is June–July anomalies of the zonal wind at 200 mb over selected stations in the Caribbean Basin; SOI and SSTA are El Niño predictors, where the SOI is the value of the Southern Oscillation index for June–July, and SSTA is sea surface temperature anomalies for the central Pacific Ocean during June–July for the 1 August forecast and during April–May for the 1 June forecast; and ΔSSTA and ΔSOI are the change in the SSTA and SOI predictors from January–February to April–May. Data for RG, RS, and SOI used in model development are expressed in terms of standardized deviations, while data for SLPA, ZWA, and SSTA are departures from the long-term (1950 through 1990) means. Although model coefficients are different for each category of tropical cyclone activity the type of model (i.e., LAD regression) is the same for all categories and at all forecast periods. Elsner and Schmertmann (1993) recently showed that a nonlinear Poisson model is significantly better for long-lead predictions of intense hurricanes. Intense (or major) hurricanes account for more than 70% of all destruction caused by tropical cyclones in the United States (Landsea 1993). Table 2 lists Gray's forecasts of hurricanes and hurricane days since 1984 along with the verification and performance numbers. Forecast performance as indicated by the mean absolute error (MAE) over the ten years (1984–93) is respectable, although the improvement over climatology is only marginal.

7. Recent improvements in prediction models

Current skill in forecasting seasonal tropical cyclone activity is derived from predictors having a direct relationship with the large-scale tropical environment. This is to be expected since a significant percentage of Atlantic hurricane events have antecedents entirely from synoptic-scale easterly waves in the Tropics. However, as mentioned previously, it is well known

TABLE 2. Gray et al.'s predictions and verifications of seasonal Atlantic tropical cyclone activity [number of hurricanes (HUR) and number of hurricane days (HD)] for the years 1984–93. The average number of hurricanes per year is 5.8, and the average number of hurricane days per year is 23.3. Climatology forecasts over the same period result in an MAE of 1.6 hurricanes and an MAE of 8.8 hurricane days.

	Forecasts						Observed	
	1 Dec		1 June		1 Aug			
Year	HUR	HD	HUR	HD	HUR	HD	HUR	HD
1984			7	30	7	30	5	18
1985			8	35	7	30	7	21
1986			4	15	4	10	4	10
1987			5	20	4	15	3	5
1988			7	30	7	30	5	24
1989			4	15	4	15	7	32
1990			7	30	6	25	8	27
1991			4	15	3	10	4	8
1992	4	15	4	15	4	15	4	16
1993	6	25	7	25	6	25	4	10
MAE_{Gray}	1.0	8.0	1.4	9.5	1.3	7.4		

