Long-Term Variations of Western Sahelian Monsoon Rainfall and Intense U.S. Landfalling Hurricanes

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ABSTRACT

Western Sahelian rainfall during the primary rainy season of June through September is shown to be significantly associated with concurrent intense U.S. landfalling hurricanes during the last 92 years. The most intense hurricanes (i.e., Saffir–Simpson Scale Category 3, 4, or 5) have an especially strong relationship with Sahelian rainfall, whereas weaker hurricanes show little or no association. The hurricane–Sahelian rainfall association is most evident along the U.S. East Coast but is negligible in the U.S. Gulf Coast region.

1. Introduction

Recent work by Gray (1990) has presented evidence for a very strong relationship between western Sahelian rainfall and concurrent intense hurricane activity in the Atlantic basin during the last four decades. Landsea (1991) and Landsea and Gray (1991a) also provided evidence that this relationship was also significantly reflected in the U.S. landfalling cyclones, especially those along the East Coast from the Florida peninsula to Maine. Rosenthal (1991) has argued that this relationship is not statistically significant at the 0.05 level for the Florida peninsula alone. However, it is not surprising that such a narrow spatial stratification using just over four decades of information would yield a weak result. Landfalling hurricanes, especially the intense hurricanes, are very infrequent events for a comparatively small length of coastline.

This paper extends our analysis of the African rainfall and Atlantic hurricane association back to 1899 utilizing the best available precipitation and tropical cyclone data. The additional 50 years of data appear to confirm our earlier assessments; we find that the Sahelian rainfall–hurricane relationship *is* highly significant for the Florida peninsula and the remaining U.S. East Coast states, both together and separately, and that no association can be shown for the U.S. Gulf Coast.

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2. U.S. landfalling hurricane activity

One of the factors limiting direct comparisons of seasonal rainfall in the western Sahel and tropical cyclones throughout the Atlantic basin (North Atlantic Ocean, Gulf of Mexico, and Caribbean Sea) is that reliable quantitative tropical cyclone data are available only for recent years. Only since aircraft reconnaissance programs began in the mid-1940s has there been accurate accounting of the seasonal incidence of tropical storms and hurricanes (Neumann et al. 1987).

Nevertheless, reliable tropical cyclone data are available for hurricanes that made landfall along the U.S. mainland back to 1899. The large coastal populations in these areas make it unlikely that any hurricanes passed unnoticed across the U.S. coast since the turn of the century. A dataset by Neumann et al. (1987) categorizes these hurricanes by intensity. The Saffir–Simpson Scale (Simpson 1974), shown in Table 1, is used to rank the hurricanes from a 1 (minimal) to a 5 (catastrophic). Saffir–Simpson Category 3, 4, and 5 hurricanes are collectively referred to as "intense," while Categories 1 and 2 are characterized as "minor."

Not every hurricane that forms in the Atlantic basin makes landfall in the United States; however, the eastern U.S. coastline is so extensive that it often lies directly in the path of these cyclones. Just less than two of the basin's annual average of six hurricanes hit the U.S. coast. Consequently, more hurricanes strike the United States during relatively active hurricane seasons, while the United States usually experiences fewer landfalling hurricanes in calm seasons. The linear correlation between seasonal U.S. landfalling hurricanes and

TABLE 1. Maximum sustained wind speed, minimum surface pressure, storm surge, and general damaging effects for the five Saffir–Simpson Hurricane Scale (Simpson 1974) values. "Intense" hurricanes are those of Saffir–Simpson Scale 3, 4, and 5. "Minor" hurricanes are Saffir–Simpson's 1 and 2.

Saffir–Simpson Category	Maximum sustained wind speed (m s^{-1})	Minimum surface pressure (mb)	Storm surge (m)	Potential damaging effects
1	33 to 42	≥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

total seasonal Atlantic hurricanes is $r = 0.50$ for the years 1949 to 1990. Therefore, while not corresponding precisely on a year-to-year basis, the long-term variations of U.S. landfalling hurricanes back to 1899 provide a good estimate of the overall variations of the total Atlantic basin activity for decades prior to aircraft reconnaissance.

