A Climatology of Intense (or Major) Atlantic Hurricanes

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ABSTRACT

The variability of intense (or major) hurricanes in the Atlantic basin is investigated on both intraseasonal and interannual time scales. Differences are highlighted in characteristics between intense hurricanes and the weaker minor hurricanes and tropical storms. Intense hurricanes show a much more peaked annual cycle than do weaker tropical cyclones. Ninety-five percent of all intense hurricane activity occurs during August to October. In addition, over 80% of all intense hurricanes originate from African easterly waves, a much higher proportion than is observed for weaker cyclones. Of all classes of Atlantic basin tropical cyclones, the intense hurricanes display the greatest year-to-year variability. The incidence of intense hurricanes also has decreased during the last two decades. A small portion of this decreased activity appears to be due to an overestimation of hurricane intensity during the period spanning the 1940s through the 1960s. After adjusting for this bias, however, a substantial downward trend in intense hurricane activity during recent years is still apparent. Given that intense hurricanes are responsible for more than 70% of all destruction caused by tropical cyclones in the United States, an understanding is needed of the physical mechanisms for these observed variations of intense hurricane activity.

1. Introduction

Climate change due to an increase of anthropogenic "greenhouse gases" may warm tropical sea surface temperatures, although the magnitude, timing, and spatial variations of such a warming are very uncertain (IPCC 1990). One hypothesis is that increased sea surface temperatures will cause "a higher frequency and greater intensity of hurricanes" (AMS Council and UCAR Board of Trustees 1988). Gray (1989), however, has suggested that warmer sea surface temperatures do *not* necessarily mean increased hurricane activity. He stated that "scenarios can just as easily be made for reductions in hurricane activity due to greenhouse influences."

In either case, before extrapolations to future frequencies of intense hurricanes can be attempted, it is essential that there be an understanding of the current annual cycle and interannual variability of intense hurricane occurrence. Intense (or major) hurricanes (IH) are defined as those tropical cyclones with maximum sustained (1 min) surface winds of 50 m s^{-1} during some part of their lifetimes (Hebert and Taylor 1978). These are the Saffir–Simpson (Simpson 1974) category 3, 4, and 5 hurricanes (Table 1).

Previous climatologies of Atlantic basin (i.e., North Atlantic Ocean, Caribbean Sea, and Gulf of Mexico) tropical cyclones by Mitchell (1924), Cry (1965), and Neumann et al. (1987) have primarily focused on the seasonal numbers of named storms (i.e., storms with maximum sustained wind speeds of 18 m s^{-1}) and hurricanes (33 m s^{-1}). Hebert and Taylor (1978), Hebert and Case (1990), and Hebert et al. (1992) discussed IH that have affected the United States, including details of United States IH frequency and United States IH-spawned death and destruction. No work has been done, however, on basinwide IH activity for either the intra-annual or interannual time scales.

This paper partly fills this void by providing discussions of the annual cycle of IH activity, the interannual climatology of Atlantic basin IH since the mid-1940s, and the interannual variations in the origins of IH, as well as providing updates on the United States IH frequency and on the IH contribution to United States tropical cyclone–spawned damage.

2. Data

a. Data sources

Most of the datasets utilized for this study are detailed in Landsea and Gray (1992). The Atlantic basin "best track" (Jarvinen et al. 1984) dataset includes the 6-h positions, estimated maximum sustained surface winds, and any measured central pressures of tropical cyclones from 1886 to 1991. The second dataset, which includes United States landfalling hurricanes since 1899 categorized by intensity with the Saffir–Simpson scale, was first documented by Hebert and Taylor

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TABLE 1. Maximum sustained wind speed, minimum surface pressure, storm surge, and potential damaging effects for the five Saffir–Simpson hurricane scale (Simpson 1974) values.

Saffir–Simpson category	Maximum sustained wind speed (m s^{-1})	Minimum surface pressure (mb)	Storm surge (m)	Potential damaging effects
1	33 to 42	$\geqslant$980	1.0 to 1.7	Minimal
2	43 to 49	979 to 965	1.8 to 2.6	Moderate
3	50 to 58	964 to 945	2.7 to 3.8	Extensive
4	59 to 69	944 to 920	3.9 to 5.6	Extreme
5	>69	<920	>5.6	Catastrophic

(1975). Circulation features associated with the origins of all Atlantic basin tropical cyclones since 1967 were provided by Avila (personal communication). In addition, variations in dollar values for tropical cyclone–spawned damage in the United States were studied utilizing the yearly summaries appearing in the *Monthly Weather Review* from 1944 to 1991. Changes in some of the damage figures are given in Hebert and Case (1990).

b. Data descriptions and limitations

As stated previously, no climatology has adequately described basinwide IH variability. Part of this neglect may be due to a lack of confidence in analyzed tropical cyclone intensity (as measured by maximum sustained surface winds or by the lowest central pressure) until recent years. The United States Air Force and Navy began the practice of routine reconnaissance flights into the storms in 1944 (see Sumner 1944). Before then, unless a tropical cyclone went directly over a ship or a coastal station, the exact intensity of the cyclone was unknown. Of course, not every tropical cyclone in the Atlantic basin since 1944 has received aircraft monitoring every 6 h of its existence. As described by Clark (1960), however, tropical cyclones that may threaten coastal areas are kept under nearly continuous aircraft surveillance. This is still true, as was the case for 1991's Hurricane Bob (McAdie and Rappaport 1991).

There is also the question of incidence of unobserved storms during the early days of hurricane forecasting. Certainly, before 1944 a number of short-lived tropical cyclones in the eastern and central Atlantic were likely completely missed. The monitoring situation improved greatly with the advent of aircraft reconnaissance. Nonetheless, while synoptic flights were sent out regularly into the central Atlantic before reports of tropical cyclones were received, some tropical cyclones may still have gone undetected in the presatellite, postaircraft era. These, however, are likely few in number and weak in intensity.

