The Strong Association between Western Sahelian Monsoon Rainfall and Intense Atlantic Hurricanes

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ABSTRACT

Seasonal variability of Atlantic basin tropical cyclones is examined with respect to the monsoon rainfall over West Africa. Variations of intense hurricanes are of the most interest, as they are responsible for over three-quarters of United States tropical cyclone spawned destruction, though they account for only one-fifth of all landfalling cyclones. Intense hurricanes have also shown a strong downward trend during the last few decades. It is these storms that show the largest concurrent association with Africa's western Sahelian June–September rainfall for the years 1949–90.

Though the Sahel is currently experiencing a multidecadal drought, the relationship between Atlantic tropical cyclones and western Sahelian rainfall is not dependent on the similar downward trends in both datasets. A detrended analysis confirms that a strong association still exists, though reduced somewhat in variance explained. Additionally, independent data from the years 1899 to 1948 substantiate the existence of the tropical cyclone–western Sahelian rainfall association.

The fact that the Sahel periodically experiences multidecadal wet and dry regimes suggests that the current Sahelian drought, which began in the late 1960s, could be a temporary condition that may end in the near future. When this occurs, the Atlantic hurricane basin—especially the Caribbean islands and the United States East Coast—will likely see a large increase in intense hurricane activity associated with abundant Sahelian rainfall similar to the period of the late 1940s through the 1960s.

1. Introduction

Mechanisms of rainfall variability in the African Sahel received little attention until the severe drought years of 1972 and 1973. The magnitude of the drought in those years was such that it caused widespread crop failure and the deaths of thousands of people. Since that time, a variety of studies, both in observational and numerical modeling methods [see reviews by Hastenrath (1988, 1990b)] have been employed for analysis and predictions of Sahelian rainfall.

In contrast, seasonal variability of Atlantic basin tropical cyclones has intrigued researchers for almost a century. Garriott (1906) attempted to relate the exceptionally high hurricane activity in September 1906 to fluctuations in Atlantic basin surface pressure. Subsequently, many researchers have attempted to relate the frequencies and intensities of tropical cyclones to sea surface temperature anomalies (Ray 1935) and general circulation patterns (Namias 1955; Ballenzweig 1959), as well as surface pressure variations (Shapiro 1982a,b).

In the early 1980s, Gray (1984a, 1984b) showed strong predictive relationships of seasonal tropical cyclone activity to the presence or absence of an El Niño event, the phase and trend of the stratospheric quasi-biennial oscillation (QBO), and sea level pressure anomalies in the Caribbean basin. Gray has since modified the forecast scheme (Gray 1990a, 1990b) to include 200-mb Caribbean zonal wind anomalies and discounted temporal variability of the QBO phase. Yearly forecasts and verifications exhibiting some skill in seasonal predictions (Gray 1990d) have been issued since 1984.

However, the fact that there is a strong interrelationship between seasonal intense hurricane activity in the Atlantic basin and the amount of rainfall that fell in the Sahel had not been fully realized until very recently. This is somewhat understandable because named storm activity (which receives more attention in the literature) has not seen the types of decadal changes that the more infrequent intense hurricanes have. Yet, it is quite plausible that such a relationship might be present since it is known that the same weather systems that contribute especially large amounts of rainfall to the Sahel also frequently serve as the genesis points for tropical cyclones (Riehl 1945). These, of course, are the African-spawned easterly waves.

The first mention of a possible interannual connection between Sahelian rainfall and tropical cyclone variability appears in class notes from Carlson and Lee

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(1978). They speculated that "the severe drought conditions" over the African Sahel might be related to "the diminution of hurricane activity" in the Atlantic basin. They did not pursue this further, however, nor did they appear to recognize the primary association of intense hurricane activity and Sahelian rainfall conditions.

Gray (1987) revived interest in the possible Sahelian rainfall and hurricane association when he noted the similarity in his seasonal measure of hurricane intensity and duration—hurricane destruction potential—and the strong downward trend in the Sahelian rainfall, which continued through much of the 1980s. However, it took a failed seasonal forecast in 1989 (where Gray attributed his underestimation to conditions associated with a return of rainfall to the Sahel) to stress the importance of the intense hurricane–Sahelian rainfall relationship (Gray 1989, 1990c) and to stimulate research on this topic.

2. Definitions

Much confusion can arise when discussing the various categories of tropical cyclones. The United States (U.S.) Department of Commerce/National Oceanic and Atmospheric Administration (NOAA) (1977) technically defines *tropical cyclones* as nonfrontal low pressure synoptic-scale systems that develop over tropical or subtropical waters and have a definite organized circulation. Two additional requirements that should be added: the cyclone must have a relatively warmer tropospheric inner-core structure than the environment (i.e., a "warm core") and the maximum intensity of tangential winds should be located in the lower troposphere.

The tropical cyclone designation is a broad term under which various strength systems in the Atlantic basin are divided into

tropical depression—maximum sustained surface wind speed (1 min mean) < 18 m s^{-1},
tropical storm—wind speed 18 to <33 m s^{-1},
hurricane—wind speed at least 33 m s^{-1}.

Often, the term "tropical storm" refers to *any* cyclone of tropical storm *or* hurricane strength. This kind of reference will be avoided. In this paper, tropical storms and hurricanes will be collectively referred to as *named storms* (in deference to the fact that since 1950 all tropical cyclones that were of at least tropical storm force were given a name for identification (Neumann et al. 1987), though some cyclones were determined to be of tropical storm strength after the fact and thus lack a formal name].

The "hurricane" status can be further categorized by the severity of the cyclone. The Saffir–Simpson (Simpson 1974) Hurricane Scale provides a measure of intensity from a Category 1 (minimal) to Category 5 (catastrophic) hurricane. Table 1 summarizes the delineation of strength and effect. For purposes of this study, it became instructive to consider the Saffir–Simpson Category 3, 4, and 5 cyclones collectively as *intense* or *major hurricanes.*

One method for objectively determining the seasonal amount of tropical cyclone activity is through the summed duration of each storm. This partially removes the subjectivity involved in categorizing the intensity of tropical cyclones. Dunn and Staff (1965) first utilized the term *hurricane days.* A seasonal total of hurricane days is the amount of days in which a hurricane existed (two existing simultaneously count as two days). However, their calculations and a similar one done by Gray (1984a) count a full hurricane day even if the cyclone was of hurricane strength for just 6 h of that 24-h period. The computations for this report count days in one-quarter increments (6-h periods). This will slightly reduce the numbers obtained by these earlier studies. Similar calculations have been performed for intense hurricane days and named storm days.

Another way to measure tropical cyclone variability on a seasonal basis is through Gray's (1987) hurricane destruction potential (HDP). This measure gives a combined reflection of both the intensity and duration of the tropical cyclones. It is defined as the sum of the sustained wind speed (in knots) squared for every 6 hours that the cyclone is of hurricane strength (65 kt or 33 m s^{-1}). Hurricane destruction potential is defined to approximate the idea that hurricanes can cause damage relative to the square of their wind speed (i.e., a proxy of the summed kinetic energy of the cyclone's maximum winds). Both the intense hurricane days and HDP are used extensively in this report as measures of seasonal activity.

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

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

3. Data

a. Atlantic basin tropical cyclones

The positions and intensities (sustained wind speed and minimum surface pressure) of all Atlantic basin tropical cyclones of at least tropical storm strength have been archived and are continually being updated by the National Hurricane Center (NHC) in Miami, Florida. (The "Atlantic basin" is defined as the tropical and subtropical regions north of the equator in the Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico.) This dataset extends from 1886 to 1990 and is described in detail by Jarvinen et al. (1984). This "best track" dataset (as it is known since it is composed of the "best" estimate of positions and intensities in a postanalysis of all data available), or HURDAT (short for hurricane data), has been used quite extensively in our Tropical Meteorology Project at Colorado State University.

We have followed the recommendations by Neumann et al. (1987) to use tropical cyclone statistics based on data since the mid-1940s, when organized aircraft reconnaissance began, since this "probably best represents Atlantic tropical cyclone frequencies." The same logic follows for the day-to-day assessment of the intensity of individual storms; again because in the earlier period "storms that were detected could have been misclassified as to intensity."

Another consideration in using tropical cyclone frequency and intensity data is the subjectivity inherent in the categorization. Satellite-based tropical cyclone intensity estimations are pattern recognition and empirical methods that do not directly measure the storm's winds (Dvorak 1977, 1984). Aircraft reconnaissance usually records maximum wind speeds at flight levels (usually 850 or 700 mb). These are instantaneous values and do not necessarily represent a very accurate estimate of maximum surface winds. Nevertheless, satellite and aircraft data usually give rather close independent intensity estimates (Sheet 1990). [Landsea (1992b) has determined that the strength of the intense Atlantic hurricanes were slightly overestimated ($\sim$2–3 m s^{-1}) during the mid-1940s to the late 1960s. However, this bias is small and does not alter the main conclusions of this study.]

Tropical cyclones that have affected the United States mainland have a longer period of reliability concerning their frequency and intensity. This is because of the large coastal populations that the United States has along the Gulf of Mexico and the Atlantic Ocean. It is unlikely that any tropical storms or hurricanes were unnoticed crossing the coastline since the late 1800s. Hebert and Taylor (1975) have made a Saffir–Simpson categorization of all United States landfalling hurricanes from 1900 to 1974. They based their estimates primarily on minimum central pressures of the storm at the time of landfall. Neumann et al. (1987) have also analyzed 1899 and 1975–86. This paper has extended the analysis period through 1990 using NHC's end of the season write-ups (Case and Gerrish 1988; Lawrence and Gross 1989; Case and Mayfield 1990; and Mayfield and Lawrence 1991).

Besides the various categories of landfalling hurricanes, this report also makes use of tropical storms that affected the United States. This information was also gleaned from the Neumann et al. (1987) reference book and the recent annual reports.