For the purpose of characterizing hurricane activity, the eastern U.S. coastline can be approximately separated into three regions: the Gulf Coast (including panhandle Florida), the Florida peninsula, and the upper Atlantic Coast as seen in Fig. 1. The Florida peninsula and the upper Atlantic Coast are collectively referred to as the East Coast, as defined in Landsea and Gray (1991a). In constructing the time series of U.S. landfalling hurricanes, cyclones that made two separate landfalls along the United States are counted twice (for example, Hurricane Betsy in 1965 struck south Florida, reintensified over the Gulf of Mexico, and then hit Louisiana). This procedure is appropriate in view of the immense destructive potential of a hurricane (such as Betsy) that makes two distinct and separate landfalls. (Nevertheless, counting such storms singly results in almost identical statistical conclusions.)

While the Gulf Coast intense hurricanes have experienced a relatively constant frequency, East Coast intense hurricanes have decreased sharply during the last 25 years as shown in Fig. 2. Most of this East Coast reduction is due to the extreme lack of intense hurricane strikes along the Florida peninsula and, to some degree, a lessening of strikes along the upper Atlantic Coast. During this century, a reduction of hurricane activity of this magnitude is without precedent, with only the period from 1900 to 1918 vaguely reflecting the decrease seen recently. However, as pointed out by Sheets (1990), this diminished activity in recent years,

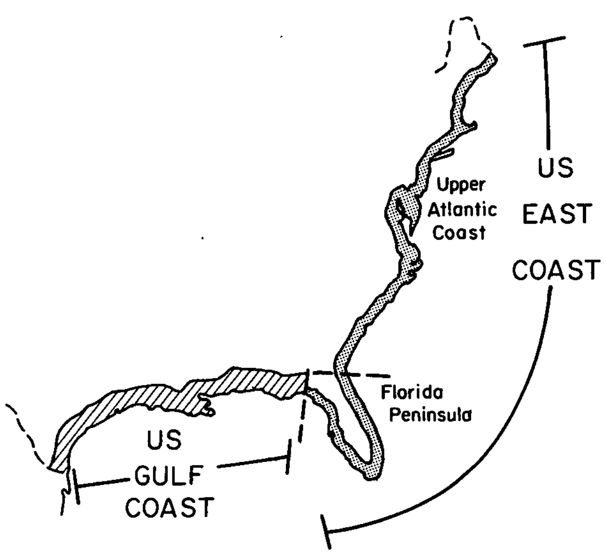

FIG. 1. United States coastal regions that experience differing levels of intense hurricane activity in association with variable western Sahelian rainfall: the upper Atlantic Coast, the Florida peninsula, and the Gulf Coast. The upper Atlantic Coast and the Florida peninsula are collectively referred to as the East Coast.