Because of these uncertainties, Neumann et al. (1987) suggest utilizing tropical cyclone statistics since 1944 since this period probably best represents the frequencies and intensities of tropical cyclones in the Atlantic. For this reason, the Atlantic basin interannual variability study includes only best-track data after 1943, a severe limitation for analysis of daily incidence of activity because of the relative scarcity of IH in the Atlantic basin relative to the more active northwest Pacific basin. The intraseasonal statistics, however, are based upon the entire best-track dataset from 1886 to 1991. Although the data from 1886 to 1943 are incomplete because of unobserved and misclassified tropical cyclones, there is likely no systematic intraseasonal bias induced in using the longer-term record.

Reliable data are available, however, for hurricanes that have affected the United States since 1899. There are a few minor inconsistencies, though, between this dataset and the best track because of slight differences in classification methodology (see Hebert and Taylor 1975 and Jarvinen et al. 1984). These small differences do not, however, affect the conclusions in this paper.

Before continuous satellite coverage in the mid-1960s, identification of the storm formation characteristics of individual tropical cyclones is unreliable except for a few storms. Starting in 1967, the National Hurricane Center has maintained records on the type of cyclogenesis occurring for every Atlantic basin tropical cyclone (e.g., Avila 1991). While some terminology has changed since 1967, these summaries are the most complete set of information regarding the interannual variations of the origins of tropical cyclogenesis.

Statistics on tropical storm and hurricane-caused destruction in the United States were obtained from the yearly summaries. Landsea (1991) tabulated this information. Other recent studies (e.g., Sheets 1990; Hebert et al. 1992) normalize long-term damage values to current dollars using the monthly Department of Commerce implicit price deflator for construction (U.S. Department of Commerce 1991) to account for inflation.

To perform a comparative assessment of interannual variations in United States damage, however, the large increases in population along the United States coastal zones must also be considered. Sheets (1990) noted a 60% rise in the number of Atlantic coastal inhabitants, a 250% increase in coastal Texas, and an enormous 400% increase in coastal Florida between 1950 and 1985. Obviously, an adjustment only for inflation severely underestimates the potential for damage in areas where population has increased substantially.

To overcome this deficiency of comparative studies that adjust only for inflation, this paper utilizes both the implicit price deflator for construction as well as population changes for specific locations. Hurricane King, which struck Miami in 1950 and caused $28 million damage, provides a good example of the normalization procedure. Since 1950, construction costs have increased by a factor of 5.7 and population along coastal southeast Florida has increased by a factor of 6.0. This combined factor of 34.2 normalizes the damage to $957 million in 1990 dollars.

3. Intraseasonal variability

a. Entire basin characteristics

Atlantic basin tropical cyclones show a very pronounced seasonal cycle in the level of activity. Neumann et al. (1987) have provided the most recent analysis of the intraseasonal variation of named storms and hurricanes. Atlantic basin tropical cyclone activity either before 1 June or after 30 November is nearly negligible. Both named storms and hurricanes show a strong maximum in mid-September, with most cyclones occurring between 1 August and 31 October. This late summer–early fall maximum corresponds to the time of the largest areal extent of warm SSTs and low tropospheric vertical shear in the tropical Atlantic (Gray 1979). It is difficult to determine, however, whether named storms and hurricanes have the same peak in terms of percent of annual activity per day.

The annual cycle of IH occurrence in Fig. 1 illustrates the "noisy" aspect of the unfiltered data (light curve), reflecting the relatively low climatological incidence of these cyclones. Following Neumann et al. (1987), a 9-day running mean was applied to the data, as shown by the solid dark curve. With this filter, the main features of the IH annual cycle appear similar to that identified by Neumann et al. (1987) of the weaker cyclones: namely, a sharp peak of occurrence during mid-September; most activity occurring between 1 August and 31 October; and almost no events before 1 July or after 30 November. The secondary peak in IH activity in late August is likely not physically meaningful.

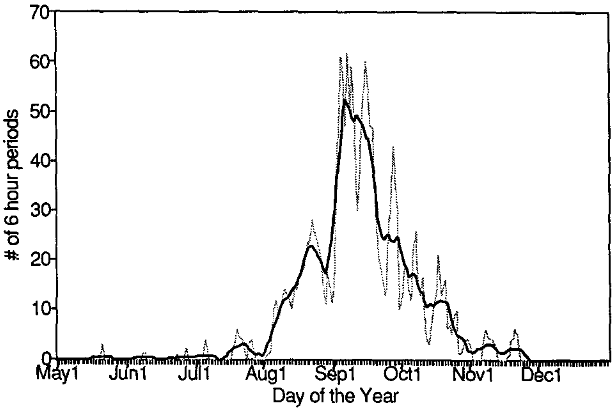

FIG. 1. Intraseasonal variation of intense hurricane (IH) activity expressed in total occurrence of 6-h periods with an active intense hurricane for each day between 1 May and 31 December during the years 1886–1991. A 9-day running mean is shown in boldface.

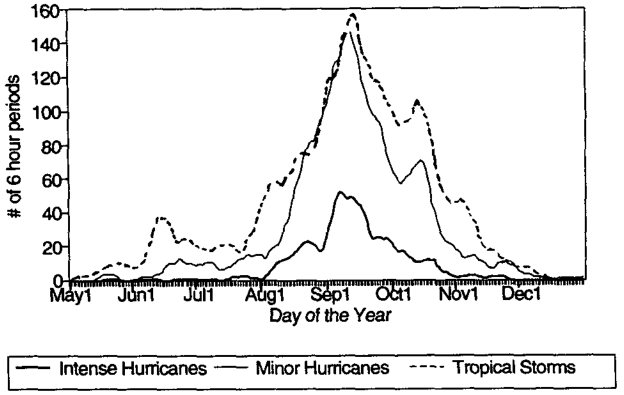

FIG. 2. Intraseasonal variation (with a 9-day running mean) of IH activity (dark curve), minor hurricanes (light curve), and tropical storms (dashed curve) expressed in total number of 6-h occurrences for each day.

