Strong Association Between West African Rainfall and U.S. Landfall of Intense Hurricanes

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Intense hurricanes occurred much more frequently during the period spanning the late 1940s through the late 1960s than during the 1970s and 1980s, except for 1988 and 1989. Seasonal and multidecadal variations of intense hurricane activity are closely linked to seasonal and multidecadal variations of summer rainfall amounts in the Western Sahel region of West Africa. The multidecadal nature of West African precipitation variations and their association with variations of intense Atlantic hurricane activity can be observed in data going back nearly a century. The apparent recent breaking of the 18-year Sahel drought during 1988 and 1989 suggests that the incidence of intense hurricanes making landfall on the U.S. coast and in the Caribbean basin will likely increase during the 1990s and early years of the 21st century to levels of activity notably greater than were observed during the 1970s and 1980s.

USUALLY, THE VAST MAJORITY OF HURRICANE-RELATED damage is caused by the comparatively infrequent but very powerful storms. An understanding of the long-term variable frequency of intense hurricane activity is important in planning for hurricane damage mitigation. The growing population and the vastly increasing property values along the U.S. Atlantic and Caribbean coastlines that have taken place since the late 1960s indicate that a return to a greater incidence of intense hurricanes, such as has occurred in earlier decades, would be accompanied by a period of significantly greater coastal property damage.

In this article, I examine the association between West African rainfall and intense Atlantic hurricanes and discuss the possible physical basis for a link between the two. In consideration of the proximity of West Africa to the tropical Atlantic and the observation that the most intense hurricanes are spawned from easterly waves that move out of Africa, it is perhaps not surprising that variable aspects of both West African summer rainfall and Atlantic hurricane activity might be related.

The relation between precipitation and intense hurricane activity is best observed for summertime monsoon rainfall in the Subsahara, or Sahel, region (Fig. 1) of Africa. Data taken throughout this century, as well as the reasonably reliable rainfall records or proxy estimates that can be assembled for the last few centuries (*1–3*), show that alternating multidecadal periods of comparatively wet and dry conditions are characteristic of the climate in this semiarid region. Multidecadal variations and the association with intense hurricanes are especially strong with regards to rainfall records from stations in the Western Sahel area encompassing Senegal, southern Mauritania, western Mali, Gambia, and Guinea Bissau (Fig. 2). The data on year to year variations of June through September rainfall at these stations from 1947 to 1989 (Fig. 3) show that large amounts of rainfall occurred over the Western Sahel from the late 1940s through the 1960s, whereas drought conditions occurred during much of the 1970s and 1980s, before the summer of 1988.

Hurricane Activity and Sahel Rainfall Variations

In general, the annual frequency of intense Atlantic hurricanes was appreciably greater from 1947 to 1969, when plentiful amounts of rainfall occurred in West Africa, than during the years between 1970 to 1987, when drought conditions prevailed. This multidecadal association is best observed in the incidence of the strongest and most destructive hurricanes; more so than in the total frequency of named (*4*) or tropical storms. For example, the seasonal frequency and the lengths of tracks of intense category 3, 4, and 5 hurricanes, as defined by the Saffir-Simpson (*2, 3*) intensity scale (Table 1), were substantially greater during the period from 1947 through 1969, in comparison with those of the 18-year period of 1970 through 1987 (Fig. 4). Differences in track length are particularly evident to the east of the U.S. mainland (Fig. 4). As shown in Fig. 5, these variations are strongly associated with Western Sahel rainfall for June through September during the last 50 years (a 5-year running average has been applied to the data in Fig. 5 to smooth out excursions during individual years so as to better portray such longer period variability). The average incidence of the stronger Saffir-Simpson category 3, 4, and 5 hurricanes for 1947 to 1969 versus 1970 to 1987 show interdecadal differences of more than 2:1 (Table 2).

Various other measures of hurricane and (named) tropical storm frequency for the most recent wet (1947 to 1969) and dry (1970 to 1987) periods show similar variations (Table 2 and Fig. 5). Although interdecadal differences in the total frequency of Atlantic hurricanes and of total named tropical storms are not great, differences in both the incidence of the more intense hurricanes and the numbers of hurricanes in the Caribbean are quite significant. There is virtually no difference, however, for the incidence of the less

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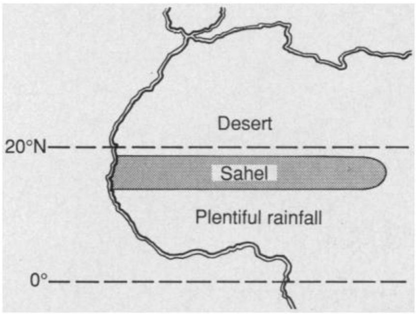

Fig. 1. Approximate location of the Sahel region (shaded) of Subsaharan Africa; this region is characterized by marginally adequate rainfall and large multidecadal variations in rainfall.