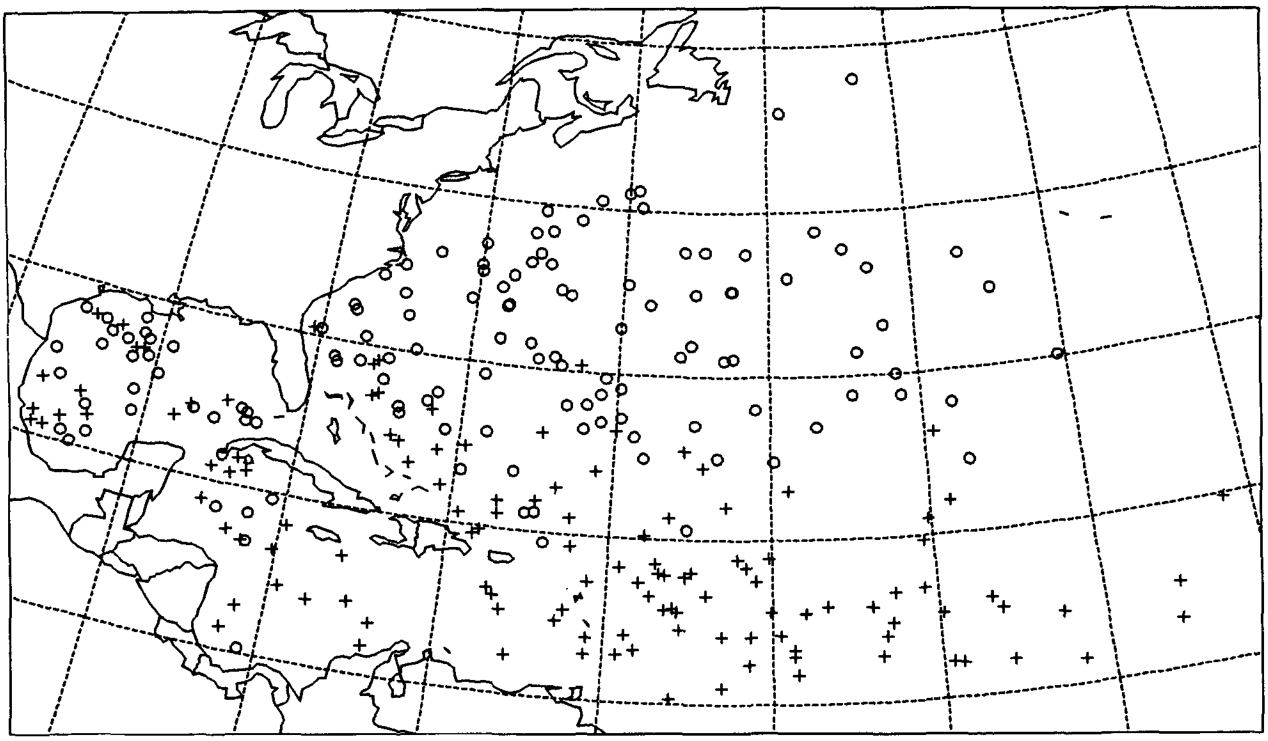

FIG. 4. Plots of the location at which each of the 255 tropical storms over the period 1950–93 reached hurricane strength for baroclinically influenced (o) and tropical-only (+) hurricanes.

that hurricanes can form from other sources such as cutoff lows in the westerlies or frontal intrusions. Additionally, relatively benign easterly waves can develop rapidly into hurricanes as a result of interactions with baroclinic waves. In fact, Gray (1968) found that tropical cyclone development in portions of the Atlantic basin poleward of 20°N latitude often takes place under significantly different environmental conditions. It thus seems natural to consider whether or not currently used predictors are useful in forecasting this component of seasonal tropical cyclone activity.

Recently, Hess and Elsner (1994) and J. C. Hess, J. B. Elsner, and N. E. LaSeur (1994, unpublished manuscript) have addressed this issue by reducing the Atlantic hurricane dataset over the period 1950–93 to include only those hurricanes having formed exclusively from tropical influences. Screening of storms was done by consulting seasonal summaries published in *Monthly Weather Review* and historical daily synoptic charts. Locations of hurricane formation (where the tropical storm initially reached hurricane strength) for the two groups of baroclinically influenced and tropical-only storms are depicted in Fig. 4. As expected, the 20°N line of latitude offers a reasonable first guess at dividing the two groups, particularly over the eastern Atlantic. However, the simple division is markedly flawed over the Caribbean and Gulf of Mexico, where latitudinal independence of hurricane type is observed. The latitudinal dependence holds nicely over the open waters of the Atlantic but disappears in regions closer to the continents.

A relative comparison of the value of Gulf of Guinea rainfall as a predictor for all hurricanes versus hurricanes formed solely from tropical influences is shown in Fig. 5. Hurricane tracks are plotted for the ten wettest (top panels) versus ten driest (bottom panels) for both tropical-only (right panels) and all (left panels) hurricanes. Total number of tracks are shown in the upper corner of each panel. Clearly, Gulf of Guinea rainfall is a better indicator of tropical-only hurricanes than of all hurricanes. Indeed, when the five predictors used previously to forecast seasonal numbers of hurricanes 6 to 11 months in advance are used to forecast tropical-only numbers at this same lead time, the cross-validated (out of sample) correlation coefficient increases from 0.58 to 0.82. Increases in hindcast skill are noted for all forecast ranges and for all categories of hurricane activity (J. C. Hess, J. B. Elsner, and N. E. LaSeur 1994, unpublished manuscript) and are above what would be expected from arbitrary reductions of seasonal numbers (Hess and Elsner 1994).