Figure 2 gives a more quantitative comparison of the annual cycles for various categories of tropical cyclones. This figure shows the daily incidence of tropical storms (maximum sustained wind speed greater than 17 m s^{-1} but less than 33 m s^{-1}), minor hurricanes (Saffir–Simpson categories 1 and 2), and IH. The total incidence of IH is much less than that of minor hurricanes and tropical storms.

Although this figure indicates that the three categories peak at about the same time, it does not assess the relative strengths of the three maxima. Normalization by percent of annual activity per day accentuates differences in activity among the three groups, as shown in Fig. 3. Intense hurricanes have a much sharper peak during the height of the season. During mid-September, IH experience a maximum of 2.5% of their total annual

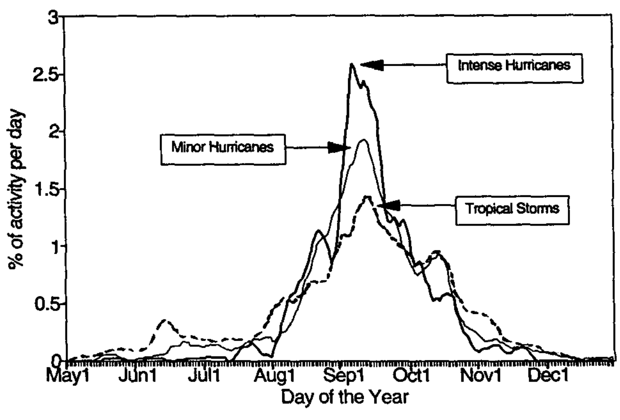

FIG. 3. As in Fig. 2 but normalized as percent of total annual activity per day.

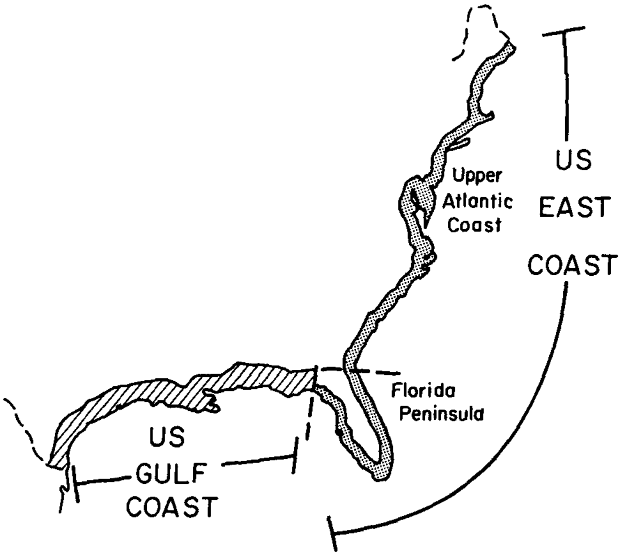

FIG. 4. The two regions of the United States coast that experience differing characteristics of IH activity: the Gulf Coast and the East Coast. The East Coast can further be stratified into the upper Atlantic coast and the Florida Peninsula (from Landsea et al. 1992).

activity per day, as compared to 1.9% for minor hurricanes and 1.4% for tropical storms. During 1–20 September, the average annual occurrence of IH, minor hurricanes, and tropical storms is 43%, 34%, and 25%, respectively. The rankings are reversed for the early and late portions of the hurricane season. In particular, on or before 31 July, the historical mean activity is 13% for tropical storms, 7% for the minor hurricanes, and only 2% for IH. Comparing the variances of the IH with the tropical storm activity shows that the two distributions are significantly different (at the 0.05 level) using a two-tailed *F*-distribution test (Mendenhall 1979).

The small range of dates during which IH form is likely indicative of the limited duration of favorable environmental conditions available for deep intensification of Atlantic basin tropical cyclones into IH. The more marginal conditions for tropical cyclogenesis (Gray 1979), which occur in this basin from late May to late July and from early November to early December, allow only the occasional tropical storm and infrequent minor hurricane.

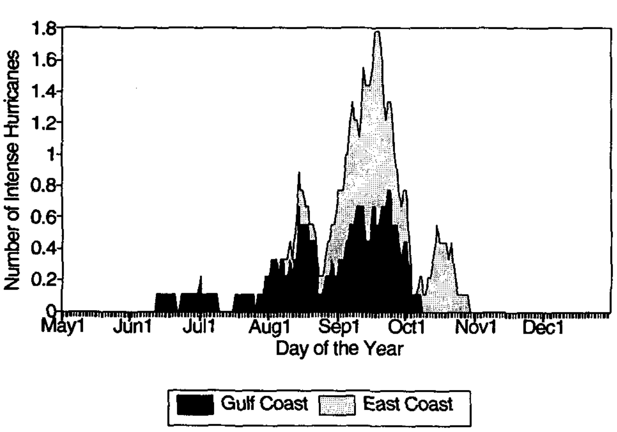

FIG. 5. Intraseasonal variation of United States IH activity for the Gulf Coast (dark shading) and East Coast (light shading) expressed in total number of IH strikes during the 93-yr period of 1899–1991.

TABLE 2. Variations in the dates of landfall of United States landfalling IH along the East Coast and Gulf Coast between 1899 and 1991.

Region	First date of landfall	Median date of landfall	Last date of landfall
East Coast	12 Aug	24 Sept	25 Oct
Gulf Coast	16 Jun	5 Sept	4 Oct

b. Spatial characteristics and United States landfalling cyclones

For climatological studies of IH that strike the United States, it is instructive to stratify the coastline into two regions. As shown in Fig. 4 (Landsea et al. 1992), these two areas are the Gulf Coast, from Texas to the Florida panhandle, and the East Coast, from the Florida Peninsula up to Maine. The entire peninsula of Florida has been included in the East Coast category because cyclones that struck the peninsula were more characteristic, both intraseasonally and interseasonally, of the remainder of the East Coast than the Gulf Coast.