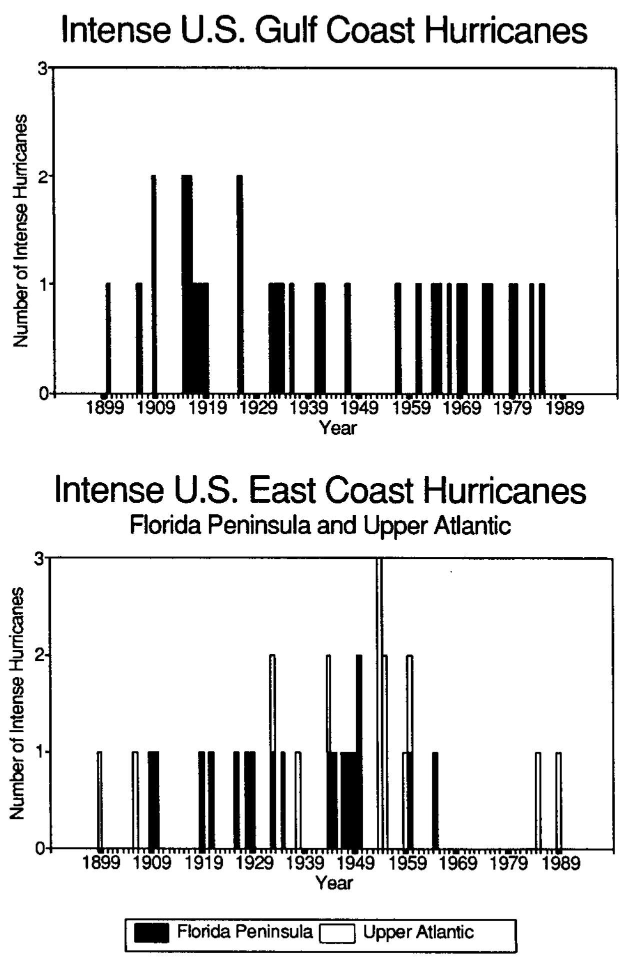

FIG. 2. Time series of intense U.S. landfalling hurricane activity from 1899 to 1990 for the U.S. Gulf Coast (upper panel) and the East Coast (the Florida peninsula and the upper Atlantic Coast) (lower panel).

while being beneficial in the short term, may lead to disastrous consequences "when hurricane activity inevitably returns to the frequencies experienced during the 1940s–60s." Likewise, "the decreased [hurricane] death total [in recent years] may be as much a result of [a] lack of major hurricanes striking the most vulnerable areas as they are of any fail-proof forecasting, warning, and observing system" (Hebert and Case 1990). Thus, it is necessary to identify associated meteorological features so that a better understanding of these multidecadal variations can be attained and adequate preparation taken when the frequency of intense hurricanes that affect the United States increases.

3. Sahelian monsoon rainfall

Our previous work with West African data utilized a 38-station index for the June to September western Sahelian rainfall (Gray 1990; Landsea and Gray 1991a). For each year, individual station rainfall for this 4-month period is compared against the station's long-term mean and standard deviation to define individual station deviation values (i.e., a z score). The regional index value for that year is simply the average of the available station deviations. This type of index formulation, which avoids biasing the data toward either normally dry or wet stations, was first described by Kraus (1977).

Unfortunately, only five stations in the western Sahel are still operating that have relatively continuous records back to the beginning of this century (Fig. 3). These five stations are used to form our "turn of the century" (TOC) western Sahelian rainfall index; the time series of this index is shown in Fig. 4. Table 2 is a tabular listing of the time series ranked from wettest to driest and Table 3 provides statistics for the individual stations.

Note that while the available data show a wide range of rainfall means (Table 3) for the 4-month period, the individual stations correlate at a level of at least $r = 0.59$ versus the combined TOC index. In addition,

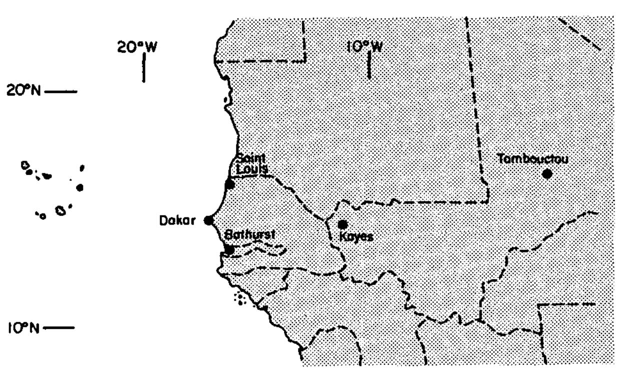

FIG. 3. Geographical locations of the five western Sahel stations in the TOC rainfall index.