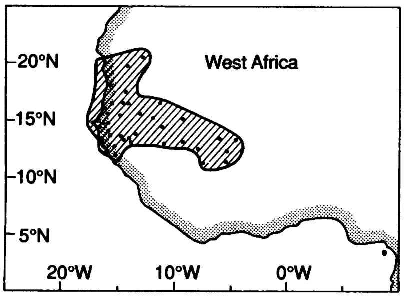

Fig. 2. Location of 38 Western Sahel observation stations where combined rainfall is best correlated with intense hurricane activity.

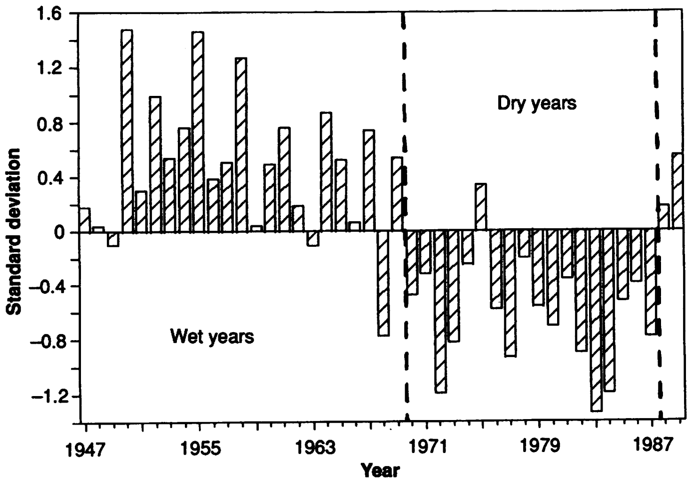

Fig. 3. Seasonal precipitation anomalies, expressed in terms of the standard deviation of June through September average rainfall, for 1947 to 1989 at the 38 Western Sahel stations shown in Fig. 2.

Table 1. Wind speed and storm surge criteria for Saffir-Simpson (S-S) hurricane intensity categories and hurricane potential destruction (PD) scale; PD is assumed to increase with the square of the Saffir-Simpson category.

S-S category	Range of central pressure (mbar)	Maximum sustained wind speed (m/s)*	Storm surge (m)	PD value
1	≥980	33 to 42 (74 to 95)	1 to 2	1
2	965 to 979	43 to 49 (96 to 110)	2 to 2.5	4
3	945 to 964	50 to 58 (111 to 130)	2.5 to 4	9
4	920 to 944	59 to 69 (131 to 155)	4 to 5.5	16
5	<920	≥69 (155)	≥5.5	25

*Miles per hour given in parentheses.

Table 2. Summary data for the annual incidence of various classes of tropical cyclones for the entire Atlantic basin (including the Caribbean and the Gulf of Mexico), stratified by wet (1947 to 1969) versus dry (1970 to 1987) conditions in the Western Sahel. Ratios of the values for 1947 to 1969 to those for 1970 to 1987 are shown in the last column. A comparison of the average data for the 1988 and 1989 seasons is also shown.

Class	Annual incidence			
	Wet 1947 to 1969	Dry 1970 to 1987	Wet 1988 to 1989	Ratio (wet/dry)
Total named storms	9.96	8.28	11.50	1.20
Total hurricanes				
Atlantic Basin	6.48	4.94	6.00	1.30
Caribbean Basin	1.48	0.50	1.50	2.96
Total Atlantic hurricanes*				
3, 4, and 5	3.30	1.55	2.50	2.13
1 and 2	3.18	3.44	3.50	0.92
Total named storm days	53.6	37.3	56.5	1.44
Total hurricane days	30.1	15.0	28.0	2.01
Category 3, 4, and 5 days	8.53	2.10	9.38	4.13

*Saffir-Simpson intensity category.

intense, category 1 and 2 hurricanes. These comparisons become even more striking for the annual incidence of intense hurricane (category 3, 4, and 5) days, which were more than four times as great during 1947 through 1969 as during 1970 through 1987. The incidence of category 3, 4, and 5 days has again risen during the last 2 years (Table 2).

