The Extremely Active 1995 Atlantic Hurricane Season: Environmental Conditions and Verification of Seasonal Forecasts

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ABSTRACT

The 1995 Atlantic hurricane season was a year of near-record hurricane activity with a total of 19 named storms (average is 9.3 for the base period 1950–90) and 11 hurricanes (average is 5.8), which persisted for a total of 121 named storm days (average is 46.6) and 60 hurricane days (average is 23.9), respectively. There were five intense (or major) Saffir–Simpson category 3, 4, or 5 hurricanes (average is 2.3 intense hurricanes) with 11.75 intense hurricane days (average is 4.7). The net tropical cyclone activity, based upon the combined values of named storms, hurricanes, intense hurricanes, and their days present, was 229% of the average. Additionally, 1995 saw the return of hurricane activity to the deep tropical latitudes: seven hurricanes developed south of 25°N (excluding all of the Gulf of Mexico) compared with just one during all of 1991–94. Interestingly, all seven storms that formed south of 20°N in August and September recurved to the northeast without making landfall in the United States.

The sharply increased hurricane activity during 1995 is attributed to the juxtaposition of virtually all of the large-scale features over the tropical North Atlantic that favor tropical cyclogenesis and development. These include extremely low vertical wind shear, below-normal sea level pressure, abnormally warm ocean waters, higher than average amounts of total precipitable water, and a strong west phase of the stratospheric quasi-biennial oscillation. These various environmental factors were in strong contrast to those of the very unfavorable conditions that accompanied the extremely quiet 1994 hurricane season.

The favorable conditions for the 1995 hurricane season began to develop as far back as late in the previous winter. Their onset well ahead of the start of the hurricane season indicates that they are a cause of the increased hurricane activity, and not an effect. The extreme duration of the atmospheric circulation anomalies over the tropical North Atlantic is partly attributed to a transition in the equatorial Pacific from warm episode conditions (El Niño) to cold episode conditions (La Niña) prior to the onset of the hurricane season.

Though the season as a whole was extremely active, 1995's Atlantic tropical cyclogenesis showed a strong intraseasonal variability with above-normal storm frequency during August and October and below normal for September. This variability is likely attributed to changes in the upper-tropospheric circulation across the tropical North Atlantic, which resulted in a return to near-normal vertical shear during September. Another contributing factor to the reduction in tropical cyclogenesis during September may have been a temporary return to near-normal SSTs across the tropical and subtropical North Atlantic, caused by the enhanced tropical cyclone activity during August.

Seasonal hurricane forecasts for 1995 issued at Colorado State University on 30 November 1994, 5 June 1995, and 4 August 1995 correctly anticipated an above-average season, but underforecast the extent of the extreme hurricane activity.

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1. Introduction

During the 1991–94 period, tropical storm and hurricane activity over the Atlantic basin (i.e., the North Atlantic, the Caribbean, and the Gulf of Mexico) averaged the lowest on record since the beginning of reliable archives in the mid-1940s (Landsea et al. 1996). During these years, there was an average of 7.2 named storms. (i.e., tropical storms and hurricanes—those tropical cyclones having maximum sustained 1-min surface winds of at least 18 m s^{-1}), 3.8 hurricanes (winds of at least 33 m s^{-1}), and 1.0 intense (or major) hurricanes [winds of at least 50 m s^{-1}, and indicated by categories 3–5 on the Saffir–Simpson scale (Simpson 1974)]. Additionally, the Caribbean Islands experienced no hurricanes during this period—and none since Hurricane Hugo in 1989—the longest hurricane-free interval for that region in this century.

In contrast, the June–November 1995 Atlantic hurricane season was extremely active in nearly every aspect (Table 1, Fig. 1). During this season, there were 19 named storms, 11 of which became hurricanes and 5 of which reached intense hurricane status. Additionally, five named storms (two being hurricanes) struck the mainland United States and three hurricanes affected the countries surrounding the Caribbean Sea.