The improvement in predictive skill is consistent with Goldenberg and Shapiro (1993), who found evidence that during El Niño years and years of drought over the Sahel there is actually less vertical wind shear

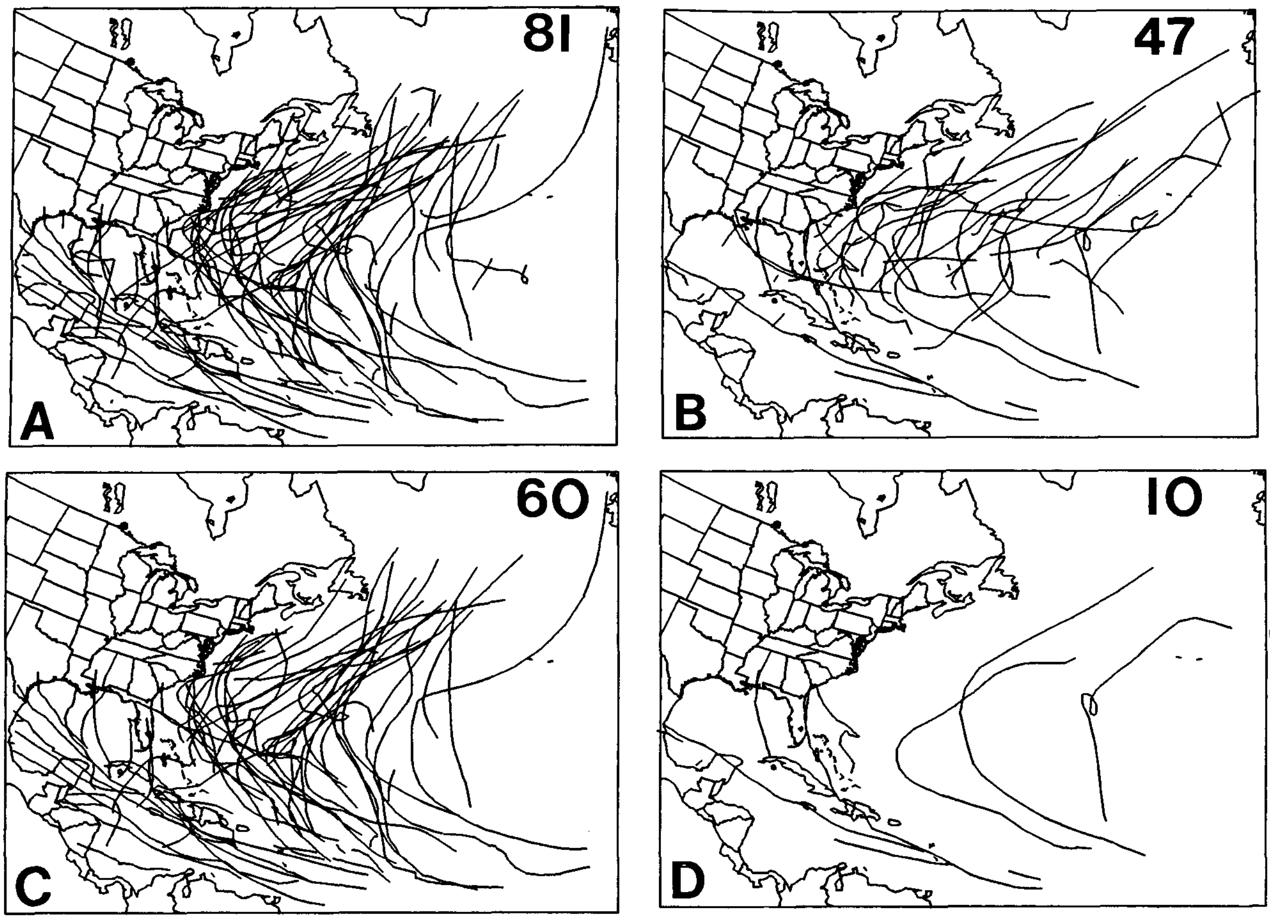

FIG. 5. Comparison of hurricane tracks for the wet versus the dry years based on Gulf of Guinea rainfall over the period 1950–93. (a) Ten wettest years and all hurricanes; (b) ten driest years and all hurricanes; (c) ten wettest years and tropical-only hurricanes; (d) ten driest years and tropical-only hurricanes. Number of hurricanes for each category is shown in the upper-left corner of each panel.

(and perhaps more tropical cyclogenesis) in regions poleward of 25°N latitude, in contrast to more shear (and less cyclogenesis) equatorward of 20°N. These recent results strongly suggest that important future advances can be made in the study of seasonal hurricane variability over the Atlantic basin by considering differences in storm origin and intensification mechanisms.

In this paper we have tried to present a coherent historical summary of important research leading to current algorithms for forecasting seasonal numbers of Atlantic basin hurricanes. In doing so we have come across an area of possible future research that might lead to improvements of forecast models. Concerning the practical utility of such forecasts we mention that since a tremendous amount of money and effort is necessary for proper hurricane preparedness, even modest forecast accuracy can lead to substantial savings. Having said this, however, we caution that to date we know of no work that has demonstrated skill at forecasting U.S. landfalling hurricanes.