Recently, Avila and Clark (1989) have revived the annual summary of Atlantic basin tropical disturbances in *Monthly Weather Review.* These articles are companion papers to the annual summary of Atlantic basin tropical cyclones [see the original paper by Simpson et al. (1968)]. Since 1967, when daily satellite analysis made it possible, NHC has attempted to report on the origins of tropical cyclogenesis and the numbers and varieties of tropical disturbances. Avila of NHC provided a detailed list of the origins of all Atlantic basin tropical cyclones of at least tropical storm strength from 1967 to 1990.

b. African rainfall data

The Sahel, lying between approximately 11° and 20°N in Africa, is the region that separates the hyperarid Sahara desert to the north and the rain forests along the Gulf of Guinea and the Congo River basin to the south. It is only during 3 to 5 months in the summer and early fall when the Sahel receives substantial precipitation. This rainfall is due to the annual cycle of the intertropical convergence zone (ITCZ), which reaches its northernmost position at that time. Over West Africa, the ITCZ takes the form of low-level southwesterlies (monsoonal flow) that converge with low-level northeasterlies. An excellent qualitative overview of West African meteorology is given by Hayward and Oguntoyinbo (1987).

For this study, "African rainfall" refers to any form of precipitation. However, since temperatures in the Sahel range from 15° to 45°C, the only nonrain precipitation possible is hail, which occurs very infrequently.

The main statistical method used for analyzing rainfall variations is the area-average normalization developed by Kraus (1977). To best look at the regional aspect of rainfall variations, Kraus attempted to combine stations without inducing a bias toward any station or any subgrouping of stations. Using mean percentages for a group of stations would favor the drier stations that experience huge percentage variations of rainfall. Using mean absolute deviations could slant the regional value toward stations with higher average rainfall. To avoid either of these problems, Kraus used a normalization of rainfall based on the mean and standard deviation at each station. This method is currently utilized by several observational researchers in Sahelian rainfall variability (Hastenrath 1990a; Lamb et al. 1990; Nicholson 1986; Shinoda 1989), as well as by the Climate Analysis Center (CAC) (U.S. Department of Commerce 1990) in their real-time analysis of United States and worldwide precipitation patterns.

Using the following definition for the mean, $\bar{r}_i$, and for the variance, σ_i^2, at station i,

$$\bar{r}_i = \frac{1}{J_i} \sum_j r_{ij}$$

$$\sigma_i^2 = \frac{1}{J_i - 1} \sum_j (r_{ij}^2 - \bar{r}_i^2)$$

where r_{ij} is the period (e.g., weekly, monthly, multimonth) rainfall at station i during year j and J_i is the number of years of data station i contains. The normalization for station i in year j is

$$x_{ij} = (r_{ij} - \bar{r}_i)/\sigma_i$$

which essentially tells how many standard deviations from the mean that rainfall is for that particular year.

The resulting regionally averaged index value of x_{ij} for the year j is defined as

$$a_j = \frac{1}{I_j} \sum_i x_{ij}$$

where I_j is the number of stations in the region available in year j.

We have spent considerable effort in the gathering and analyzing of the African rainfall data from a number of sources. The Appendix lists our African rainfall data sources and the many individuals who have assisted us.

The beginning point in the rainfall analysis was chosen to correspond to the first year Gray (1984a,b) used in his studies—1949. His analysis was limited to that date because of the lack of tropical stratospheric data before then; this data being essential due to the strong relationship between the stratosphere QBO and Atlantic basin tropical cyclones (Gray 1984a; Shapiro 1989). This starting date also agrees well with Neumann et al.'s (1987) assessment (mentioned earlier) that quantitative climatological studies on Atlantic basin tropical cyclones are most valid since the mid-1940s.

4. Intense hurricane variability

Landsea (1992b) has documented the intra- and interseasonal climatology of intense Atlantic hurricanes (Saffir–Simpson Categories 3, 4, and 5). Three main features were identified that differentiate these cyclones from weaker hurricanes and tropical storms. First, intense hurricanes have experienced the largest linear downward trend and show the most year-to-year variation. The reduction in major hurricanes during the last 20 years has also been observed in United States landfalling intense hurricanes, especially along the East Coast and the Florida peninsula (Sheets 1990). Second, these storms account for three-quarters of all United States tropical cyclone–spawned damage, even though they strike on average only twice in 3 years. Third, since over 98% of the intense hurricane activity occurs after July, this later starting date of their annual cycle allows a prediction of occurrence to be made on 1 August—two months after the beginning of the "official" hurricane season.

Figure 1 portrays the time series of intense hurricane activity as measured both by seasonal number of intense hurricanes and by seasonal number of days in which an intense hurricane was present. Note the extreme reduction in recent years as accentuated by the linear trend lines. The 42-yr means for the intense hurricanes and the intense hurricane days are 2.5 and 5.7, respectively. While all tropical cyclone activity exhibit positive correlations with Sahelian rainfall, it is the intense hurricanes that show the strongest association. This holds true even after these strong downward trends are removed from the tropical cyclone data.

5. African rainfall variability

As described in the Introduction, Gray (1987) hypothesized that the general downtrend in Atlantic basin tropical cyclone activity had a connection to Sahelian rainfall conditions. While the numbers of named storms and hurricanes showed little multidecadal (1949–69 and 1970–86) variation, the numbers and durations of stronger hurricanes (in intense hurricanes, hurricane days, and HDP) varied by a factor of 2 to 1 between these periods. Gray noted that the analysis of Sahelian rainfall by Lamb (1985) also showed a large downward trend in the data. More quantitatively, the 20-station Lamb index, for the years 1949–90, is associated with intense hurricanes by a linear correlation coefficient of $r = 0.61$ and with intense hurricane days at $r = 0.64$. However, since Lamb's index includes the western and central Sahel and covers the multimonth period of April–October, the signal that Sahelian rainfall has with Atlantic basin tropical cyclones may not be maximized. The following section isolates which regions and time frames best relate the two phenomena.

a. Monthly rainfall variability

The most dominant feature in causing precipitation over the continent of Africa is the ITCZ. Its latitudinal extent as measured by the 100-mm isohyet covers over 15° long (1650 km) meridionally during the Northern Hemisphere summer. Direct extratropical influences are relatively minor, only producing precipitation in the most poleward (>30° latitude) extent of the continent. It is during the Northern Hemisphere's monsoon season when substantial rainfall reaches north of 11°N that the Sahel gets almost all of its precipitation (June–September). Precipitation during these 4 months showed the strongest individual month associations with intense hurricane activity.

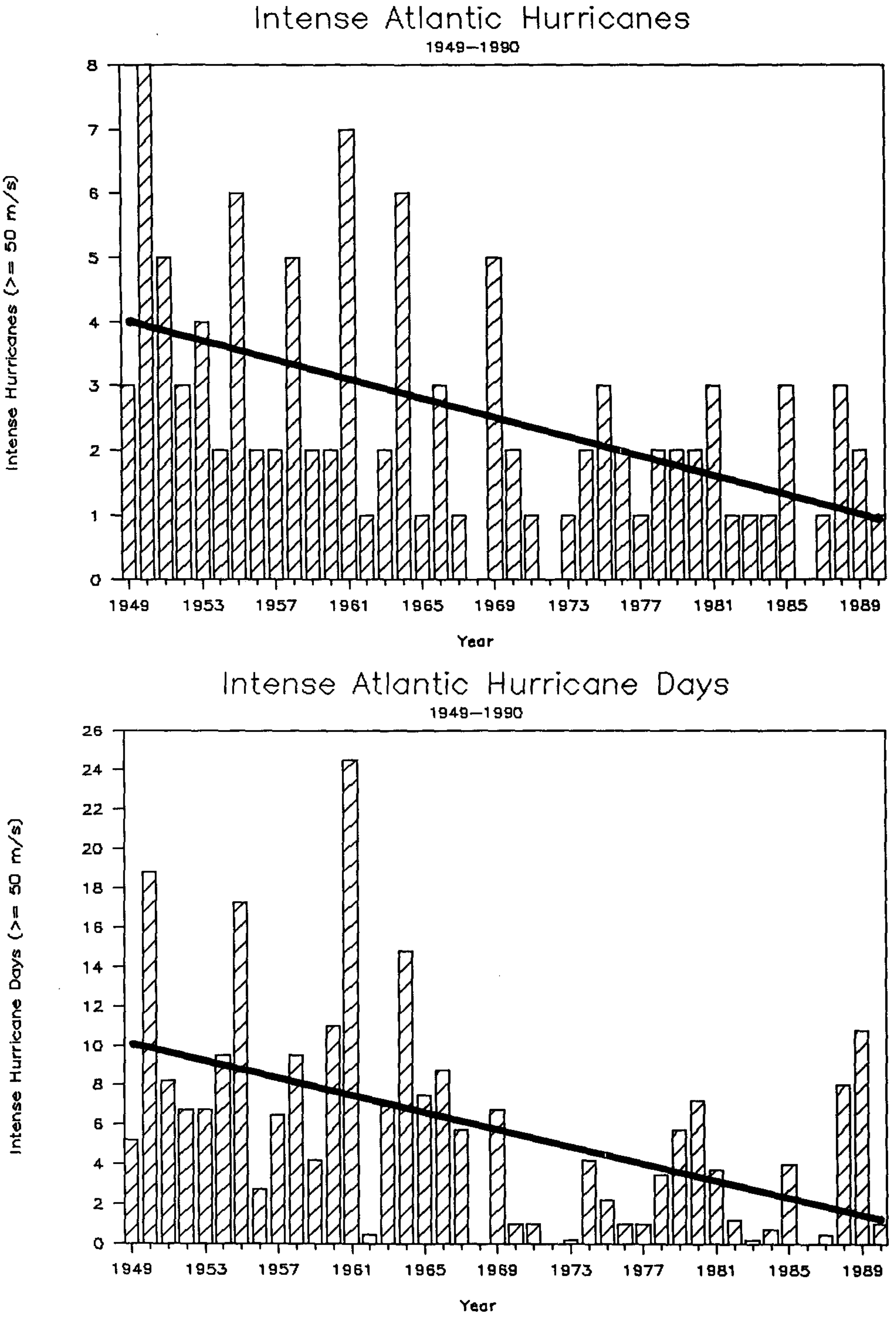

FIG. 1. Intense Atlantic hurricane activity from 1949 to 1990 by intense hurricanes (upper panel) and intense hurricane days (lower panel). The solid line is the least-squares linear trend.