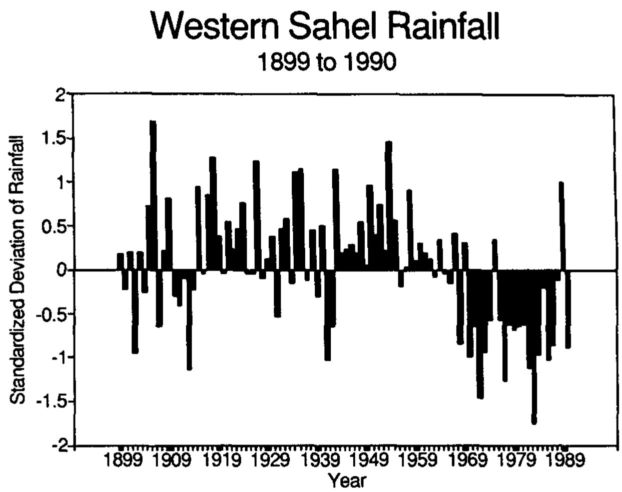

FIG. 4. Time series of the TOC rainfall index for the years 1899 to 1990. Rainfall values are shown in mean standard deviations from the norm.

this five-station index shares 83% of its variance with the larger 38-station western Sahelian index (Landsea and Gray 1991a) when compared for the common years 1949 to 1990. Thus, the TOC rainfall index is representative of individual locations in the western Sahel and is compatible with the more dense network of stations available in recent years.

Strongly apparent in the time series of the rainfall in Fig. 4 is the recent and unprecedented dry period that appears to be continuing at the present time. Aside from a few years in the periods between 1899 to 1914 and 1937 to 1942, the rainfall was consistently more abundant than the amounts which have been reported since the late 1960s. These features, which qualitatively appear similar to the intense hurricane activity (especially along the U.S. East Coast), will be shown to be quantitatively significant as well.

4. Concurrent long-term variations

The Sahelian rainfall data are ranked from the wettest (1906—rank 1) to the driest year (1983—rank 92) in Table 2. The recent extreme drought is represented in this ranking in that 18 of the 23 driest years occurred between 1968 and 1990. The wettest 23 years occur throughout a wider range of decades, with 3 to 5 wet years observed from each decade between 1900 and 1959.

With a ranked dataset 92 years in length, one can test the significance levels of the hurricane–Sahelian rainfall associations by making comparisons of rainfall quartiles that contain 23 years of data in each. Table 4 presents data for U.S. landfalling intense hurricanes and minor hurricanes, stratified by the amount of western Sahelian rainfall. While the minor hurricanes show no relationship with western Sahelian rainfall,

TABLE 2. Western Sahel TOC rainfall index ranked by rainfall amounts in mean standard deviations from 1899 to 1990. Number of stations (NS) available (out of a possible five per year) are also indicated in parentheses.