Acknowledgments. Thanks are extended to N. LaSeur for his patience and guidance and to several anonymous reviewers for their extremely thorough and thoughtful critiques. Partial support for this research came from NOAA through the Cooperative Institute for Tropical Meteorology (CITM).

References

Arkin, P. A., 1982: The relationship between interannual variability in the 200-mb tropical wind field and the Southern Oscillation. *Mon. Wea. Rev.,* **110,** 1393–1404.

Avila, L. A., 1991: Atlantic tropical systems of 1990. *Mon. Wea. Rev.,* **119,** 2027–2033.

——, and R. Pasch, 1992: Atlantic tropical systems of 1991. *Mon. Wea. Rev.,* **120,** 2688–2696.

Ballenzweig, E. M., 1959: The relation of long period circulation anomalies to tropical storm formation and motion. *J. Meteor.,* **16,** 121–139.

Brennan, J. F., 1935: Relation of May–June weather conditions in Jamaica to the Caribbean tropical disturbances of the following season. *Mon. Wea. Rev.,* **63,** 13–14.

Bunting, A. H., M. D. Dennett, J. Elston, and J. R. Milford, 1975: Seasonal rainfall forecasting in West Africa. *Nature,* **253,** 622–623.

Colon, J. A., and W. R. Nightingale, 1963: Development of tropical cyclones in relation to circulation patterns at the 200-millibar level. *Mon. Wea. Rev.,* **91,** 329–336.

DeMaria, M., J. Baik, and J. Kaplan, 1993: Upper-level eddy angular momentum fluxes and tropical cyclone intensity change. *J. Atmos. Sci.,* **50,** 1133–1147.

Dunn, G. E., 1940: Cyclogenesis in the tropical Atlantic. *Bull. Amer. Meteor. Soc.,* **21,** 215–229.

——, 1956: Areas of hurricane development. *Mon. Wea. Rev.,* **84,** 47–51.

——, and B. I. Miller, 1960: *Atlantic Hurricanes.* Louisiana State University Press, 377 pp.

Elsner, J. B., and C. P. Schmertmann, 1993: Improving extended-range seasonal predictions of intense Atlantic hurricane activity. *Wea. Forecasting,* **8,** 345–351.

Erickson, C. O., 1967: Some aspects of the development of Hurricane Dorothy. *Mon. Wea. Rev.,* **95,** 121–130.

Fett, R. W., 1966: Upper-level structure of the formative tropical cyclone. *Mon. Wea. Rev.,* **94,** 9–18.

Frank, N. L., 1970: Atlantic tropical systems of 1969. *Mon. Wea. Rev.,* **98,** 307–314.

——, and G. B. Clark, 1977: Atlantic tropical systems of 1976. *Mon. Wea. Rev.,* **105,** 676–683.

Garriott, E. B., 1895: Tropical storms of the Gulf of Mexico and the Atlantic Ocean in September. *Mon. Wea. Rev.,* **23,** 167–169.

——, 1906: The West Indian hurricanes of September 1906. *Mon. Wea. Rev.,* **34,** 416–417.

Goldenberg, S. B., and L. J. Shapiro, 1993: Relationships between tropical climate and interannual variability of North Atlantic tropical cyclones. Preprints, *20th Conf. on Hurricanes and Tropical Meteorology,* San Antonio, Amer. Meteor. Soc., 102–105.

Gray, W. M., 1968: Global view of the origins of tropical disturbances and storms. *Mon. Wea. Rev.,* **96,** 669–700.

——, 1984a: Atlantic seasonal hurricane frequency. Part I: El Niño and 30 mb quasi-biennial oscillation influences. *Mon. Wea. Rev.,* **112,** 1649–1668.

——, 1984b: Atlantic seasonal hurricane frequency. Part II: Forecasting its variability. *Mon. Wea. Rev.,* **112,** 1669–1683.

——, 1990: Strong association between West African rainfall and U.S. landfall of intense hurricanes. *Science,* **249,** 1251–1256.

——, C. W. Landsea, P. W. Mielke Jr., and K. J. Berry, 1992: Predicting Atlantic seasonal hurricane activity 6–11 months in advance. *Wea. Forecasting,* **7,** 440–455.