Figure 2 presents an analysis of the individual months using linear correlation coefficients for individual station monthly rainfall versus seasonal intense hurricane days. While each map shows areas of both positive and negative correlation, these were not accepted as showing meaningful significance unless they persisted for at least 3 months at a correlation of $|r| > 0.15$ (a subjective threshold of just 2% of variance

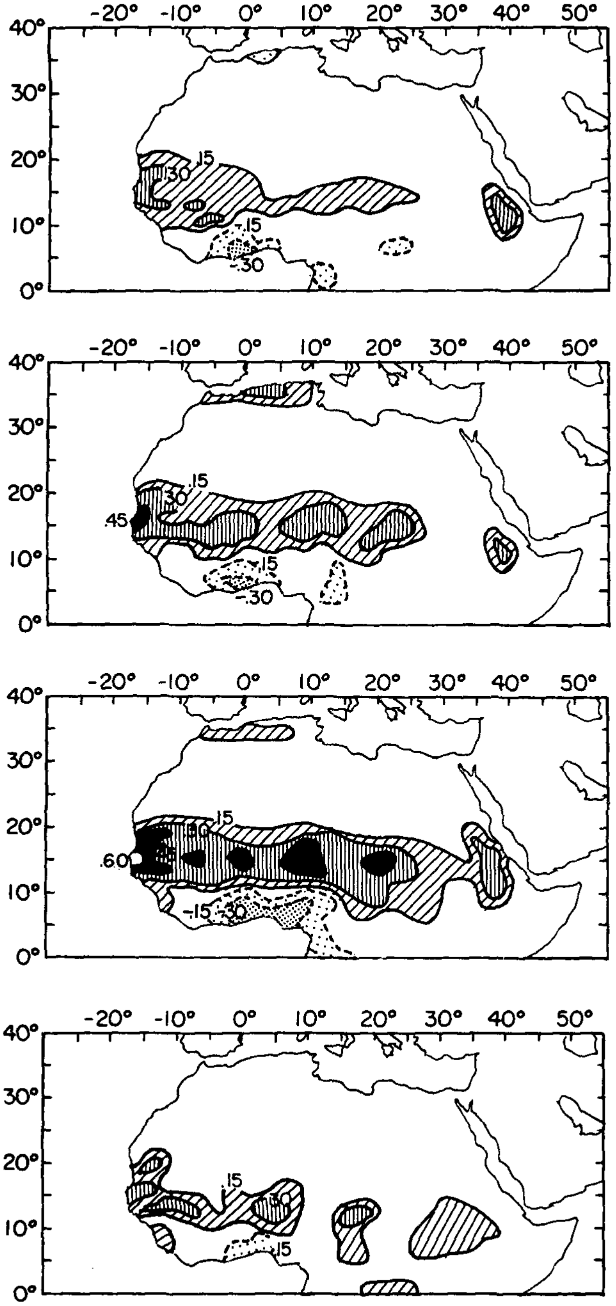

FIG. 2. Smoothed values of linear correlation coefficient for individual station rainfall versus seasonal intense hurricane days for (top to bottom) June, July, August, and September from 1949 to 1989. Contours are at $r = \pm 0.15$, 0.30, and 0.45.

explained) over a region greater than 3° square ($\sim$100 000 km^2). Only one coupled region appears to meet the criteria: A strong positive correlation throughout the Sahel with an associated weaker negative correlation along the Gulf of Guinea. The Sahel consistently shows this positive relationship from June to September, while the negative dipole is seen for July through September. It is the western and central Sahel that shows the highest correlations versus intense hurricane days with several monthly correlation values of at least $r = 0.50$. August has the strongest association of any month with the seasonal hurricane activity. The presence of an inverse relationship of Sahelian rainfall with the Gulf of Guinea region to its south is consistent with the findings of Nicholson (1986). She showed that the Sahel and the Gulf of Guinea often (but not always) show opposite anomalies during the same year: When the Sahel has abundant rainfall, the area along the Gulf of Guinea is usually dry; conversely, when the Gulf of Guinea receives above-normal amounts of rainfall, the Sahel is often drier than normal.

Thus, the strongest monthly rainfall associations with intense hurricane activity occur in the western and central Sahel during the months June–September with a maximum in August. The following section presents the combined association of the 4-month total rainfall.

b. June–September rainfall variability

Using combinations of the monthly correlations shown in the previous section, it was determined that June–September Sahelian rainfall has the strongest concurrent relationship with intense hurricane days. It is this 4-month period that comprises most of the precipitation that occurs over the Sahel.

Confirming what was also observed in the Lamb index, the Sahel shows increasingly positive correlations with tropical cyclones as the intensity category of the tropical cyclone increases. The three analyses in Fig. 3 show linear correlations for named storms, hurricanes, and intense hurricanes versus individual station June–September rainfall. The correlations were computed using data from 1949 to 1989, but as mentioned previously, many stations have very spotty temporal coverage. Because of this, stations with even 12 years of data are included in the analysis (though several in the Sahel have over 95% coverage).

Though all three analyses show a basic structure of positive correlations throughout the Sahel (strongest at the westernmost portion) and a weaker area of negative correlations along the Gulf of Guinea, it is the magnitudes of the associations that are of note. For the correlation with named storms, the highest values are only $r = 0.35$. For the strongest hurricanes, values of $r = 0.65$ and higher are seen in the western Sahel. Figure 4 is an enlargement of North Africa with the correlation coefficients for intense hurricane days versus rainfall.

6. Western Sahelian rainfall index

a. Development of index

An accepted way of creating rainfall indices for a particular region is to combine stations through their

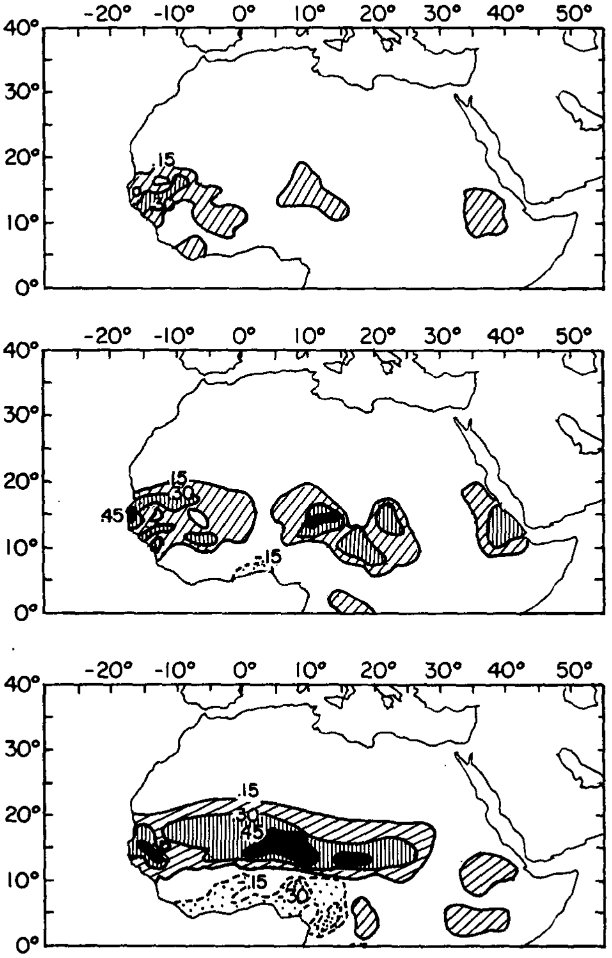

FIG. 3. Correlation coefficients of individual station June–September rainfall versus named storms (top), hurricanes (middle), and intense hurricanes (bottom) from 1949 to 1990. Contours indicate values of $r = \pm 0.15$, 0.30, 0.45, and 0.60. Positive correlations are within solid contours, while negative contours are indicated by dashed lines.

mean standard deviations for that particular period (as discussed in section 3). Thirty-eight stations are utilized in such a method to create the June–September western Sahelian rainfall index. Figure 5 shows the locations of the stations that comprise the index.

Countries included in the region are Senegal, Gambia, northern Guinea-Bissau, southern Mauritania, and western Mali. All available stations within the boundary are utilized if they provided at least 30 years of rainfall data in the period 1949–90. Although this data threshold may appear somewhat low (only 74% of years needed), the quantity of data available over the western Sahel is actually more reliable than over much of the rest of tropical Africa.

Rainfall in the Sahel has shown a strong tendency for year-to-year persistence during the last four decades. As seen in Fig. 6, consistently wet anomalies were observed from 1950 to the mid-1960s and then almost continuous dry anomalies were experienced from 1968 onward, with above average rainfall only in 1969, 1975, 1988, and 1989. The tendency for decreasing precipitation amounts with time is highlighted by the boldface trend line, which gives the least-squares best fit the data. Removal of the linear trend in the rainfall data is shown in a detrended analysis in Fig. 7. The strong correlations between the western Sahelian rainfall and tropical cyclones, however, are not dependent on concurrent trends in the datasets.

Table 2 provides the mean standard deviations of rainfall (the same information as in Fig. 6), as well as the number of stations that were included in each year's calculations. Data for the years 1949–50 and 1987–90 are not as complete because the datasets from which several stations are drawn were not available for those time periods.

Information on the individual stations utilized in the western Sahelian index are provided in Table 3. This region covers a wide meridional area (11°–20°N) and a large range of rainfall means. The individual stations show a high degree of correlation with the entire western Sahelian index, with only 3 of 38 stations showing a correlation less than $r = 0.62$. This kind of

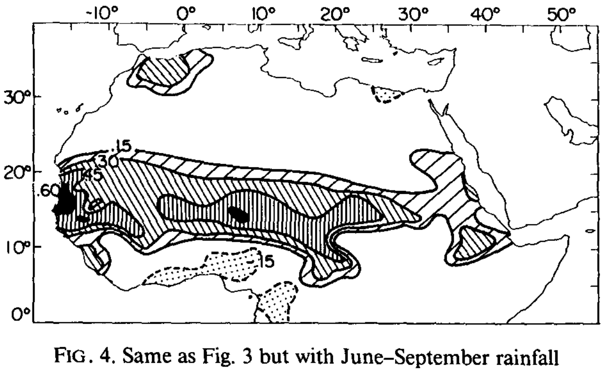

FIG. 4. Same as Fig. 3 but with June–September rainfall versus intense hurricane days.