Figure 5 shows that the two geographical regions delineated in Fig. 4 are susceptible to IH strikes at differing times of the year. While the timing of the overall activity is similar to that shown for IH in the entire Atlantic basin in Fig. 1, the Gulf Coast seems to experience IH somewhat earlier in the calendar year than does the East Coast. These differences are explicitly delineated in Table 2 in terms of the first, median, and last date of occurrence.

Figure 6 portrays all IH tracks from 1944 to 1991 by individual months. The regional variations in Figs. 5 and 6 and in Table 2 are likely related to the favorable areas for genesis of tropical cyclones, as well as variations of the general circulation steering. From mid-June to July, IH are infrequent, tend to form in the Gulf of Mexico or in the western Caribbean Sea, and generally track toward the west or north. The preferred area of formation and direction of motion favor landfall along the Gulf Coast. From August to early October, intensification of cyclones into IH can occur nearly anywhere in the central and western Atlantic basin between 10° and 35°N. But by mid-October, IH form almost exclusively in the western Caribbean or the Atlantic Ocean between the Bahamas and Bermuda and typically begin taking a due north or northeast course, though occasionally moving into the East Coast.

Table 3 summarizes the intraseasonal variability by month. Note that this table suggests that, in general,

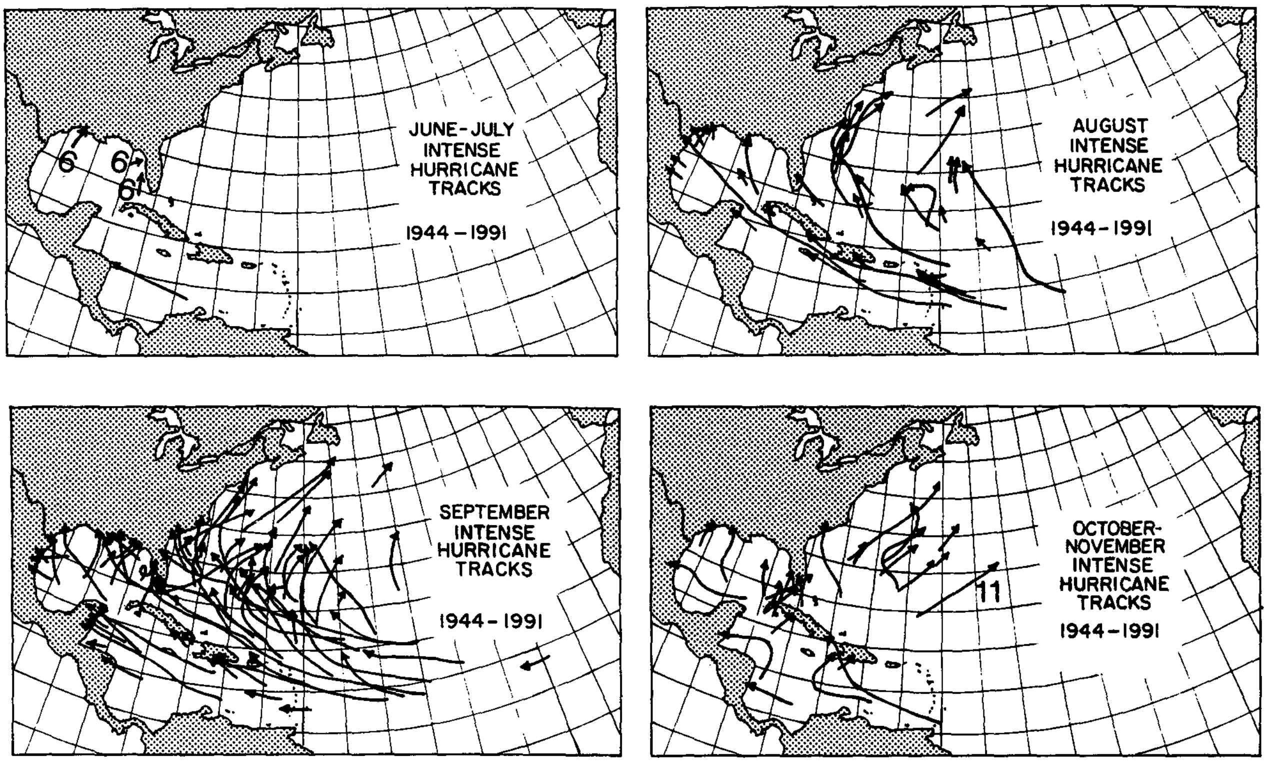

FIG. 6. Intense hurricane track climatology by monthly periods for the years 1944–91. June tracks are labeled "6" and November tracks are labeled "11" (see last panel). Tracks are shown for IH only while they were of IH strength (at least 50 m s^{-1} maximum sustained surface winds).

the amount of August activity is equivalent to that in October. This, at first glance, appears to contradict Table 4 from Neumann et al. (1987), which tabulates the average number of tropical cyclones that form each month. They found that more tropical cyclones form in August than October. Table 3, however, measures total occurrence, not formation. The different findings for occurrence and formation are reconciled in that while more tropical cyclones form in August than October, more cyclones form in late September and continue into October than form in late July and continue into August.

4. Interseasonal variability

a. *Atlantic basin cyclones*

1) ORIGINAL BEST-TRACK DATASET

Year-to-year variations of Atlantic basin IH since 1944 are depicted in Fig. 7. A large range of activity is apparent, varying from no IH occurrences in 1968, 1972, and 1986, to eight major cyclones during 1950. This large year-to-year variability is reflected in a high coefficient of variation (i.e., the ratio of the standard deviation to the mean) of 0.71, which is much larger

TABLE 3. Mean monthly occurrence (in percent of total annual) of various categories of Atlantic basin tropical cyclone activity (based on duration of individual storms; data from 1886 to 1991) and of United States IH strikes (data from 1899 to 1991).