The strong association of Atlantic hurricane activity and West African rainfall is also evident in comparative composites based on the number of tracks for category 3, 4, and 5 hurricanes occurring during the ten wettest versus the ten driest Western Sahel rainfall years during the 43-year period 1947 to 1989 (Fig. 6). An annual average of 12.4 intense hurricane days occurred during the ten wettest years versus 1.2 during the ten driest years, a difference of 10 to 1. Whereas a total of 45 category 3, 4, and 5 hurricanes occurred during the ten wettest years, only ten such hurricanes occurred during the ten driest years, a greater than 4 to 1 difference.

Landfall of Intense Hurricanes on the U.S. Coastline

When analyzed by intensity category, data for hurricanes of Saffir-Simpson categories 3, 4, and 5 striking the United States also show large multidecadal differences in frequency, particularly data for intense hurricanes making landfall on Florida and the U.S. East Coast. During the dry Sahel period of 1970 through 1987, for example, only one category 3 hurricane (Gloria, 1985) made landfall along the U.S. East Coast and Florida, excluding the Panhandle area (Fig. 4B). By contrast, 13 category 3 or greater hurricanes made landfall along this same coastline during the period of 1947 to 1969 when the Western Sahel was wet (Fig. 4A). Five of these (Carla, 1961; Donna, 1960; Audrey, 1957; Hazel, 1954; no name, Florida and Mississippi, 1947) were category 4 and one (Camille, 1969) was category 5. In contrast, no category 4 or 5 hurricanes made a U.S. landfall during the 18-year dry period of 1970 to 1987.

The frequency of intense hurricanes striking the U.S. Gulf Coast (including the Florida Panhandle) shows less sensitivity to variations in Western Sahel rainfall conditions, however. Intense hurricanes making landfall along the Gulf Coast appear to be more dependent upon meteorological conditions farther downwind from West Africa. Intense hurricanes can develop in the Gulf of Mexico from non–

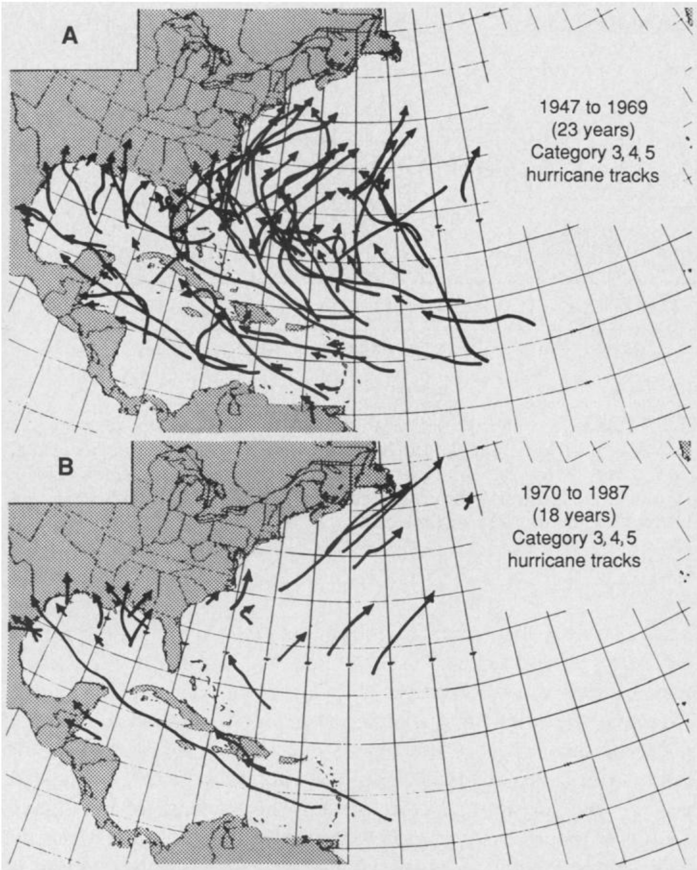

Fig. 4. Comparison of tracks for all major hurricanes (Saffir-Simpson category 3, 4, and 5) for the 23-year period 1947 to 1969 (**A**) when West Africa was wet versus the 18-year period 1970 to 1987 (**B**) when it was dry.

of hurricanes making landfall can be approximated in a parameter called potential destruction, or PD.