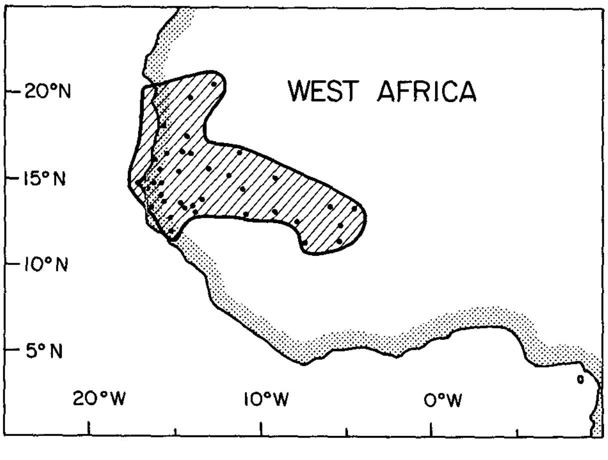

FIG. 5. Location of rainfall stations that comprise the western Sahelian rainfall index.

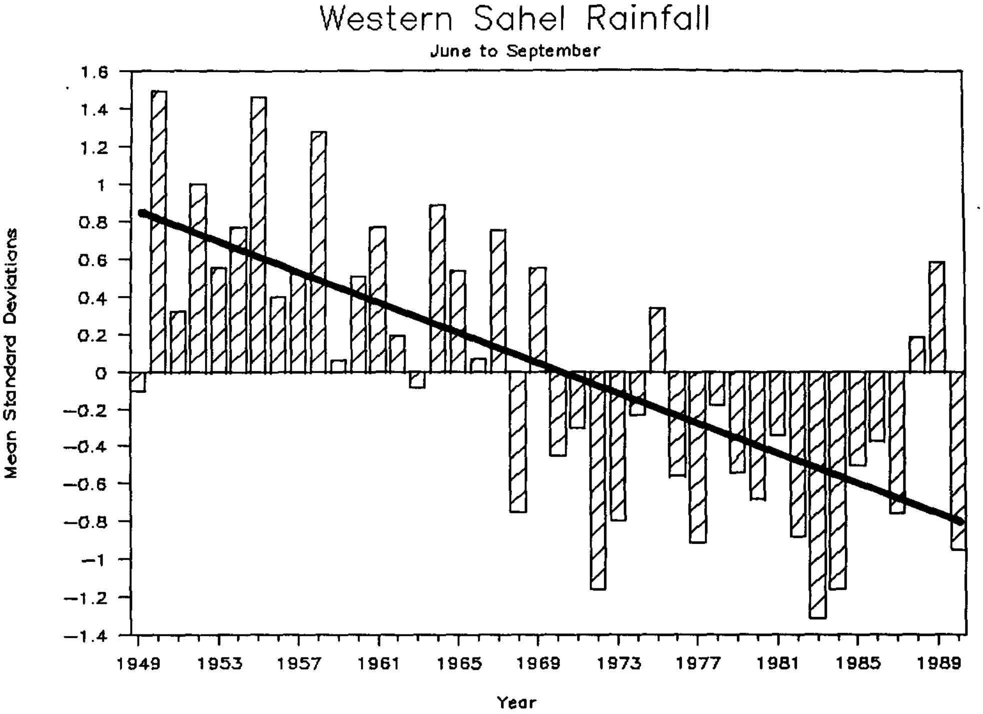

FIG. 6. Mean standard deviations of rainfall for the 38-station June–September western Sahelian index. The boldface line indicates the least-squares best fit line to the data. Data presented are from 1949 to 1990.

internal consistency is vital where a single index is utilized in portraying precipitation for a widespread region.

Table 4 shows a month-by-month analysis of the combined 38-station means and standard deviations, including the percent contribution to the main June–

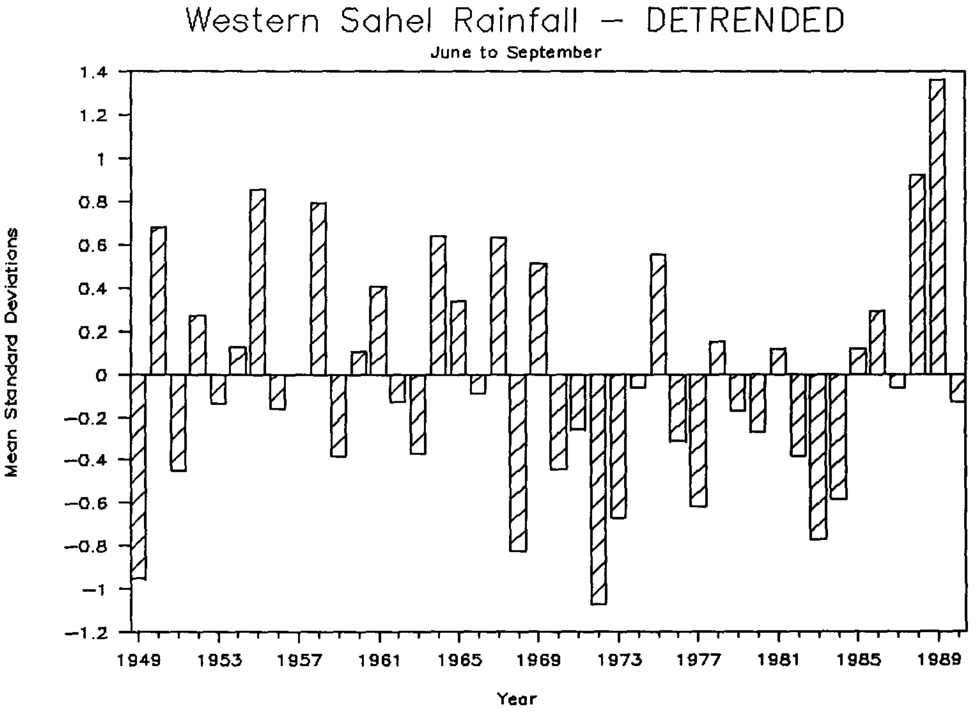

FIG. 7. Same as Fig. 6 but with the downward linear trend removed from the data.

TABLE 2. Mean standard deviations and data availability (out of a possible 38 stations per year) for the June–September western Sahelian rainfall.

Year	Standard deviation	Number of stations	Year	Standard deviation	Number of stations
1949	−0.10	24	1970	−0.45	37
1950	1.49	24	1971	−0.30	37
1951	0.32	37	1972	−1.16	38
1952	1.00	37	1973	−0.80	38
1953	0.55	38	1974	−0.23	38
1954	0.77	38	1975	0.34	38
1955	1.46	38	1976	−0.56	38
1956	0.40	38	1977	−0.91	37
1957	0.52	38	1978	−0.18	38
1958	1.28	37	1979	−0.54	38
1959	0.06	36	1980	−0.68	37
1960	0.51	35	1981	−0.34	37
1961	0.77	38	1982	−0.88	37
1962	0.19	37	1983	−1.31	37
1963	−0.09	38	1984	−1.16	37
1964	0.88	38	1985	−0.50	37
1965	0.54	37	1986	−0.37	37
1966	0.07	38	1987	−0.76	26
1967	0.75	37	1988	0.18	26
1968	−0.75	37	1989	0.58	25
1969	0.55	37	1990	−0.95	25

September rainfall period and to the entire rainy season of May–November. Though not shown, the remaining months, December–April, receive in total only about 1% of the annual mean. Note that the main rainfall month is August, with both July and September receiving considerable amounts as well. It is also seen that with the higher means in July–September there is lower overall variability (i.e., a lower coefficient of variation). The higher variability during the fringe months of the monsoon (May–June and October–November) is likely due to typically having no rainfall or else receiving considerable amounts of rain (25–100 mm). Nevertheless, Table 4 documents that the June–September period chosen for inclusion in the western Sahelian rainfall index covers the large majority of the annual rainfall of this region.

b. Association with tropical cyclones

The concurrent associations that the western Sahelian index has with various Atlantic basin tropical cyclone parameters are presented in Table 5, including a detrended analysis. The goal of focusing on the relationship seen in the Lamb index is achieved. In agreement with Figs. 3 and 4, the association is strongest for the most intense hurricane activity and weakest for the numbers of named storms. Figure 8 depicts the scatterplot of the western Sahelian rainfall–intense hurricane days relationship, where 58% of the variance between the two is explained by a linear regression. Note that, except for named storms, all parameters are significant beyond the 0.005 level using the one-tailed test (Spiegel 1988).

However, the methodology of selecting a posteriori the region with the highest association induces artificial skill into the association (Davis 1976; Shapiro 1984). It is likely that the amount of bias is not large, as the Lamb index (developed without regard to the intense hurricane activity) also showed a linear correlation of $r = 0.64$ with intense hurricane activity. Therefore, a caveat is recognized that significance testing for the relationships may slightly overestimate the degree of association. Additionally, independent data, though less reliable, verify the existence of the association as discussed later.

One uncertainty regarding this relationship is whether the strong correlations are simply due to coexisting trends in the datasets. One test that can be done is to break the record into two periods and then check the correlations. The obvious years that the break should be used would be after 1969, as the long-term drought began in 1970 and has proceeded relatively uninterrupted since. The correlations with intense hurricane days then become

1949–69 (21 years—wet period): $r = 0.66$

1970–90 (21 years—dry period): $r = 0.66$,

which are just moderately lower than the overall relationship of $r = 0.76$ (a reduction of 14% of the variance explained). Since the trend is essentially removed by stratifying the data into two separate time periods, this confirms that the relationship is not trend dependent.

A second method for checking for trend-induced associations would be to remove any linear trend from both datasets. Figure 7 showed the detrended time series of the western Sahelian rainfall index. Though both the rainfall index and the intense hurricane activity show very substantial decreasing linear trends, removal of the trends has little effect. Detrended intense hurricane days correlate with the detrended western Sahelian rainfall index at $r = 0.68$ (Fig. 9), again moderately lower than the $r = 0.76$ value presented earlier for the original relationship. The remaining tropical cyclone parameters (Table 5) show even less of a reduction in the detrended analysis.