Intensity	Percentages								
	Jan–Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tropical storms	0.1	1.7	6.6	6.2	20.0	35.5	22.9	6.3	0.8
Minor hurricanes	0.3	0.5	2.6	4.4	21.6	46.0	19.8	4.2	0.6
Intense hurricanes	0.0	0.1	0.2	1.7	21.9	57.2	16.6	2.3	0.0
Named storms	0.2	1.1	4.5	5.1	20.8	41.5	21.1	5.1	0.6
United States intense hurricanes									
East Coast	0.0	0.0	0.0	0.0	11.8	67.6	20.6	0.0	0.0
Gulf Coast	0.0	0.0	5.7	8.6	31.4	51.4	2.9	0.0	0.0

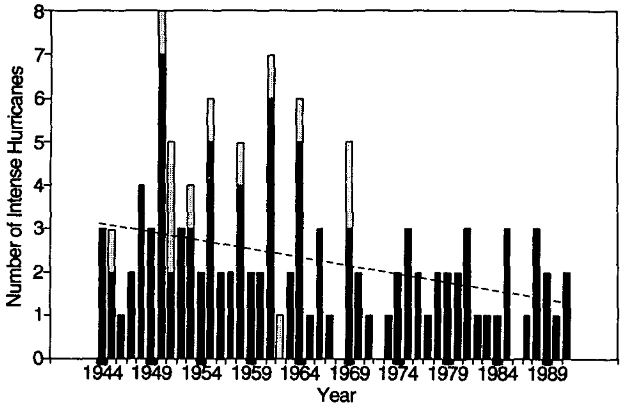

FIG. 7. Atlantic basin IH for 1944–91. The original values are represented by the combined black and gray portions of the bars, whereas the data with bias removed are represented by just the black bars. The linear trend of the bias-removed data is represented by the superimposed dashed line.

than that observed for total named storm activity (0.30). This implies that the interannual variability for IH is much greater than weaker cyclones.

As presented in Landsea and Gray (1992), intense-hurricane days (IHD) are an additional measure of the seasonal incidence of strong cyclones. One unit of IHD (see Fig. 8) represents four 6-h periods during which an IH was in existence. This type of measure is intrinsically biased to those IH that persist for several days. Historically, long-lasting IH originate as strong easterly waves over West Africa and develop in the central North Atlantic. These are termed "Cape Verde" hurricanes (Dunn and Miller 1960), of which Donna, 1960; Allen, 1980; and Hugo, 1989 are notable examples.

Figure 8 details the yearly variations of the Atlantic basin IHD. The seasonal incidence of IHD fluctuates from 0 to 24.5; the coefficient of variation is 0.93, which is even higher than that observed for IH. Both IH and IHD show a substantial decrease in activity with time. This trend may account for a portion of the high coefficients of variation observed.

2) BIAS-CORRECTED BEST-TRACK DATASET

It is possible that artificial differences of IH activity related to changes in measurement technology are responsible for the apparent trend in the seasonal numbers of IH and IHD. To test for bias between the earlier versus the later decades, the relationship between wind speed and surface pressure was examined. A simplified but useful empirical relationship between the maximum sustained wind speeds and lowest surface pressures of Atlantic basin tropical cyclones was given by Kraft (1961):

$$V_{\max} = 7(1013 - P_c)^{0.5}, \qquad (1)$$

where $V_{\max}$ is the maximum sustained wind speed ($\mathrm{m\ s^{-1}}$) and P_c is the minimum sea level pressure (mb).

The best-track dataset contains wind speeds at 6-h intervals for the lifetime of each tropical cyclone (even if an estimation was required). The dataset also includes observations of surface pressure, when available. No estimates of this were derived from the winds (Jarvinen et al. 1984). There have been no significant changes in the measurement of actual or extrapolated surface pressure in tropical cyclones. The methodologies of extrapolating aircraft reconnaissance height data to surface pressures developed in the 1940s and early 1950s (see Jordan 1958) are still being utilized. Hence, we may deduce that any changes in the wind–pressure relationship are due to alterations in the way sustained wind speeds were measured or estimated.

The best-track dataset reports the maximum sustained wind speeds in 5-kt ($2.5\ \mathrm{m\ s^{-1}}$) intervals. A finer-tuned estimate of the strength of the cyclones is not feasible with the uncertainties of the various observational platforms. Table 4 presents means and standard deviations of pressure readings stratified for the decades under consideration. For specific wind speed categories, there has been a shift to lower observed pressures, a possible indication that the decades of the 1940s to the 1960s had overestimated wind speeds as compared to later years. In addition, the higher standard deviations for the decades from the 1940s to the 1960s suggest that there was more uncertainty as to what wind speed to assign to strong hurricanes.

To better delineate this bias, Table 5 presents a combined decadal classification that contains at least ten cases per wind division. The corresponding wind speed suggested by Kraft's relationship is included next to the observed minimum pressure. As the criterion used to define IH and IHD in the best-track dataset is a threshold of 100 kt ($51\ \mathrm{m\ s^{-1}}$), it is important to understand the decadal differences (or bias) at that intensity. Hurricanes in the $51\ \mathrm{m\ s^{-1}}$ category during the years 1970–91 have a mean minimum sea level pres-

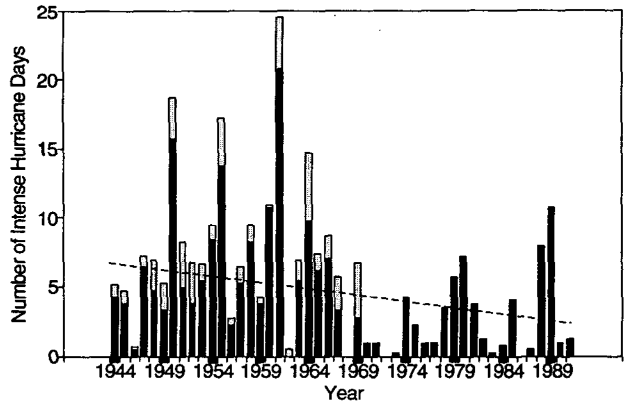

FIG. 8. As in Fig. 7 except for IHD.