With this assumption, rather reliable historical estimates of the relative damage potential of hurricanes that have struck the United States can be made. Records of the Saffir-Simpson category of each hurricane to hit the United States this century are available. Squaring these values, it is possible to determine the long period relative differences in U.S. coastal hurricane potential destruction; large multidecadal variations in the annual averages of PD for U.S. hurricanes are evident in the data. As in the comparisons above, we again observe particularly large multidecadal variations in PD for hurricanes making landfall on peninsular Florida and the U.S. East Coast (Fig. 7). Similar differences occur in the PD data from the Caribbean. These variations fit rather well with the multidecadal variations in African Sahel precipitation.

Sahel rainfall data indicate that alternating multidecadal wet and dry conditions prevailed during the following approximate periods of the last century. These include: the 25 to 30 years before 1900 (generally wet); 1900 to 1914 (distinctly dry); 1915 to 1935 (generally wet); 1936 to 1946 (generally dry); 1947 to 1969 (distinctly wet); 1970 to 1987 (distinctly dry); and 1988 to 1989 (becoming wet). Annual values of category 3, 4, and 5 hurricane days for these wet and dry periods also show large differences. An average of 2.53, 2.34, and 2.10 of intense hurricane days per season respectively was reported during the three dry periods as compared to an average of 5.52 and 8.53 intense hurricane days per season during the two most recent wet periods (other than 1988 to 1989).

Over these several cycles, wet periods in the African Sahel have also been associated with two to four times as much PD from hurricane landfall as occurred during Sahel dry periods. These multidecadal variations are especially striking in regard to hurricanes striking Florida.

African wave origins; Audrey (1957) and Alicia (1983) are notable examples. But during the ten driest years in the Western Sahel between 1947 and 1989, no category 3, 4, or 5 hurricanes, other than two category 3 storms in Texas, made landfall anywhere along the U.S. coast (Fig. 6). Clearly, peninsular Florida, the U.S. East Coast, and the Caribbean Basin have experienced the largest decrease in intense hurricanes in association with the long-running Western Sahel drought of 1970 to 1987. It is these coastal areas (not so much the Gulf Coast), that will likely see the largest upswing in landfall of intense hurricanes when a long period of heavier rainfall returns again to West Africa. Intense Caribbean hurricanes Gilbert, Joan, and Hugo of 1988 to 1989 may be the forerunners of this change.

Relative Potential Destruction of Hurricanes Making U.S. Landfall

Damage by category 4 and 5 hurricanes is typically a factor of 15 to 25 greater than damage by category 1 and 2 hurricanes (*5*). The contrast between the vast damage from a category 4 storm (for example, Hurricane Hugo) in 1989 versus the minimal effects of the 1989 category 1 hurricanes, Chantal and Jerry, in the Houston area, illustrates this difference. To a reasonable approximation, it can be assumed that the potential damage from a hurricane increases as the square of the integer value for the Saffir-Simpson category (Table 1). This assumption accommodates the observation that wind and storm surge destruction by hurricanes is more closely related to the square of the maximum wind. This relative potential destructiveness

Rainfall Predictive Signals

Intense hurricanes occur mostly (83% of the total) during August and September. Landsea (*6*) showed that there are good predictors (before the active hurricane season) for Western Sahel precipitation and hence for intense hurricane activity. Late summer and autumn precipitation during the previous year along the West African Gulf of Guinea area plus early season, May through July, Western Sahel precipitation are found to be good predictors of hurricane activity. Together, pre- and early-season rainfall amounts account for some-