For independent verification of the association, rainfall data from Landsea et al. (1991) can be utilized in conjunction with reliable data regarding landfalling intense hurricanes along the East Coast (see Fig. 10). In the study, a 5-station western Sahelian rainfall index was created for the years 1899–1990. For the years 1949–90, the 5-station index correlates at $r = 0.91$ ($r = 0.85$ in a detrended analysis) versus the larger 38-station index shown here. Thus, the 5-station index likely represents the rainfall time series adequately. For intense hurricanes striking the East Coast, the 38-sta-

TABLE 3. The 38 stations used in the June–September western Sahelian rainfall index: station name and country, June–September mean and standard deviation (SD) (in millimeters), years of data in analysis, correlation coefficients versus the western Sahelian index itself, and correlation coefficient versus intense hurricane days.

	Rainfall data			Correlation coefficient	
Station	Mean	SD	Years	Versus index	Versus intense hurricane days*
Nioro Du Sahel, Mali	483.9	159.75	42	0.809	0.511
Kayes, Mali	611.3	121.28	42	0.641	0.475
Kita, Mali	865.6	185.37	42	0.705	0.460
Segou, Mali	591.7	126.96	42	0.774	0.548
San, Mali	635.0	108.13	42	0.602	0.571
Kenieba, Mali	1045.2	241.41	40	0.768	0.509
Bamako/Senou, Mali	814.7	169.17	42	0.647	0.461
Koutiala, Mali	789.0	171.43	42	0.676	0.630
Bougouni, Mali	926.1	174.60	42	0.677	0.579
Sikasso, Mali	925.4	143.01	41	0.554	0.454
Atar, Mauritania	66.0	43.27	42	0.496	0.344
Akjoujt, Mauritania	58.7	45.29	40	0.628	0.555
Nouakchott, Mauritania	86.8	54.98	42	0.814	0.578
Boutilimit, Mauritania	133.3	76.44	42	0.734	0.615
Rosso, Mauritania	221.8	104.86	40	0.700	0.563
Kiffa, Mauritania	280.4	118.51	42	0.780	0.466
Saint Louis, Senegal	261.3	128.88	42	0.572	0.442
Podor, Senegal	232.3	120.71	42	0.706	0.620
Linguere, Senegal	399.7	115.33	42	0.747	0.632
Matam, Senegal	405.2	177.28	42	0.674	0.513
Dakar/Yoff, Senegal	421.2	177.83	42	0.853	0.680
Thies, Senegal	527.1	202.63	37	0.864	0.643
Diourbel, Senegal	544.5	177.29	42	0.864	0.632
Kaolack, Senegal	615.0	183.10	40	0.753	0.541
Tambacounda, Senegal	725.2	168.38	42	0.694	0.466
Bathurst/Yundum, Gambia	998.4	286.76	42	0.882	0.552
Bissau Airport, Guinea-Bissau	1542.1	337.73	40	0.773	0.574
Bansang, Gambia	823.7	290.44	34	0.781	0.562
Georgetown, Gambia	811.7	189.83	31	0.783	0.518
Basse Met, Gambia	842.1	221.00	34	0.774	0.698
Boghe, Mauritania	250.4	89.88	36	0.749	0.610
Selibaby, Mauritania	493.5	145.51	36	0.782	0.495
Louga, Senegal	336.3	157.19	31	0.825	0.570
Mbour, Senegal	576.8	216.54	36	0.834	0.538
Nioro Du Rip, Senegal	685.6	184.95	33	0.807	0.495
Velingara Casamance, Senegal	863.6	208.37	34	0.691	0.689
Sedhiou, Senegal	1094.6	303.71	36	0.764	0.553
Bambey Met, Senegal	538.5	151.72	36	0.871	0.586

* Significance level is 0.005 for all stations except 0.025 for Atar, Mauritania.

tion index correlates at $r = 0.45$ ($r = 0.29$ in a detrended analysis, significant beyond the 0.05 level) for the years 1949–90. The 5-station index correlates independently at $r = 0.20$ ($r = 0.19$ in a detrended analysis, significant beyond the 0.10 level) versus the East Coast intense hurricanes for the years 1899–1948. Thus, after accounting for uncertainties due to less reliable rainfall and tropical cyclone data in the earlier period and after removing the substantial trend mainly in the later period, a confirmation of the western Sahelian–Atlantic tropical cyclone association is seen in earlier independent data.

TABLE 4. Monthly means, standard deviations, ratios, and coefficients of variability for the 38 stations western Sahelian rainfall index.

	May	Jun	Jul	Aug	Sep	Oct	Nov	Jun–Sep	May–Nov
Mean (mm)	18	66	149	217	162	51	4	595	668
Standard deviation (mm)	15	38	65	94	74	48	9	164	177
Coefficient of variability (%)	83	57	44	43	46	94	225	28	26
Percent of Jun–Sep mean	—	11	25	36	28	—	—	—	—
Percent of May–Nov mean	3	10	22	32	24	8	1	89	—

TABLE 5. Regression equations and correlation coefficients of June–September western Sahelian rainfall index (x) versus Atlantic basin tropical cyclone parameters (y) using data from 1949–90 for both original datasets and detrended analysis. (Asterisks refer to significance level: 0.025 for '*' and 0.005 for '**'.)

Tropical cyclone parameter	Correlation coefficient	Regression equation	Standard error of y
		Original data	
Named storms	0.35*	$y = 9.42 + 1.406x$	±2.8
Named storm days	0.56**	$y = 47.12 + 15.052x$	16.7
Hurricanes	0.47**	$y = 5.85 + 1.404x$	2.0
Hurricane days	0.67**	$y = 23.73 + 12.192x$	10.1
Intense hurricanes	0.71**	$y = 2.47 + 1.805x$	1.3
Intense hurricane days	0.76**	$y = 5.68 + 5.713x$	3.6
HDP	0.73**	$y = 73.21 + 47.936x$	33.8
		Detrended data	
Named storms	0.34*	$y = 0.05 + 1.862x$	±2.8
Named storm days	0.54**	$y = 0.12 + 19.053x$	16.7
Hurricanes	0.41*	$y = -0.02 + 1.575x$	2.0
Hurricane days	0.60**	$y = 0.13 + 13.681x$	10.1
Intense hurricanes	0.59**	$y = 0.03 + 1.766x$	1.3
Intense hurricane days	0.68**	$y = 0.04 + 6.115x$	3.6
HDP	0.65**	$y = 0.52 + 51.916x$	33.8

c. *"Wet" versus "dry" years*

To facilitate discussions of "wet" and "dry" western Sahelian rainfall years, the June–September western Sahelian rainfall index values are ranked from wettest to driest for 1949–90 in Table 6. This will allow composite analyses to be performed for groupings of wet versus dry seasons.

Another use of this ordering by rainfall is to utilize rank correlations versus tropical cyclone activity. The correlation coefficient between ranked rainfall data and ranked intense hurricane days is $r = 0.81$, with 65% of the variance explained. This is slightly higher than the linear correlation between the two ($r = 0.76$), suggesting that a nonlinear relationship as measured by the rank correlation may be the best description of the association.

The reason for compositing parameters with respect to the wettest and driest western Sahelian rainfall seasons is that physical differences between the two regimes are accentuated. In a single season other factors (such as El Niño, stratospheric QBO, etc.), which show as much control on the tropical cyclone variance as the Sahelian rainfall, may obscure the tropical cyclone–African rainfall signal. This problem is greatly reduced in a composite analysis. For the following analyses, the 10 wettest years (mean western Sahelian index value of $\sigma = 0.95$) are contrasted with the 10 driest years (mean value of $\sigma = -0.94$).

Table 7 details how various tropical cyclone parameters differ in the 10 wettest and 10 driest western Sahelian years. Significant differences are seen in every category but are most pronounced for the strongest hurricane activity: a 5 to 1 ratio in all intense hurricane

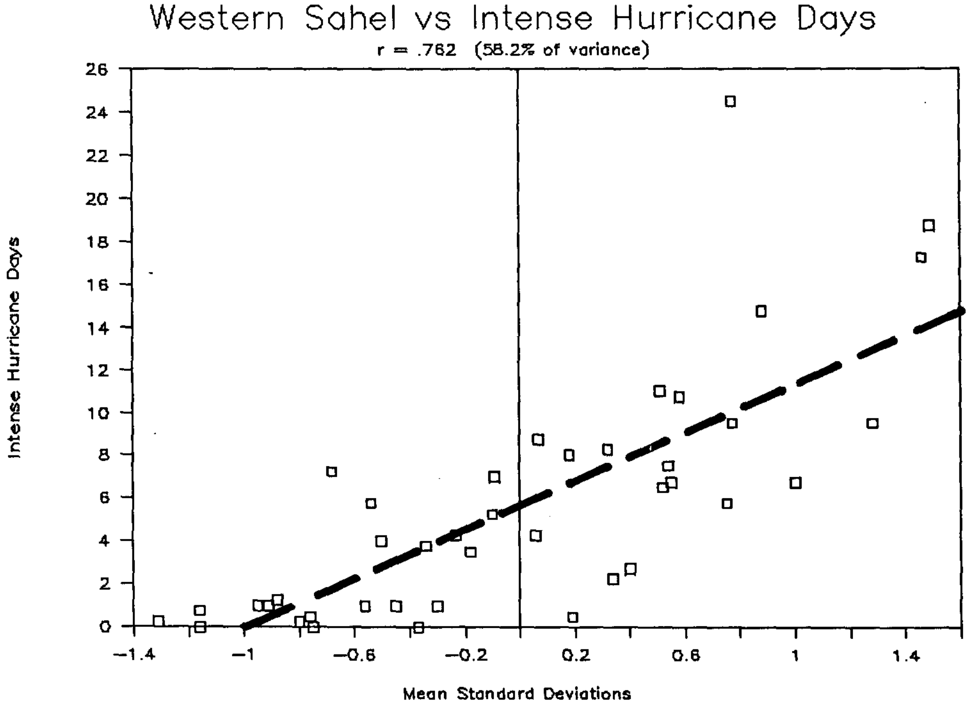

FIG. 8. Scatterplot of 1949–90 values of June–September western Sahelian rainfall index versus intense hurricane days. The dashed line is the least-squares best fit.