——, ——, ——, and ——, 1993: Predicting Atlantic basin seasonal tropical cyclone activity by 1 August. *Wea. Forecasting,* **8,** 73–86.

——, ——, ——, and ——, 1994: Predicting Atlantic basin seasonal tropical cyclone activity by 1 June. *Wea. Forecasting,* **9,** 103–115.

Hastenrath, S., 1990: Tropical climate prediction: A progress report, 1985–1990. *Bull. Amer. Meteor. Soc.,* **71,** 819–825.

Hess, J. C., and J. B. Elsner, 1994: Extended-range seasonal hindcasts of easterly-wave origin Atlantic hurricane activity. *Geophys. Res. Lett.,* **21,** 365–368.

Landsea, C. W., 1993: A climatology of intense (or major) Atlantic hurricanes. *Mon. Wea. Rev.,* **121,** 1703–1713.

——, and W. M. Gray, 1992: The strong association between western Sahel monsoon rainfall and intense Atlantic hurricanes. *J. Climate,* **5,** 435–453.

Miller, B. I., 1958: On the maximum intensity of hurricanes. *J. Meteor.,* **15,** 184–195.

Molinaro, J., and D. Vollaro, 1989: External influences on hurricane intensity. Part I: Outflow layer eddy angular momentum fluxes. *J. Atmos. Sci.,* **46,** 1093–1105.

Namias, J., 1955: Secular fluctuations in vulnerability to tropical cyclones in and off New England. *Mon. Wea. Rev.,* **83,** 155–162.

——, and G. E. Dunn, 1955: The weather and circulation of August 1955. *Mon. Wea. Rev.,* **83,** 163–170.

Pfeffer, R., and M. Challa, 1992: The role of environmental asymmetries in Atlantic hurricane formation. *J. Atmos. Sci.,* **49,** 1051–1059.

Ramage, C. S., 1974: The typhoons of October 1970 in the South China Sea: Intensification, decay, and ocean interaction. *J. Appl. Meteor.,* **13,** 739–751.

Raper, S. C. B., 1993: Observational data on the relationship between climatic change and the frequency and magnitude of severe tropical storms. *Climate and Sea Level Change: Observations, Projections and Implications,* R. A. Warrick, E. M. Barrow, and T. M. L. Wigley, Eds., Cambridge University Press, 192–212.

Ray, C. L., 1935: Relation of tropical cyclone frequency to summer pressures and ocean surface water temperatures. *Mon. Wea. Rev.,* **63,** 10–12.

Riehl, H., 1956: Sea surface temperatures anomalies and hurricanes. *Bull. Amer. Meteor. Soc.,* **37,** 413–417.

——, and R. J. Shafer, 1944: The recurvature of tropical storms. *J. Meteor.,* **1,** 42–54.

——, and N. M. Burgner, 1950: Further studies of the movement and formation of hurricanes and their forecasting. *Bull. Amer. Meteor. Soc.,* **31,** 244–253.

Sadler, J. C., 1978: Mid-season typhoon development and intensity changes and the tropical upper tropospheric trough. *Mon. Wea. Rev.,* **106,** 1137–1152.

Shapiro, L. J., 1982: Hurricane climate fluctuations. Part II: Relation to large-scale circulation. *Mon. Wea. Rev.,* **110,** 1014–1023.

——, 1987: Month-to-month variability of the Atlantic tropical circulation and its relationship to tropical storm formation. *Mon. Wea. Rev.,* **115,** 2598–2614.

——, 1989: The relationship of the quasi-biennial oscillation to Atlantic tropical storm activity. *Mon. Wea. Rev.,* **117,** 1545–1552.

Simpson, R. H., 1974: The hurricane disaster potential scale. *Weatherwise,* **27,** 169, 186.

——, N. Frank, D. Shideler, and H. Mo. M. Johnson, 1969: Atlantic tropical disturbances of 1968. *Mon. Wea. Rev.,* **97,** 240–255.

Street-Perrott, F. A., and R. A. Perrott, 1990: Abrupt climate fluctuations in the tropics: The influence of Atlantic Ocean circulation. *Nature,* **343,** 607–612.

Wu, G., and N.-C. Lau, 1992: A GCM simulation of the relationship between tropical-storm formation and ENSO. *Mon. Wea. Rev.,* **120,** 958–977.

Yanai, M., 1968: Evolution of a tropical disturbance in the Caribbean Sea region. *J. Meteor. Soc. Japan,* **46,** 86–109.