Rank	Year	NS	Index value	Rank	Year	NS	Index value	Rank	Year	NS	Index value	Rank	Year	NS	Index value
1	1906	(5)	1.69	24	1938	(4)	0.44	47	1949	(5)	0.05	70	1976	(5)	−0.56
2	1954	(5)	1.46	25	1967	(5)	0.41	48	1957	(5)	0.04	71	1974	(5)	−0.57
3	1918	(3)	1.27	26	1951	(5)	0.39	49	1965	(5)	−0.04	72	1978	(5)	−0.62
4	1927	(4)	1.24	27	1919	(3)	0.38	50	1916	(3)	−0.05	73	1981	(5)	−0.62
5	1936	(5)	1.14	28	1930	(4)	0.37	51	1920	(4)	−0.05	74	1907	(5)	−0.64
6	1943	(5)	1.14	29	1964	(5)	0.35	52	1925	(4)	−0.05	75	1942	(5)	−0.64
7	1935	(5)	1.10	30	1975	(5)	0.34	53	1926	(4)	−0.05	76	1971	(5)	−0.64
8	1989	(5)	1.00	31	1960	(5)	0.30	54	1963	(5)	−0.08	77	1980	(5)	−0.64
9	1950	(5)	0.97	32	1969	(5)	0.30	55	1928	(4)	−0.09	78	1979	(5)	−0.67
10	1915	(3)	0.97	33	1946	(4)	0.29	56	1912	(5)	−0.10	79	1968	(5)	−0.85
11	1958	(5)	0.91	34	1922	(5)	0.24	57	1937	(4)	−0.11	80	1987	(5)	−0.86
12	1917	(3)	0.85	35	1945	(5)	0.23	58	1988	(5)	−0.11	81	1990	(5)	−0.89
13	1909	(5)	0.82	36	1908	(5)	0.21	59	1934	(5)	−0.14	82	1973	(5)	−0.93
14	1924	(4)	0.77	37	1953	(5)	0.21	60	1966	(5)	−0.16	83	1902	(5)	−0.96
15	1952	(5)	0.74	38	1901	(4)	0.20	61	1956	(5)	−0.18	84	1984	(5)	−0.97
16	1905	(5)	0.72	39	1903	(4)	0.19	62	1985	(5)	−0.20	85	1970	(5)	−1.00
17	1933	(4)	0.58	40	1944	(5)	0.19	63	1914	(3)	−0.22	86	1986	(5)	−1.02
18	1955	(5)	0.56	41	1947	(5)	0.19	64	1900	(4)	−0.23	87	1941	(5)	−1.03
19	1948	(5)	0.55	42	1961	(5)	0.19	65	1904	(4)	−0.25	88	1982	(5)	−1.12
20	1921	(3)	0.54	43	1899	(3)	0.18	66	1910	(5)	−0.29	89	1913	(4)	−1.14
21	1940	(5)	0.51	44	1929	(4)	0.13	67	1939	(4)	−0.29	90	1977	(5)	−1.26
22	1923	(4)	0.47	45	1962	(5)	0.12	68	1911	(5)	−0.40	91	1972	(5)	−1.47
23	1932	(5)	0.47	46	1959	(5)	0.11	69	1931	(5)	−0.53	92	1983	(5)	−1.77

the East Coast intense hurricanes show extreme differences both in the wet-half versus the dry-half stratification and in the quartile analysis. Strong significance is also realized in the further stratification of the East Coast into the two subregions: the Florida peninsula and the upper Atlantic Coast. Note that even with the addition of the Gulf Coast (which shows no association), more than three times as many intense hurricanes are seen along the entire U.S. coast during the 23 wettest years as compared to the 23 driest years. Correlation coefficients for western Sahelian rainfall versus intense hurricane strikes are $r = 0.11$ (not significant) for the Gulf Coast, $r = 0.23$ (significant at the 0.05 level) for the Florida peninsula, and $r = 0.32$ (significant at the 0.01 level) for the upper Atlantic Coast.

Figure 5 contrasts the tracks of U.S. landfalling intense hurricanes during the wettest and driest quartiles.

TABLE 3. The five stations used in the turn of the century (TOC) western Sahelian rainfall index: station name and country, June to September mean and standard deviation (in mm), years of data in analysis, and correlation coefficients versus the TOC index.

Station	Rainfall Mean	Rainfall Std dev	Years	*r* vs index
Tombouctou, Mali	183.4	59.8	80	.67
Kayes, Mali	635.5	146.5	79	.70
Saint Louis, Senegal	321.3	159.1	91	.59
Dakar, Senegal	454.0	167.8	91	.79
Bathurst, Gambia	1025.7	269.5	84	.78

This figure graphically illustrates that the large wet-to-dry differences are manifested primarily along the East Coast (the Florida peninsula and the upper Atlantic Coast). Along the Gulf Coast, the quartile ratio in intense hurricanes is only 10 to 7 for the wettest versus the driest years. However, for the area extending from the Florida peninsula up to Maine, the East Coast, the ratio is an extreme 15 to 0.

An additional feature of Table 4 indicates that the East Coast variations arise from nearly equal contributions of intense hurricanes striking the Florida peninsula and the upper Atlantic Coast. Both subregions received intense hurricane strikes about once every three years during the wettest 23 western Sahelian years, whereas *none* occurred during the 23 driest years.