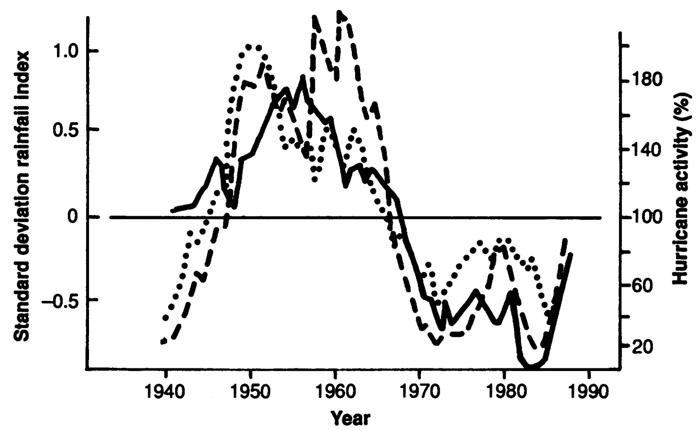

Fig. 5. Comparison of 5-year running averages for June through September rainfall in the Western Sahel (solid line) versus the percent variability of Saffir-Simpson category 3, 4, and 5 hurricanes (dashed line) and of category 3, 4, and 5 hurricane days (dotted lines).

what more than half the variance of the later Western Sahel rainfall season and of intense hurricane activity during the subsequent August to September period. These pre- and early-season rainfall predictive signals may be an indication of a strong influence by differing amounts of rain-induced vegetation and soil moisture on later season rainfall.

Causes of Multidecadal Variability

Multidecadal climate cycles are a pervasive feature of the global ocean-atmospheric circulation, appearing in meteorological and ocean data as far back as measurements have been made. The factors most directly responsible for variable Sahel rainfall conditions on multidecadal time scales appear to be linked to basic changes in the larger scale global circulation patterns; these changes in turn appear to be linked to long-term variations in global-scale sea-surface temperature (SST) anomalies. Although not yet well understood, such SST variations are generally thought to be associated with variations of ocean circulation and vertical mixing processes, which are also known to occur on time scales of decades or longer (*7*). A number of additional large-scale climatic variations occur on time frames closely paralleling those occurring in Sahel precipitation, intense Atlantic hurricanes, and global sea surface temperatures; these include interdecadal trends in: hemispheric 500-mb height fields (*8*); hydrologic data including long-term trends in the surface elevations of the Great Salt Lake and the Great Lakes of North America (*9*); the distribution of salinity and sea ice in the North Atlantic (*10*); predictive indices for seasonal weather forecasting (*11*); the incidence of cyclogenesis over North America (*12*); and other more complex indices of global climate termed "climate state vectors" and "clustering factors" (*13*). Collectively, these and numerous other studies suggest that the interdecadal precipitation in the Sahel and intense hurricane variability are regional manifestations of a global-scale climate variation, involving both tropical and extratropical regions, which is largely modulated by global-scale oceanic thermohaline processes. The global-scale associations listed above, or others, may also be useful in the near term as proxy indices for delineating long-term variations of wet or dry Sahel conditions and hence of relatively active or inactive hurricane conditions.

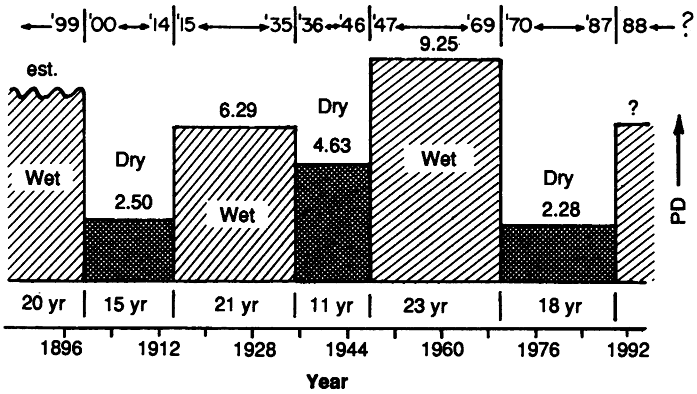

Fig. 7. Selected multidecadal mean annual values of hurricane potential destruction (PD) (Table 1) for hurricanes making landfall on peninsular Florida and along the U.S. East Coast, separated on the basis of rainfall periods in the Western Sahel. Mean annual PD and dates for each period are indicated at the top (est., estimated).