TABLE 4. Decadal means and standard deviations for observed minimum pressure values of intense Atlantic basin hurricanes by 5-kt (2.5 m s^{-1}) intervals since 1944. The number of observations per decade are given in parentheses.

Wind speed		1944–49			1950–59			1960–69			1970–79			1980–89			1990–91		
(kt)	(m s^{-1})	(No.)	Mean (mb)	Std dev (mb)	(No.)	Mean (mb)	Std dev (mb)	(No.)	Mean (mb)	Std dev (mb)	(No.)	Mean (mb)	Std dev (mb)	(No.)	Mean (mb)	Std dev (mb)	(No.)	Mean (mb)	Std dev (mb)
100	51	(1)	965	—	(10)	969	21	(51)	968	10	(13)	967	8	(30)	961	9	(4)	958	4
105	54	(2)	970	7	(12)	964	13	(29)	962	13	(8)	960	3	(18)	958	6	(2)	954	2
110	57	(3)	972	7	(21)	958	15	(52)	961	12	(12)	954	9	(22)	953	6	(1)	946	—
115	59	(3)	952	8	(5)	963	23	(22)	956	14	(8)	949	5	(17)	949	7	(1)	947	—
120	62	(2)	967	1	(3)	961	8	(33)	950	11	(8)	947	8	(26)	940	8			
125	64				(13)	958	13	(17)	943	9	(5)	937	4	(12)	938	9			
130	67	(1)	954	—	(4)	941	10	(14)	939	12	(5)	937	9	(6)	934	7			
135	69	(1)	947	—	(3)	947	25	(5)	942	10				(2)	934	7			
140	72				(2)	943	5	(6)	928	15	(3)	933	7	(5)	919	14			
145	75							(1)	935	—	(4)	926	2	(4)	914	15			
150	77							(1)	935	—	(3)	925	1	(1)	940	—			
155	80													(5)	912	14			
160	82													(1)	888	—			
165	85							(1)	909	—				(1)	899	—			

sure of 962 mb, almost precisely the pressure required for such a storm by (1). The mean minimum sea level pressure for the 51 m s^{-1} hurricane in the 1940s to the 1960s was 968 mb, however, which corresponds to an equivalent wind speed from Kraft of only 48 m s^{-1}. Rather, it is the 54 m s^{-1} hurricanes in the 1940s to the 1960s that are associated with mean sea level pressure of 963 mb, the highest pressure allowed for IH status by Kraft's relationship. A larger bias of about 5 m s^{-1} is observed for stronger (category 4 and 5) hurricanes. Since the threshold in this study for IH categorization is at 51 m s^{-1} by the construction of the best-track data, that higher bias does not affect IH and IHD calculations.

In an attempt to remove the 2.5 m s^{-1} bias at the IH threshold, the criterion for IH status was increased to 54 m s^{-1} for the years 1944–69. This effectively reduces the numbers of IH by at most three storms and the numbers of IHD by at most five days in this earlier period. The resulting time series of IH and IHD are depicted in Figs. 7 and 8. Table 6 gives the means and standard deviations of the IH activity for the original and adjusted data. Note that the removal of this bias reduces the IH coefficient of variation down to 0.66, still much larger than that observed for named storms.

TABLE 5. Means of observed minimum pressure values for intense Atlantic basin hurricanes by 2.5 m s^{-1} wind speed intervals for two multidecadal groupings. The number of cases and the Kraft-derived wind speed corresponding to the mean minimum pressure values are also provided.

Observed wind speed	1944–69			1970–91		
(m s^{-1})	(No.)	Mean (mb)	Kraft's wind (m s^{-1})	(No.)	Mean (mb)	Kraft's wind (m s^{-1})
51	(62)	968	48	(47)	962	51
54	(43)	963	51	(28)	959	53
57	(76)	960	53	(35)	953	56
59	(30)	957	54	(26)	949	58
62	(38)	952	56	(34)	942	61
64	(30)	950	57	(17)	937	63
67	(19)	941	61	(11)	935	64

Removal of the early period bias in IH affects only a portion of the downward trend in IH and IHD. The trend in the bias-removed IH accounts for 13% of the variance in the data [significant at the 0.01 level, from Spiegel (1988)] and explains 8% of the variance in the corrected IHD data (significant at the 0.05 level). Additionally, removal of these trends still leaves a much higher coefficient of variation for IH than named storms (0.62–0.30).

In recent years, however, this reduced activity might not have been best characterized as a linear trend. It appears that IH activity decreased dramatically from 1961 to 1970 and has remained nearly constant through the present time at a much lower frequency than occurred during the 1940s and 1950s. Table 7 contrasts the two long-term periods of 1944–60 and 1971–91. The differences in IH and IHD between the time periods are significant at the 0.01 level using the Student's t-test with an adjustment for serial correlation (Reid et al. 1989).

b. United States landfalling cyclones

The time series of Atlantic basin IH, which struck the United States coastline between 1899 and 1991, is presented in Fig. 9 (from Landsea et al. 1992). Hebert and Taylor (1978) and Sheets (1990) have previously identified the notable lack of IH affecting the East Coast during the late 1960s to the mid-1980s. This is likely a reflection of the overall basinwide reduction in IH activity during the last two decades as discussed in the previous section. The only other period that incurred

TABLE 6. Summary of climatology of IH activity, both for the original dataset and with the bias removed.