As discussed in Landsea (1991), of the various types of Atlantic tropical cyclones, the intense hurricanes are of most interest. The large downward trend observed in the incidence of these cyclones striking the United States is also observed in the frequency of intense hurricanes affecting the Caribbean islands, as well as overall intense hurricane activity. Along the U.S. coast intense hurricanes are responsible for over three-quarters of the tropical cyclone–spawned damage, even though on average they strike only twice every three years.

5. Summary

Variations of U.S. landfalling intense hurricane activity are shown to be strongly related to western Sahelian rainfall during the last 92 years. This association

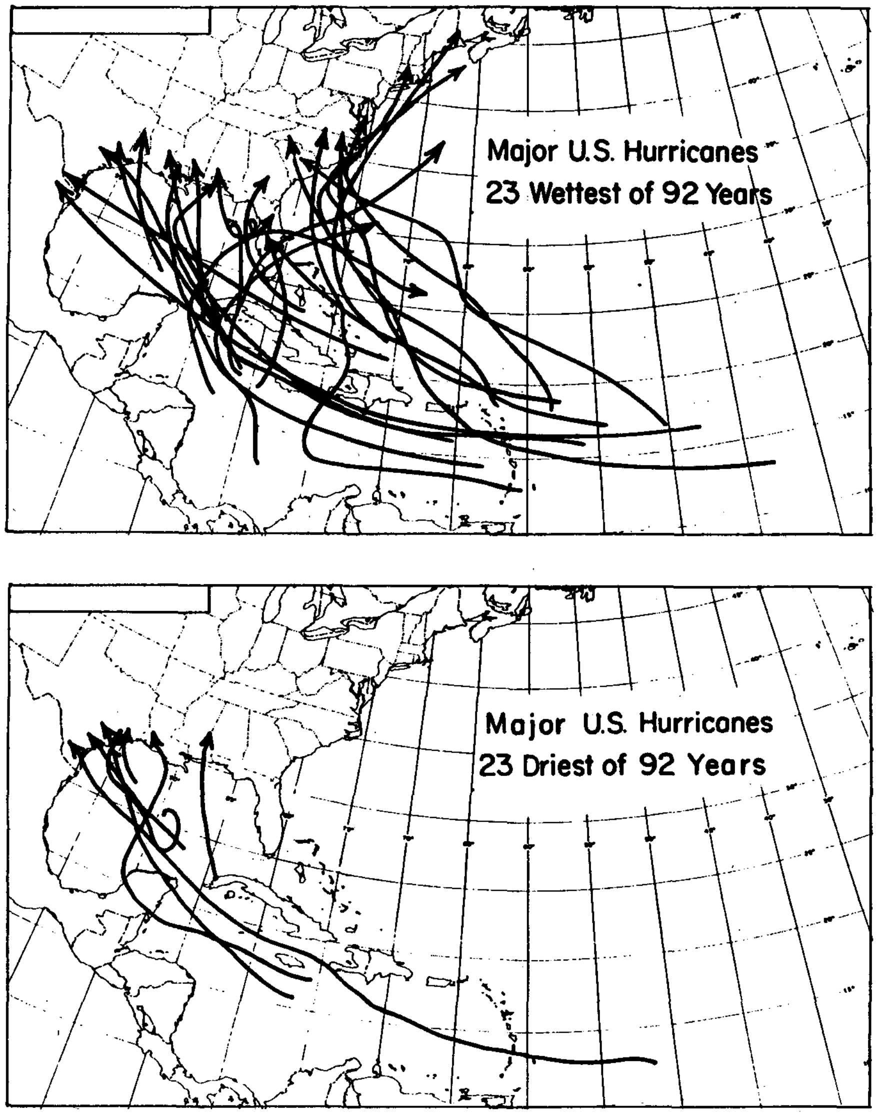

FIG. 5. Hurricane strength tracks of the tropical cyclones that made landfall as an intense hurricane (Category 3, 4, or 5) along the U.S. coastline during the 23 wettest years (upper panel) and the 23 driest years (lower panel) since 1899 in the western Sahel.

is strongest for the U.S. East Coast and is significant both for the Florida peninsula and the upper Atlantic Coast. Some physical mechanisms likely to account for such strong associations are detailed in Gray (1990) and Landsea and Gray (1991a); these include drought versus rainy variations in the amount of tropospheric vertical wind shear over the Atlantic basin and in the strength of African-spawned easterly waves.