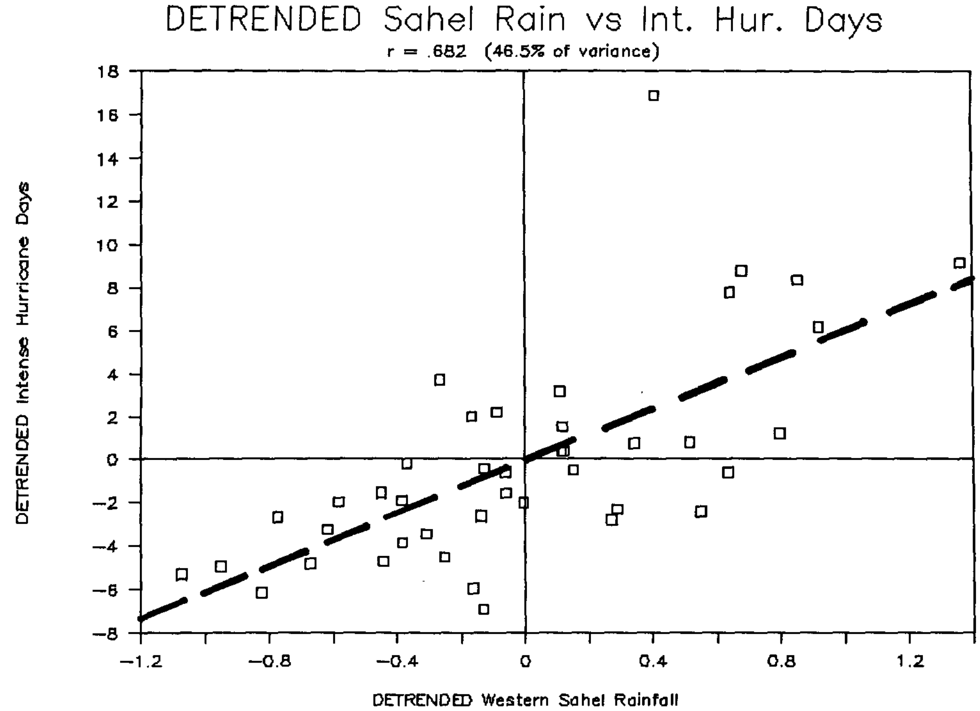

FIG. 9. Same as Fig. 8 but with linear trends removed from both datasets.

numbers and a 10 to 1 ratio in the intense hurricane days. Again, the statistical significance may be slightly exaggerated because of the rainfall region selection methodology. While the statistical significance for landfalling systems are not as high as the entire Atlantic basin statistics, this is understandable due to the small landfalling dataset being tested. Day-to-day characteristics of the mean steering flow are crucial in allowing

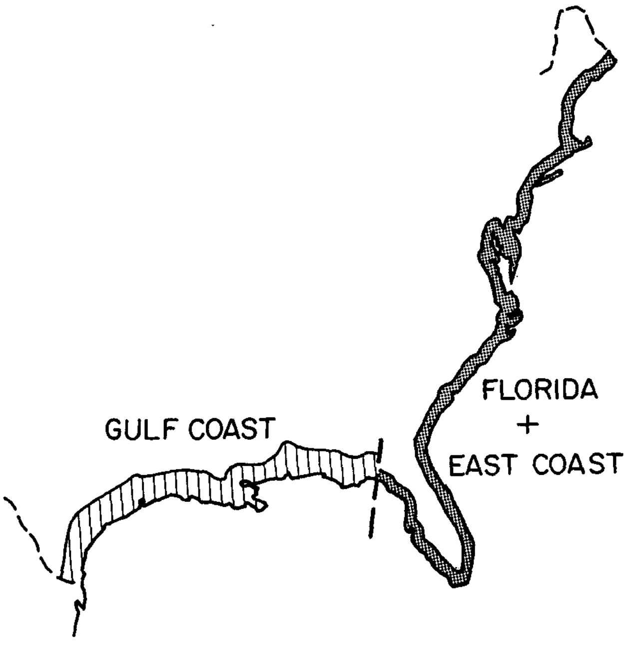

FIG. 10. United States coastal regions that experience differing responses of intense hurricane activity to western Sahelian rainfall. The approximate separation point is Apalachee Bay, Florida.

TABLE 6. June–September western Sahelian rainfall index ranked by rainfall amounts in mean standard deviations from 1949–90.

Rank	Year	Index value	Rank	Year	Index value
1	1950	1.49	22	1963	−0.09
2	1955	1.46	23	1949	−0.10
3	1958	1.28	24	1978	−0.18
4	1952	1.00	25	1974	−0.23
5	1964	0.88	26	1971	−0.30
6	1954	0.77	27	1981	−0.34
7	1961	0.77	28	1986	−0.37
8	1967	0.75	29	1970	−0.45
9	1989	0.58	30	1985	−0.50
10	1969	0.55	31	1979	−0.54
11	1953	0.55	32	1976	−0.56
12	1965	0.54	33	1980	−0.68
13	1957	0.52	34	1968	−0.75
14	1960	0.51	35	1987	−0.76
15	1956	0.40	36	1973	−0.80
16	1975	0.34	37	1982	−0.88
17	1951	0.32	38	1977	−0.91
18	1962	0.19	39	1990	−0.95
19	1988	0.18	40	1972	−1.16
20	1966	0.07	41	1984	−1.16
21	1959	0.06	42	1983	−1.31

TABLE 7. Summary statistics on the variability of tropical cyclone parameters from the 10 wettest western Sahelian years and the 10 driest years from 1949 to 1990. (Asterisks refer to significance level: 0.100 for ‘*’, 0.025 for ‘**’, and 0.005 for ‘***’.)

Tropical cyclone parameter	Climatology (42 years)	Wettest years' mean	Percent of normal	Driest years' mean	Percent of normal	Ratio wet/dry
Named storms	9.41	11.2	120	7.7	83	1.45***
Named storm days	47.2	67.0	143	34.0	73	1.97***
Hurricanes	5.85	8.0	138	4.6	79	1.74***
Hurricane days	23.8	39.1	165	13.2	55	2.96***
Intense hurricanes	2.48	4.5	180	0.9	36	5.00***
Intense hurricane days	5.69	12.4	214	1.2	21	10.33***
HDP	73.4	131.2	175	33.9	45	3.87***
U.S. landfalling:						
Named storms	3.30	3.4	103	1.9	58	1.79*
Hurricanes	1.82	2.1	130	0.7	43	3.00**
Intense hurricanes	0.72	1.2	167	0.2	28	6.00***
Gulf Coast	0.37	0.5	147	0.2	59	2.50*
East Coast	0.35	0.7	241	0.0	0	∞**
Caribbean Sea:						
Hurricanes	1.18	2.1	178	0.4	34	5.25***
Intense hurricanes	0.71	1.5	211	0.2	28	7.50***

landfall along the United States coastline; thus, variability on a seasonal basis for United States landfalling cyclones may contain more "noise."

The United States landfalling intense hurricanes can be roughly separated into two regions: the East Coast (including the Florida peninsula) and the Gulf Coast (including the Florida Panhandle). Intense hurricanes that strike the two regions have differing characteristics, such as the time of year when they come on shore and the origins of the storms (Landsea 1992b). Figure 10 illustrates the approximate separation point between the East and Gulf coasts for intense hurricane landfall. Note that while the East Coast experiences extreme differences in wet versus dry years in Table 7, the Gulf Coast shows only a moderate modification. Similarly to the East Coast, the Caribbean Sea region also shows a strong modulation of hurricane and intense hurricane numbers with respect to western Sahelian rainfall.

Since wet/dry differences in tropical cyclone frequency are accentuated with a component of duration (e.g., the named storm days, hurricane days, intense hurricane days, and HDP in Table 7), the cyclones are affected in their longevity in addition to their intensity. This assertion is supported by Table 8, in which the durations of the various tropical cyclones are contrasted by intensity. The most striking results are seen in the intense hurricane category where wet regime intense hurricanes lasted over twice as long, on average, as dry regime intense hurricanes. Figure 11 demonstrates the combination of more numerous and longer-lasting intense hurricanes in the wettest years versus the fewer, shorter-lived intense hurricanes in the driest years by the paths these cyclones took. This figure also highlights the differing number of strikes along the United States coastlines and the Caribbean Sea.

One possible mechanism that can account for the variations of tropical cyclones with western Sahelian rainfall is the differences that occur in the genesis. Although just more than half of the tropical storms and hurricanes in the Atlantic basin have been clearly demonstrated to originate from easterly waves, over three-quarters of all intense hurricanes have their origin from these waves (Landsea 1992b).

A method to study the western Sahelian rainfall effect on tropical cyclone genesis is to stratify the origins of tropical cyclones by western Sahelian rainfall index. However, as noted earlier, reliable estimates of the genesis point of Atlantic basin cyclones have only been available since 1967. Utilizing the 10 wettest versus 10 driest Sahelian years would not be possible because the majority of wet years occurred before that date. An alternative would be to name all years since 1967 from Table 2 with positive rainfall anomalies as "wet" years and those seasons with negative anomalies as "dry"

TABLE 8. Variation in durations of named storms, hurricanes, and intense hurricanes in the 10 wettest and 10 driest western Sahelian years from 1949 to 1990. (Asterisks refer to significance level: 0.100 for ‘*’, 0.025 for ‘**’, and 0.005 for ‘***’.)