	Original dataset				Bias-removed dataset			
	Intense hurricanes		Intense hurricane days		Intense hurricanes		Intense hurricane days	
Period	Mean	Std dev	Mean	Std dev	Mean	Std dev	Mean	Std dev
1944–69	3.19	2.00	7.96	5.51	2.69	1.66	6.18	4.74
1970–91	1.64	0.88	2.67	2.88	1.64	0.90	2.67	2.88
1944–91	2.48	1.77	5.54	5.21	2.21	1.47	4.57	4.37
Ratio 1944–69/1970–91	1.9	—	3.0	—	1.6	—	2.3	—

a similar (but smaller) reduction in East Coast activity was during the early 1990s to the late 1910s. Over the same 92-yr time frame, the Gulf Coast had nearly the same number of IH as the East Coast but experienced much less multidecadal variation as indicated by the smaller coefficient of variation in Table 8.

The main advantages in using this landfalling cyclone dataset are the length of record and consistency of analysis throughout the period [see Hebert and Taylor (1975) for description]. No systematic bias would be expected or is found. Additionally, the IH that strike the United States mainland can be used, to some degree, as a proxy estimate of variability for IH activity in the entire Atlantic basin. The linear correlation coefficients between landfalling versus total cyclone activity for the years 1944–91 are 0.55 for the original best-track dataset and 0.59 for the bias-removed dataset (both significant at the 0.01 level). Thus, while year-to-year variations of landfall activity explain only 35% of the total basin activity, the longer-term decadal activity of the Atlantic basin IH can be approximately represented by the decadal numbers of IH that affect the United States.

c. United States damage

The time series of normalized values for damage (in millions of 1991 dollars) in the United States is presented in Fig. 10. Note the dependence of large damage values on the occurrence of IH. The mean annual damage caused by all tropical cyclones is $1905 million 1991 dollars. The East Coast suffers more damage on average than the Gulf Coast (59% to 41%, respectively).

Table 9 presents a summary of the mean and median amounts of damage caused by tropical–subtropical storms and the various Saffir–Simpson categories of hurricanes that affected the United States. Note that median values are more representative of the dataset because the means are highly skewed by extremely large outliers. The "potential damage" is an idealized normalization of median damage relative to the category 1 hurricanes. This concept illustrates the fact that hurricane damage tends to increase exponentially with intensity. While Hebert and Taylor's (1978) study clearly showed that IH are responsible for most of the United States tropical cyclone spawned damage, it is startling to note that category 4 and 5 hurricanes typically do 100–250 times the damage of a minimal hurricane. Note that the tropical–subtropical storms are given a "0" for potential damage. Many cyclones striking the United States coast with tropical storm or minimal hurricane strength supply enough beneficial rainfall to offset any minor storm surge or wind-caused damage (Sugg 1968). Of course, occasionally these weaker storms are responsible for major rainfall-induced flooding (e.g., Diane in 1955 and Agnes in 1972).

d. Variation of genesis

An important consideration in understanding the interseasonal variability of the Atlantic basin tropical

TABLE 7. Contrast of IH and IHD for periods 1944–60 and 1971–91, where n is the number of years, n_{sc} is the number of years adjusted for serial correlation, t is the Student's t-test value, and t_{sc} is the Student's t-test number adjusted for serial correlation. Both values of t_{sc} are significant at the 0.01 level.

Years	Mean	Std dev	n	n_{sc}	t	t_{sc}
IH						
1944–60	2.88	1.41	17	17	3.20	3.20
1971–91	1.62	0.90	21	21		
IHD						
1944–60	6.21	3.93	17	17	3.01	2.92
1971–91	2.75	2.93	21	17.5		

TABLE 8. Summary of United States landfalling IH activity expressed as annual means, standard deviations, and coefficients of variation (CV) for both recent years and for the entire dataset.

	1944–91			1899–1991		
	Mean	Std dev	CV	Mean	Std dev	CV
Gulf Coast	0.29	0.46	1.59	0.35	0.56	1.60
East Coast	0.40	0.73	1.82	0.34	0.63	1.85
Florida Peninsula	0.19	0.44	2.32	0.19	0.42	2.21
Upper Atlantic	0.21	0.58	2.76	0.15	0.46	3.07
Entire United States	0.69	0.78	1.13	0.70	0.80	1.14

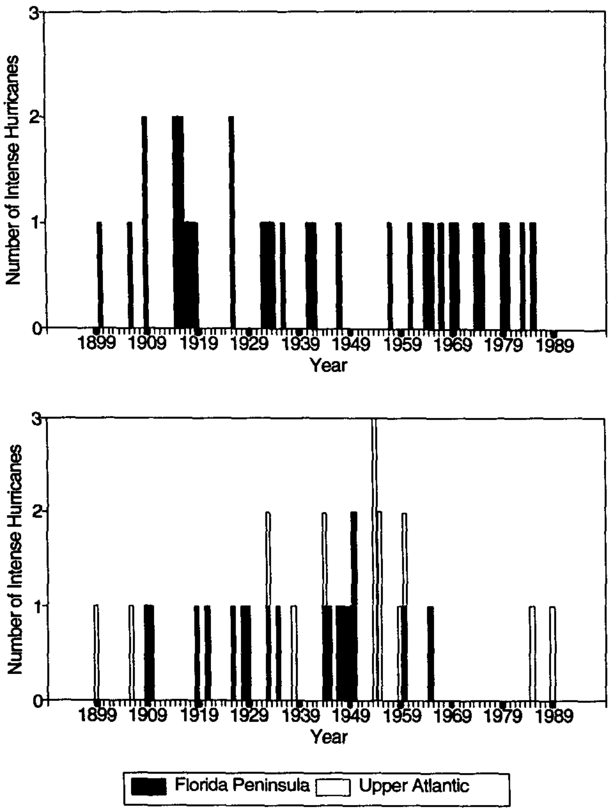

FIG. 9. Time series of the incidence of United States landfalling IH from 1899 to 1991 for (upper panel) the Gulf Coast and (lower panel) the East Coast (i.e., the Florida Peninsula and the upper-Atlantic coast) (from Landsea et al. 1992).