An additional possibility is rainfall-related variations in the tropical cyclone steering patterns. Analogous to early work by Namias (1955) and Ballenzweig (1959), the frequency with which hurricanes strike the United States is highly dependent upon tropospheric flow patterns. It is likely that a lack of U.S. intense hurricanes and drought in the western Sahel are related by the presence of a stronger-than-normal central Atlantic midtropospheric trough, which would act to recurve any tropical cyclones away from the U.S. coast. The 1990 hurricane season (Mayfield and Lawrence 1991) may be an example of both unfavorable vertical shear and a stronger central Atlantic trough being responsible for reduced Atlantic basin intense hurricane activity and no U.S. landfalling intense hurricanes during a western Sahelian drought year.

An interesting aspect of the Sahelian rainfall–hurricane association is that a strong relationship is not observed for intense hurricanes striking the Gulf Coast. It is likely that the Gulf of Mexico may be considered

TABLE 4. Quartile analysis of the 92 years of dependable data on both western Sahelian rainfall and U.S. landfalling hurricanes. Twenty-three years of data are present in each quartile.

Rainfall quartile	Mean annual rainfall	Gulf Coast	Upper Atlantic Coast	Florida peninsula	East Coast	Entire U.S. coast
			U.S. intense hurricanes			
Very wet	+0.87	10	8	7	15	25
Wet	+0.24	7	5	6	11	18
Dry	−0.17	9	1	5	6	15
Very dry	−0.93	7	0	0	0	7
Wettest vs driest half frequencies		17/16	13/1	13/5	26/6	43/22
Exact two-sided P value		1.000	0.002	0.096	<0.001	0.013
Wettest vs driest quartile frequencies		10/7	8/0	7/0	15/0	25/7
Exact two-sided P value		0.629	0.008	0.016	<0.001	0.002
			U.S. minor hurricanes			
Very wet	+0.87	14	5	6	11	25
Wet	+0.24	10	10	7	17	27
Dry	−0.17	15	8	7	15	30
Very dry	−0.93	9	7	4	11	20
Wettest vs driest half frequencies		24/24	15/15	13/11	28/26	52/50
Exact two-sided P value		1.000	1.000	0.839	0.892	0.921
Wettest vs driest quartile frequencies		14/9	5/7	6/4	11/11	25/20
Exact two-sided P value		0.405	0.774	0.754	1.000	0.551

a distinct subbasin, and that anomalous general circulation features associated with Sahelian drought and moist years are subordinate to influences that are specific to the Gulf of Mexico. It is known that intense hurricanes in the Gulf of Mexico have characteristics that are different from the remainder of the Atlantic basin (Landsea 1991). Specifically, these cyclones typically occur almost three weeks earlier in the season on average (median date of landfall along the Gulf Coast is 5 September) and their origins are often from midlatitude systems. Since 1967 (when satellite monitoring made it possible), only intense hurricanes that were spawned from African waves have made landfall along the East Coast, while midlatitude systems (e.g., stationary frontal boundaries or upper-tropospheric cutoff lows) can occasionally form an intense hurricane that makes landfall along the Gulf Coast. Hurricane Alicia, which struck the Texas coast in 1983, is a notable example of this latter phenomenon.

When the western Sahel obtains a reprieve from its multidecadal drought with a return of significant rainfall, it is very probable that the Atlantic basin, including the U.S. coastal regions and the Caribbean islands, will experience more intense hurricane activity. These hurricanes are of most concern because of their potential destructiveness and because the recent decrease of activity may have led to complacency and a lack of community preparedness. Nicholson (1989) has shown that previous droughts in the Sahel have been replaced by episodes of abundant rainfall. Hence, there is currently no reason to suspect that the processes responsible for the drought affecting the region and contributing to the lack of intense hurricanes will continue indefinitely.

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