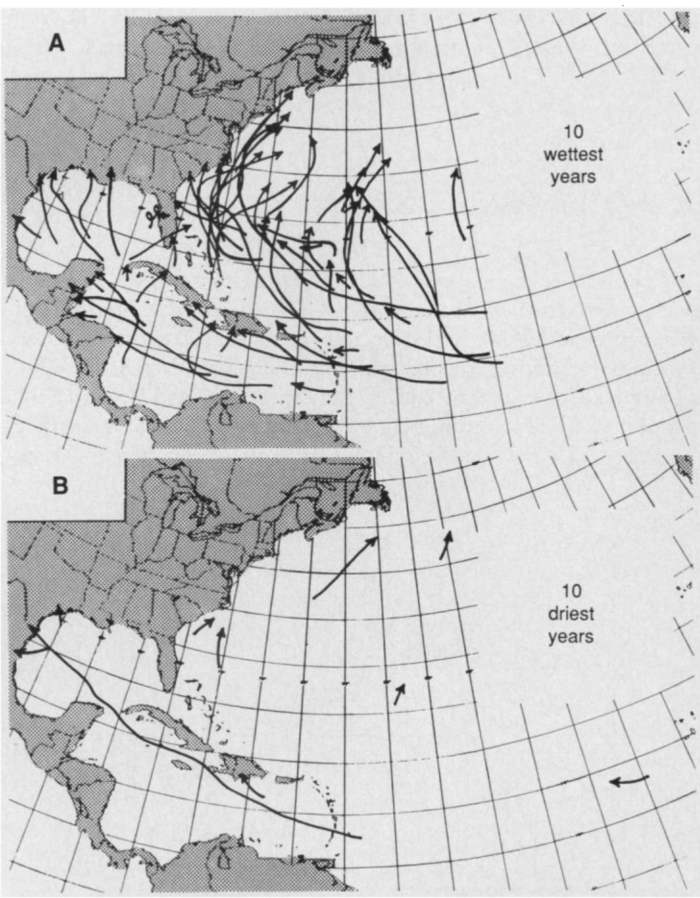

Fig. 6. Comparison of intense hurricane tracks during the ten wettest years in the Western Sahel (**A**) versus the ten driest years (**B**) during the 43-year period 1947 to 1989. In order of rain amount, the wettest years are 1950, 1955, 1958, 1952, 1964, 1954, 1961, 1967, 1989, and 1969. Driest years in order of lowest amounts of rain were 1983, 1972, 1984, 1977, 1982, 1973, 1987, 1968, 1980, and 1976.

Changes observed in the regional atmospheric circulation over the tropical Atlantic during the 1970s and 1980s appear to be closely tied to large-scale warming of tropical SSTs in the Southern Hemisphere and concurrent large-scale cooling of SST over much of the Northern Hemisphere [see (*8, 9*) and Fig. 8]. During this period, warm SST anomalies occurred over the South Atlantic Ocean, Western Indian Ocean, and the eastern tropical Pacific Ocean while comparatively cold SST anomalies developed over large parts of the Northern Hemisphere. This north to south distribution of Atlantic SST anomalies (Fig. 9) seems to have modified the regional circulation so as to inhibit the establishment of a strong summertime monsoon trough over West Africa. The strength of the westward extension of the Intertropical Convergence Zone over the Atlantic and Caribbean is also weaker during West African drought periods.

The majority of Atlantic weather disturbances that eventually develop into intense hurricanes originate from West Africa (*14*). Weather disturbances originating over West Africa typically remain over tropical waters for an appreciably greater time than do systems that form in the Western Atlantic or Caribbean and hence have more time to develop into intense hurricanes. Of the 50 to 60 westward moving wave disturbances that typically emanate from West Africa each summer, more tend to be stronger and better organized systems when heavier seasonal rainfall conditions prevail in the Western Sahel region. Therefore the number of easterly wave systems emanating out of West Africa each summer is apparently not crucial to the increased formation of intense hurricanes. Rather, it is the degree of organization and strength of some of these systems, in combination with several aspects of the tropospheric environment in the tropical Atlantic through which these organized disturbances move for several days, that is most critical.

Moist conditions in the Sahel tend to reduce the north to south temperature gradient in the lower troposphere between roughly 8° to 18°N latitude. This difference in turn diminishes the strength of the mid-to-low tropospheric (3 to 4 km) easterly jet over West Africa. Consequently, the mode of convection over the region tends to favor the production of the relatively slower moving, better organized, and deeper tropospheric weather systems that are typical of pre-hurricane cloud clusters. This is in contrast to the more rapidly moving and less conservative African squall line systems that develop during dry years and quickly dissipate as they move over the eastern Atlantic.