Tropical cyclone parameter	Climatology (42 years)	Wettest years' mean days	Percent of normal	Driest years' mean days	Percent of normal	Ratio wet/dry
Named storms	4.9	6.0	122	4.4	90	1.36***
Hurricanes	3.9	4.9	126	2.9	74	1.69***
Intense hurricanes	2.3	2.8	122	1.2	52	2.33***

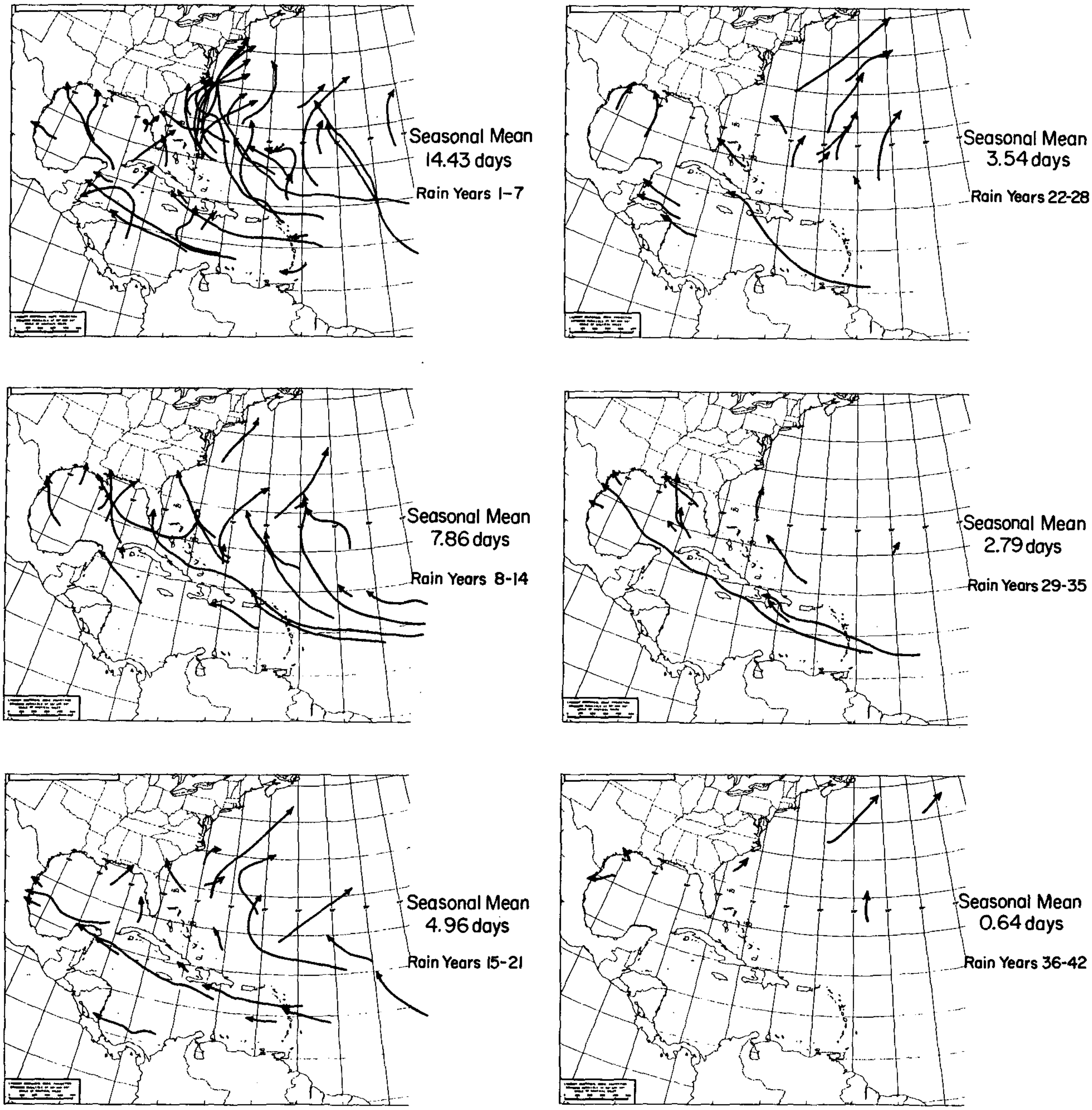

FIG. 11. Intense hurricane tracks by six 7-year groupings based on rankings of the June–September western Sahelian rainfall. Rain years 1–7 indicate the 7 wettest years, while rain years 36–42 show the 7 driest years.

years. This stratification splits the 24 years available into 5 wet years (with a mean value of $\sigma = 0.48$) and 18 dry years ($\sigma = -0.68$).

Table 9 shows the analysis of these wet- and dry-year composites. What is uncovered is a relative 10%–20% higher incidence of easterly wave contribution to named storms, hurricanes, and intense hurricane formation when the western Sahel is wet. Also, wet years show dramatic increases over dry years in the absolute numbers of easterly wave–spawned cyclones: 54% more named storms, 93% more hurricanes, and 136% more intense hurricanes. Thus, part of the increase in the total numbers of cyclones spawned in wet years is due to more storms forming from easterly waves. The non-African wave–spawned cyclones, though not explicitly described in the table, show a slightly higher incidence in the dry years. It is hypothesized that in the wet years general circulation changes and local conditions over West Africa favor more easterly waves to become tropical cyclones, especially those developing into intense

TABLE 9. Mean annual easterly wave contributions of tropical cyclone genesis for the western Sahelian rainfall index wet (5) and dry years (19) as well as the entire 24-year dataset.

	Wet years			Dry years			Twenty-four years		
Tropical cyclone intensity	All disturbances (#)	Waves (#)	Waves (%)	All disturbances (#)	Waves (#)	Waves (%)	All disturbances (#)	Waves (#)	Waves (%)
Named storms	11.4	8.0	70	8.5	5.2	61	9.1	5.8	64
Hurricanes	7.2	5.8	81	5.0	3.0	60	5.4	3.6	67
Intense hurricanes	2.8	2.6	93	1.4	1.1	80	1.7	1.5	87

hurricanes. During the dry years, the general circulation is unfavorable for easterly wave–spawned storm development, while the midlatitude-spawned systems are slightly enhanced.

7. Physical mechanisms

Two mechanisms appear to account for the consistent year-to-year covariation between western Sahelian rainfall and intense Atlantic basin hurricane activity (Gray 1990c). The first, as illustrated in Fig. 12, is that the general circulation is likely altered to be unfavorable to tropical cyclogenesis and intensification during Sahelian drought years and more favorable during abundant rainfall years in the Sahel. During the drought years, stronger upper tropospheric westerly winds are developed that typically cause more vertical wind shear—a feature that has long been known (e.g., Gray 1968) to be detrimental to tropical cyclones. As Kidson (1977) pointed out, dry years in the Sahel are typically accompanied by a weaker 200-mb tropical easterly jet over West Africa. Preliminary evidence of the circulation differences in the Atlantic basin are seen in Fig. 13, which shows a comparison of western Sahelian rainfall and Caribbean basin 200-mb zonal wind anomalies. Note that the higher amounts of western Sahelian rainfall are associated with easterly zonal wind anomalies.

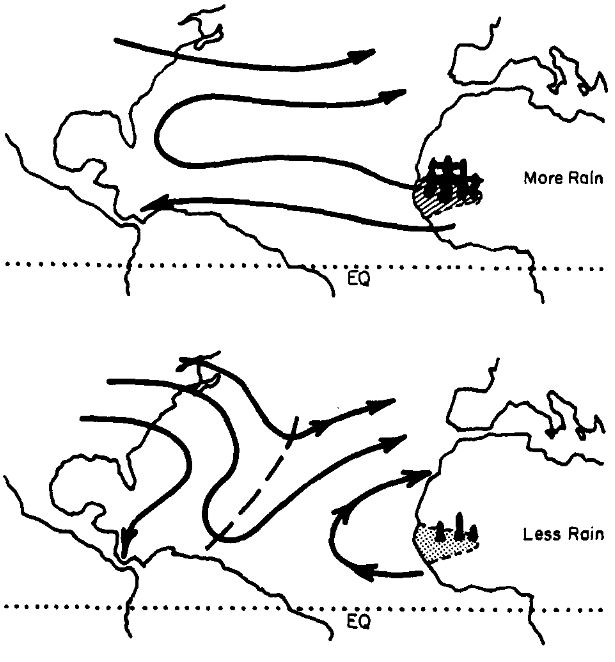

FIG. 12. Idealized portrayal of upper tropospheric wind patterns in wet (upper panel) versus dry (lower panel) western Sahelian years.

Another plausible influence of western Sahelian monsoonal strength variations on tropical cyclone activity is in the interannual modification of easterly waves. These waves were shown by Dunn (1940), who termed them westward-traveling "isallobaric waves," to act as the "seedling" circulations for tropical storms and hurricanes in the Atlantic basin. It was shown in Table 9 that over 90% of all intense hurricanes originate from easterly waves in wet western Sahelian years.

Since it has now been established that dry years in the Sahel correspond to less intense hurricane seasons, it is possible that 1) the number of easterly waves per year is decreased (as suggested by Druyan 1989), 2) the mean latitude where the waves travel is altered, or 3) the amplitudes of the waves are diminished (also as suggested by Druyan). The first hypothesis does not appear to be valid. Avila and Clark (1989) have shown that the number of waves originating over Africa is very stable. Yearly averages of 58 waves with a standard deviation of only 5 waves are observed. The second hypothesis is possible but not likely to affect tropical cyclone numbers and strengths unless the mean latitude is altered substantially. Personal communication from satellite experts Zehr and Avila do not suggest that this has happened.

Thus, the third hypothesis is the one needing most consideration. Figure 14 gives an idealized view that in wet western Sahelian years (June–September) a larger number of waves emanating from Africa have strong amplitudes (reflected in the streamlines at 700 mb and surface pressure) and have more concentrated, persistent deep convection. Some of these strong waves eventually develop into intense Atlantic hurricanes. In dry years, substantially fewer waves would be so organized and would show weaker or negligible convection, as well as having a weaker signature in the 700-mb flow field and surface pressure.