cyclones is in tracing their origins. The circulation features constituting the largest contributor to tropical cyclogenesis in the Atlantic basin are the West African easterly waves (Avila 1991). On an interannual time scale, Avila showed that the number of easterly waves observed each year is relatively steady; a mean of 60 waves per year with a standard deviation of only 6 is observed. Avila also points out that the number of waves each year has no correlation with the number of Atlantic tropical cyclones. What is noteworthy, however, is the difference in the relative frequency with which easterly waves contribute to the genesis of each of the various tropical cyclone categories. These associations are summarized in Table 10. Note that tropical storms and minor hurricanes (category 1 and 2 hurricanes) are almost identical (i.e., 57% and 58%) in their relatively moderate rate of easterly wave origins, whereas the large majority (83%) of IH form from easterly waves.

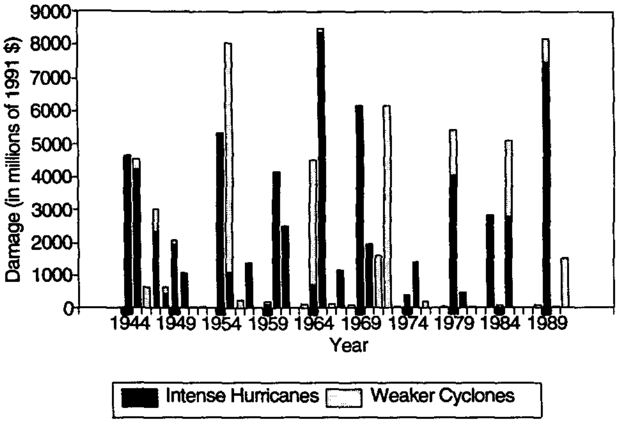

FIG. 10. Time series of United States tropical cyclone–spawned damage (in millions of 1991 dollars) from 1944 to 1991, stratified into values for IH and for weaker tropical cyclones (tropical–subtropical storms and category 1 and 2 hurricanes).

5. Summary and discussion

Intense hurricanes have substantially different climatological characteristics as compared with the weaker tropical cyclones in the Atlantic basin. On intraseasonal time scales, IH activity experiences a much sharper temporal peak than that of weaker storms, with over one-half of all IH activity occurring during September alone. Interseasonal variability of IH is also much greater than that of tropical storms and minor hurricanes. On multidecadal time scales, basinwide IH activity during the 1970s and 1980s was much reduced from that experienced during the 1940s and 1950s. Note that this reduced level of activity remains apparent in the data after a small bias to overestimation of cyclone intensity during the earlier era is removed. The recent multidecadal pattern of basinwide IH activity

TABLE 9. Summary of United States tropical cyclone–spawned damage by intensity category of cyclone at United States landfall, averaged for the years 1944–91 in millions of normalized 1991 dollars. The number of landfalls is shown in parentheses.

Intensity cases	Median damage	Potential damage	Mean damage	Percent total damage	Percent of total damage per storm
Tropical–subtropical storm (76)	<1	0	118	9.8	0.13
Hurricane category 1 (34)	25	1	301	11.2	0.33
Hurricane category 2 (15)	235	10	544	8.9	0.60
Hurricane category 3 (26)	1139	50	1517	43.1	1.66
Hurricane category 4 (6)	2342	100	3085	20.2	3.37
Hurricane category 5 (1)	6111	250	6111	6.7	6.68

TABLE 10. Total occurrences, annual means, and percent contributions of easterly wave origins for Atlantic basin tropical storms, minor hurricanes, and intense hurricanes using data from 1967 to 1991.

Category	Total number	Easterly waves	Other disturbances	Percent easterly waves
Tropical storms	93	54	39	58
(annual mean)	(3.7)	(2.2)	(1.5)	
Minor hurricanes	92	52	40	57
(annual mean)	(3.7)	(2.1)	(1.6)	
Intense hurricanes	42	35	7	83
(annual mean)	(1.7)	(1.4)	(0.3)	

has also been reflected in higher amounts of IH strikes in the 1940s and 1950s and a much reduced frequency of IH strikes during the 1970s and 1980s along the United States east coast (Hebert and Taylor 1978; and Sheets 1990). Also, whereas IH occur less frequently than tropical storms and minor hurricanes, IH are much more dependent upon easterly waves for their formation.

The importance of basic knowledge of IH climatology is underscored by the potential for damage along the United States coastal zones that these cyclones can produce. After normalization to 1991 dollars, IH are responsible for an average of $1.3 billion damage per year ($1.9 billion per IH); this is more than 70% of all United States tropical cyclone–spawned damage even though they comprise only 20% of all landfalling cyclones. It is likely that a similar ratio also applies in other countries in the Atlantic basin that are affected by IH.

The interannual and interdecadal variability of IH and IHD discussed in sections 4a and b is strongly mirrored by rainfall variations in the Sahel region of West Africa (Gray 1990; Landsea 1991; Landsea and Gray 1992; Landsea et al. 1992). Abundant rainfall in the Western Sahel during the late 1940s through the mid-1960s was concurrent with larger-than-normal numbers of IH in the Atlantic basin. Conversely, a severe two-decade-long Sahel drought occurred with fewer-than-normal numbers of IH. The current Sahel drought, however, is likely a temporary phenomena that will eventually abate (Nicholson 1989; Gray 1990). A return of rainfall in the Sahel, though beneficial for that region, will likely also bring increased IH activity to the Atlantic. The possibility that tropical cyclone–spawned damage will rise dramatically is further accentuated by the large increases of United States coastal population during recent decades. Note that these inferences are independent of any potential greenhouse gas warming effects. This climatology is an essential starting point for extrapolations into the future. Further research is needed on the variations of the general circulation that are responsible for the intra- and interseasonal fluctuations that have been described here.

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