Abundant rain in the African Sahel region during June to September is also typically accompanied by large-scale circulation patterns over the tropical Atlantic that are favorable for the development of intense hurricanes (*14, 15*). In general, the formation of hurricanes is favored by (i) upper tropospheric winds over the equatorial Atlantic that are somewhat more easterly than normal, in conjunction with comparatively weak upper tropospheric westerly winds over the low-latitude areas of the Caribbean (Fig. 10); (ii) weakening of the low-level trade winds over the equatorial Atlantic (Fig. 10); (iii) relatively low surface pressure over the equatorial Atlantic and Caribbean Basin; (iv) comparatively warm SSTs off northwest Africa (0.5° to 1.0°C above average); and (v) a stronger than average monsoon trough over West Africa. Each of these factors is a crucial component in the combination of conditions needed for the formation of tropical cyclones in the Atlantic (*16*).

In summary, hurricane activity is enhanced during the wet periods when Atlantic SST anomalies favor the development of a stronger than normal monsoon trough over West Africa and when upper tropospheric westerly winds over the central tropical Atlantic and eastern Caribbean are weaker than normal. The strengthening of the monsoon trough observed during wet Sahel years diminishes regional vertical tropospheric wind shear and thereby creates a more favorable environment for developing tropical waves. At the same time, effects (i) and (ii) over the tropical Atlantic create greater low-level north-south regional cyclonic shear vorticity while also weakening the tropospheric vertical wind shear. In contrast, regional SST conditions during the recent dry period tended to more closely resemble those shown in Fig. 9B; the West African monsoon trough was generally weak and upper tropospheric westerly winds (see Fig. 10) were stronger than normal over the lower Caribbean Basin and equatorial Atlantic. Strong westerly winds are especially effective in inhibiting tropical storm development.

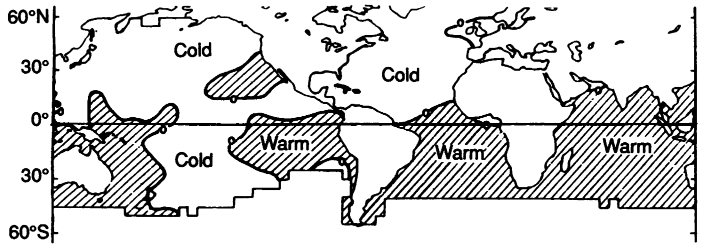

Fig. 8. Sea-surface temperature (SST) anomaly patterns associated with Sahel drought conditions. [Adapted from results in (*3*).]

then we should expect an eventual recurrence of somewhat heavier Western Sahel precipitation, possibly during the 1990s and the early years of the 21st century. With such a rainfall increase, we should also expect a return of more frequent intense hurricane activity in the Caribbean Basin and along the U.S. coastline. The historical data imply that such an increase in intense hurricane activity should be viewed as a natural change and not as a result of man's influence on his climate.

Western Sahel rainfall during June to September of 1988 and 1989 was 50% greater than the average values that occurred from 1970 through 1987. This comparatively heavy Western Sahel rainfall of 1988 and 1989 suggests that a change from drought to

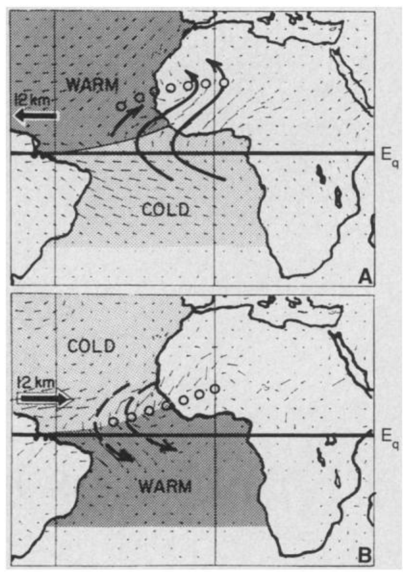

Fig. 9. Conceptual representation of the typical low-level wind anomaly patterns associated with wet Western Sahel summers and dry Western Sahel summer conditions (bottom diagram). Circles indicate typical position of the monsoon trough. Typical Western Atlantic upper troposphere (12 km) zonal wind anomaly associated with these wet and dry patterns is also indicated by the large arrow at the left in each panel.