The next obvious question then is do weaker easterly

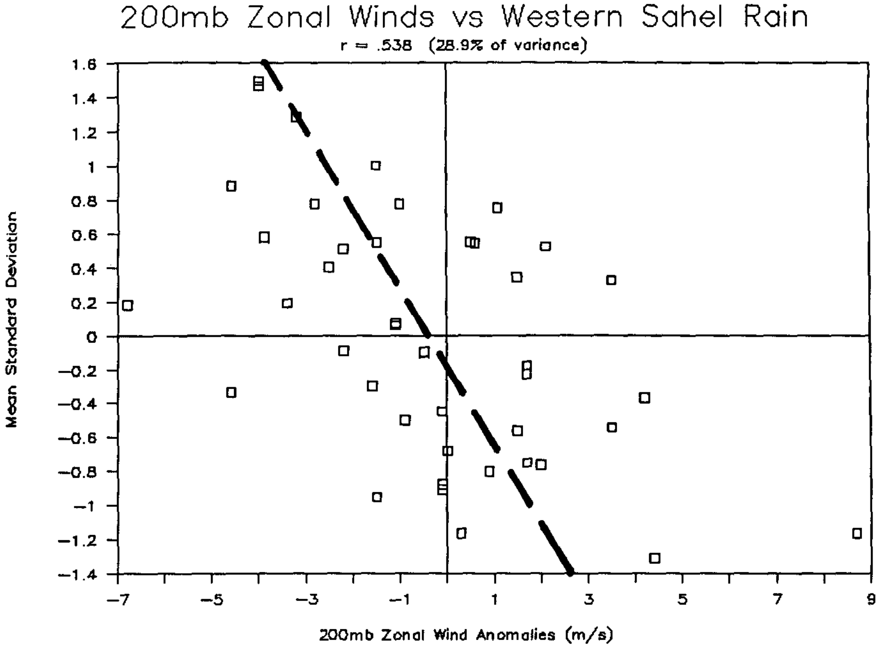

FIG. 13. August–September Caribbean basin 200-mb zonal wind anomalies (ZWA) versus the June–September western Sahelian rainfall for the years 1949–90. (Negative ZWA indicate easterly anomalies and positive indicate westerly anomalies.)

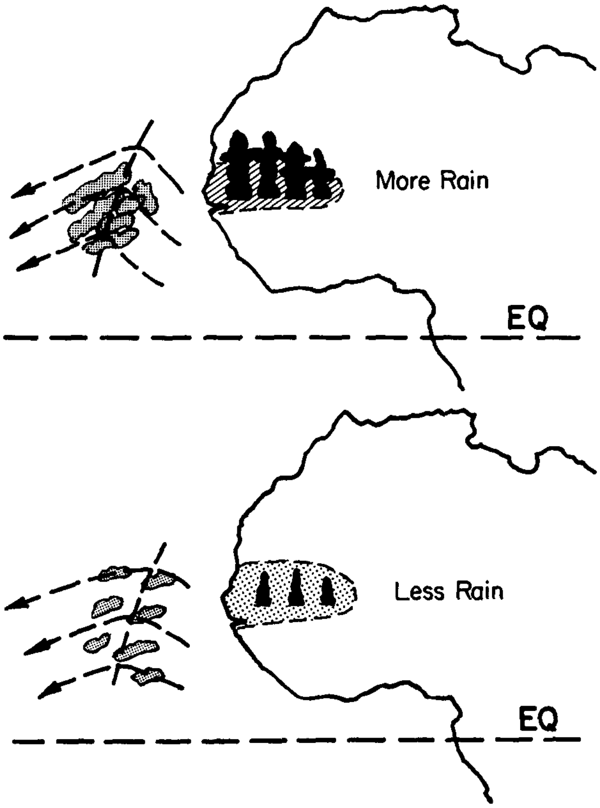

FIG. 14. Idealized portrayal of the easterly wave variations that are suggested to occur during wet (upper panel) versus dry (lower panel) western Sahelian years.

waves *cause* the Sahelian drought (since the waves with their embedded squall lines are the major contributors to the monsoon rainfall) or are weaker easterly waves a *result* of the drought conditions? It is also very possible that there is a feedback between the two and that there is no clear cause and effect. This question remains open at this time, but research is currently being conducted to help answer it.

8. Summary

Seasonal Atlantic basin tropical cyclone activity, especially that of intense hurricanes, is strongly related to concurrent western Sahelian rainfall. The association is shown to be strong even after substantial linear trends have been removed from the datasets. Additionally, an independent analysis of earlier data confirms the existence of the tropical cyclone–western Sahelian rainfall association. Plausible physical mechanisms have also been introduced to explain the association. An understanding of intense hurricane variations is extremely important because of the massive destruction these storms can cause and the recent emphasis on possible greenhouse gas warming impacts on their occurrence.

This new emphasis has taken the form of an American Meteorological Society and the University Corporation for Atmospheric Research joint statement (AMS Council and UCAR Board of Trustees 1988), suggesting that a potential greenhouse gas impact would result in "a higher frequency and greater intensity of hurricanes." Recent devastating cyclones with Hurricane Gilbert in 1988, the strongest storm ever measured in the western hemisphere (Willoughby et al. 1989), and Hurricane Hugo in 1989, "the most costly hurricane in the U.S. history" (Case and Mayfield 1990), have only raised concerns higher.

However, with the results shown here, the modulation of intense hurricane activity in the Atlantic basin is codependent on rainfall conditions in the Sahel. It is sadly ironic that 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, especially along the East Coast and the Caribbean islands, will experience many more destructive intense hurricanes. One should not identify a temporary return of intense hurricanes such as those that occurred in 1988 and 1989 as being even partially influenced by greenhouse gas warming. The association recognized here is probably not anthropogenic, but is likely due to the natural variations of the atmospheric–oceanic general circulation.

Acknowledgments. The bulk of this paper was gleaned from research toward the first author's Master's thesis at Colorado State University with the second author's tutelage (Landsea 1991). The first author had the privilege of attending the WMO Symposium on "Meteorological Aspects of Tropical Droughts with Emphasis on Long-Range Forecasting" at Niamey, Niger, in the spring of 1990. While there he had many excellent discussions of the western Sahelian rainfall and tropical cyclone association with Yinka Adebayo, Birama Diarra, Leonard Druyan, Graham Farmer, Stefan Hastenrath, Peter Hutchinson, Peter Lamb, Kevin Lane, Robert Livezey, Tim Palmer, Randy Peppler, Chet Ropelewski, M. V. Sivakumar, and Neal Ward. His time was well spent as he gained a greater appreciation for the severity of Sahelian drought conditions as well as for the people attempting to solve the mysteries of long-term droughts. It was truly a wonderful experience.

The authors are grateful for the African rainfall and Atlantic basin tropical cyclone data as detailed in section 3 and the Appendix. Much valuable computer programming expertise was contributed by Richard Taft, William Thorson, and Todd Massey. Barbara Brumit, Laneigh Walters, and Judy Sorbie-Dunn have provided important manuscript, data analysis, and figure-drafting assistance. Additional valuable discussions were had with Professors Wayne Schubert, Roger Pielke, Duane Stevens, David Randall, Paul Mielke, Kenneth Berry, and Edward Prill; with Research Associates John Sheaffer and Paul Ciesielski; with fellow Gray project students Steve Hodanish, Ray Zehr, Dan Mundell, Steve Hallin, John Knaff, and Mike Fitzpatrick here at CSU; and with Lloyd Shapiro and Stan Goldenberg at the Hurricane Research Division in Miami.

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APPENDIX

Colorado State University African Rainfall Database

The primary database for African rainfall is the "World Monthly Surface Station Climatology" (WMSSC) managed by W. M. L. Spangler and R. L. Jenne at the National Center for Atmospheric Research (NCAR). Though WMSSC provides surface data (precipitation, temperatures, surface pressures, sea level pressures, and others) globally, our interest was primarily precipitation (rainfall) data over Africa. The data collection, extending from the mid-1800s to 1988, is available mainly from the efforts of Prof. S. E. Nicholson of Florida State University for additional historical data. Including stations located on nearby islands (Azores, Canary, Madeira, Seychelles, and Madagascar), the WMSSC dataset has 584 African stations with rainfall information. The *Monthly Climatic Data for the World* (MCDW) by the National Climatic Data Center (U.S. Department of Commerce 1989) has provided an official monthly updating for the same stations through December 1989. The data presented in MCDW is essentially what will be used in the next updating of WMSSC.

A secondary dataset that supplements the WMSSC information was supplied to us by G. Farmer of the AID FEWS Project in Arlington, Virginia. He provided us with additional information on 36 WMSSC stations and data on 75 agricultural raingages that have been available since 1951. These stations are all in the Sahelian region from Senegal in the west to Chad in the east. In general, the quality on the 36 stations that overlapped with the WMSSC stations was higher in the AID stations (e.g., less rounding to the nearest 10 mm, less missing data, fewer unreasonable outliers). Therefore, in combining the datasets together, the AID data were chosen as more reliable in the case where there was a 3-mm or greater difference between WMSSC and AID for monthly rainfall amounts.

Additionally, E. O. Oladipo of Ahmadu Bello University provided us with monthly rainfall data for stations in Nigeria. Recently it has been difficult to obtain data for Nigeria. Professor Oladipo has graciously provided us with data for 13 stations from 1970 to 1988. Since the data were coming directly from the stations involved, these rainfall data were considered to be of high quality.

P. J. Lamb also provided us with the 20 stations used in his index of western Sahelian rainfall. He has used this data in connection with his research in the underlying physical mechanisms for Sahelian drought (Lamb 1982), as well as in a real-time monitoring of the Sahel in conjunction with CAC (Lamb et al. 1990). The data were very similar in quality to WMSSC, yet provided information for some stations that had missing data. Accordingly, Lamb's data were utilized to fill data gaps but were considered a lower priority than WMSSC, AID, and Nigeria data in duplications.

The final addition used in this study was more recent data provided by D. Miskus and R. J. Tinker of CAC. They provided CAC's best *estimates* of monthly rainfall, as they are able to infer from daily reports on the Global Telecommunications System (GTS) going back to 1960. This information provided excellent preliminary data that will temporarily fill in gaps until updated reports from NCDC are received. Miskus and Tinker have also been very generous in providing real-time data so as to enable us to monitor the Sahel [as it now relates to Gray's (1990a, 1990b, 1990d) seasonal hurricane forecasts]. Since these are estimates (and can be somewhat erroneous due to missing and mistaken reports) and not the official report, these data are only used in absence of any other information (i.e., WMSSC, AID, Nigeria, and Lamb).

Thus, the datasets used in this paper and the relative order of priority can be summarized as

highest priority:	Nigeria data
	AID data
	WMSSC and MCDW data
	Lamb data
lowest priority:	CAC estimated data.

Landsea (1991) has additional detailed information regarding individual station rainfall data.

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