Implications for Future Hurricane Activity

Nicholson (*1*) has obtained evidence of distinct multidecadal wet and dry periods in West Africa dating back to the 17th century. Nicholson suggested that the periods spanning 1820 to 1840 and 1895 to 1920 were generally dry, while the period from 1870 to 1895 was judged to be relatively wet. These historical studies, as well as other indirect evidence from still earlier times, indicate that multidecadal wet and dry periods similar to the ones recognized recently have occurred for several hundred years in this region. In view of this record, we should not be surprised that the Western Sahel experienced a prolonged wet period during the late 1940s through the 1960s or that a distinctive dry period occurred from 1970 to 1987; these variations appear to be natural characteristics of West African rainfall.

If these past variations are a reasonable indication of the future,

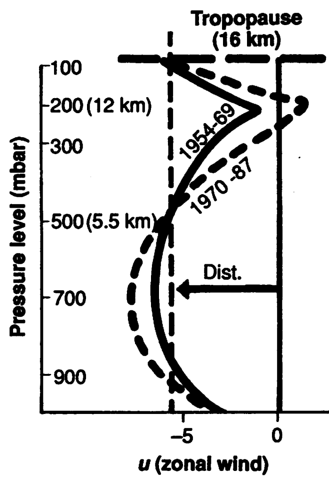

Fig. 10. Comparative mean vertical profiles of lower latitude zonal winds in the Caribbean Basin in meters per second (eastward directed winds are positive) for August to September of 1954 to 1969 versus August to September of 1970 to 1987. "Dist." indicates the typical zonal speed (hence rate of displacement) of westward propagating tropical disturbances that develop into hurricanes. There was greater vertical shear of the zonal wind during the later, drier period. Upper tropospheric data were not available before 1954.

wet conditions may already be occurring. With this possibility in mind, meteorologists need to develop a greater appreciation of the association between West African rainfall and the incidence of intense Atlantic hurricanes with a special focus on improved methods for monitoring and forecasting the West African weather conditions on weekly, monthly, and seasonal time scales. Coastal populations in the United States and Caribbean, as well as officials involved with disaster management, civil defense, and related activities should also be aware of the implications of increased West African rainfall for increases in intense hurricane activity. The observation and forecasting of West African precipitation and related large-scale circulations should now become a priority for all hurricane-related interests. Given the association of Sahel rainfall with patterns of Atlantic SST, wind, and pressure, it is likely that research aimed at developing explicit seasonal forecasts of Western Sahel rainfall should also contribute to significant improvements of seasonal hurricane prediction schemes.

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16. Although the specific processes responsible for the transformation of some tropical cloud clusters (and not others) into tropical cyclones remain the subject of extensive research, it is generally agreed that several key physical factors are implicated in the environmental conditions required for this transformation. These factors include a minimum of vertical wind shear, high humidity through the lower and middle troposphere, low-level cyclonic (horizontal) wind shear, SST values greater than about 26°, and a fairly deep thermocline. These considerations are examined at length in W. M. Gray, in *Meteorology Over the Tropical Oceans*, D. B. Shaw, Ed. (Royal Meteorological Society, Bracknell, UK, 1979), pp. 155–218 (suppl.).

17. Printed copies of Atlantic hurricane forecasts for the last 6 years and subsequent seasonal verification reports are available at no charge from the author. I thank C. Landsea and J. Sheaffer for scientific and technical assistance in the preparation of the manuscript. R. Jenne, D. Joseph, D. Miskus, D. LeComte, and P. Lamb provided West African rainfall data. This research was supported by the National Science Foundation, grant no. ATM-8814373.

Spreading of Liquids on Highly Curved Surfaces

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Because of surface tension, liquid films coating fibers or the insides of capillary tubes are usually unstable and break up into a periodic array of droplets. However, if these films are very thin (of thickness in the range of tens of angstroms), they can be stabilized by long-range van der Waals forces. A simple method for making such wetting films consists of slowly drawing the fiber out of a bath of liquid; the thickness of the film is then measured using a method based on gas chromatography. If these liquid films are thick, and are forced to flow, they may then not break up: the instability becomes "saturated."

Even those who are frightened by spiders may wonder at the architecture of their webs. For instance, *Araneus diadematus*, the common diadema garden spider, builds a radial structure (at the center of which the spider usually stands) and then superimposes a circumferential network consisting of capture threads. When these threads are extruded from the spinneret, they are uniformly coated with a sheath of glue that spontaneously breaks up into droplets upon which the spider's victims become trapped. The instability of the liquid sheath has been used by spiders for hundreds of millions of years but has been studied by scientists for

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