It was apparent by late 1994 that environmental conditions were becoming increasingly favorable for an active 1995 Atlantic hurricane season, as indicated by the first seasonal hurricane forecast issued in late November 1994 (Gray 1994). The update of this forecast in early June (Gray et al. 1995a) continued the prediction for an active hurricane season, while the forecast in early August (Gray et al. 1995b) indicated the likelihood of an even more active season than was previously expected. Collectively, these forecasts predicted more named storms, hurricanes, and intense hurricanes than any other presented in the 12-yr history of real-time forecasting at Colorado State University.

Active hurricane seasons in the Atlantic basin are generally associated with a reduction of tropospheric vertical wind shear (typically measured between 850 and 200 mb) within the critical 10°–20°N latitude belt stretching from North Africa to Central America (Gray et al. 1993). [Hereafter, following Goldenberg and Shapiro (1996), this region will be referred to as the main development region (MDR).] In contrast, quiet years are generally associated with above-normal vertical wind shear in this region, with values larger than the 7.5–10 m s^{-1}, which appears to be the threshold beyond which unfavorable conditions occur (Zehr 1992; DeMaria et al. 1993).

There are several local and remote factors that control the interannual variability of Atlantic basin hurricane activity, often through their influence on tropospheric vertical wind shear:

1) El Niño–Southern Oscillation (ENSO) is a fluctuation on a 3–5-yr timescale in the ocean–atmospheric system involving large changes in the Walker and Hadley cells throughout the tropical Pacific (Philander 1989). The state of ENSO can be characterized,

TABLE 1. Summary of information on named tropical cyclones occurring during the 1995 Atlantic season. Information on tropical storms (TS—1-min surface winds of 18–32 m s^{-1}), minor hurricanes (MH—33–49 m s^{-1}), and intense hurricanes (IH—≥50 m s^{-1}) with highest Saffir–Simpson (Simpson 1974) category is shown. Dates indicate the days in which the storm was at least tropical storm force in intensity. Individual totals of named storm days (NSD—days in which the storm has at least 18 m s^{-1} winds), hurricane days (HD—days of winds at least 33 m s^{-1}), intense hurricane days (IHD—days of winds at least 50 m s^{-1}), and hurricane destruction potential (HDP—sum of winds squared every 6 h that the storm is of hurricane force in units of 10^4 kt^2) are also provided.

Named storm	Maximum category	Dates of named storm stage	Maximum sustained surface winds (m s^{-1})	NSD	HD	IHD	HDP
1. Allison	MH-1	3–5 Jun	33	2.50	0.75	0	1.3
2. Barry	TS	7–10 Jul	31	3.25	0	0	0
3. Chantal	TS	14–20 Jul	31	6.75	0	0	0
4. Dean	TS	30–31 Jul	21	0.50	0	0	0
5. Erin	MH-2	31 Jul–4 Aug	44	4.50	2.50	0	5.3
6. Felix	IH-4	8–22 Aug	62	14.00	9.25	1.75	24.2
7. Gabrielle	TS	9–11 Aug	31	1.50	0	0	0
8. Humberto	MH-2	22 Aug–1 Sep	49	10.00	8.50	0	21.0
9. Iris	MH-2	22 Aug–4 Sep	49	12.75	7.50	0	17.6
10. Jerry	TS	23–24 Aug	23	1.25	0	0	0
11. Karen	TS	28 Aug–2 Sep	23	5.25	0	0	0
12. Luis	IH-4	29 Aug–11 Sep	62	12.75	10.50	8.25	52.3
13. Marilyn	IH-3	13–22 Sep	52	9.25	7.75	0.50	19.9
14. Noel	MH-1	27 Sep–7 Oct	33	9.75	2.75	0	4.6
15. Opal	IH-4	30 Sep–5 Oct	67	5.00	2.75	1.00	9.0
16. Pablo	TS	5–8 Oct	26	3.00	0	0	0
17. Roxanne	IH-3	9–18 Oct	52	10.00	5.00	0.25	11.2
18. Sebastien	TS	21–23 Oct	28	3.00	0	0	0
19. Tanya	MH-1	27 Oct–1 Nov	39	5.50	3.00	0	6.1

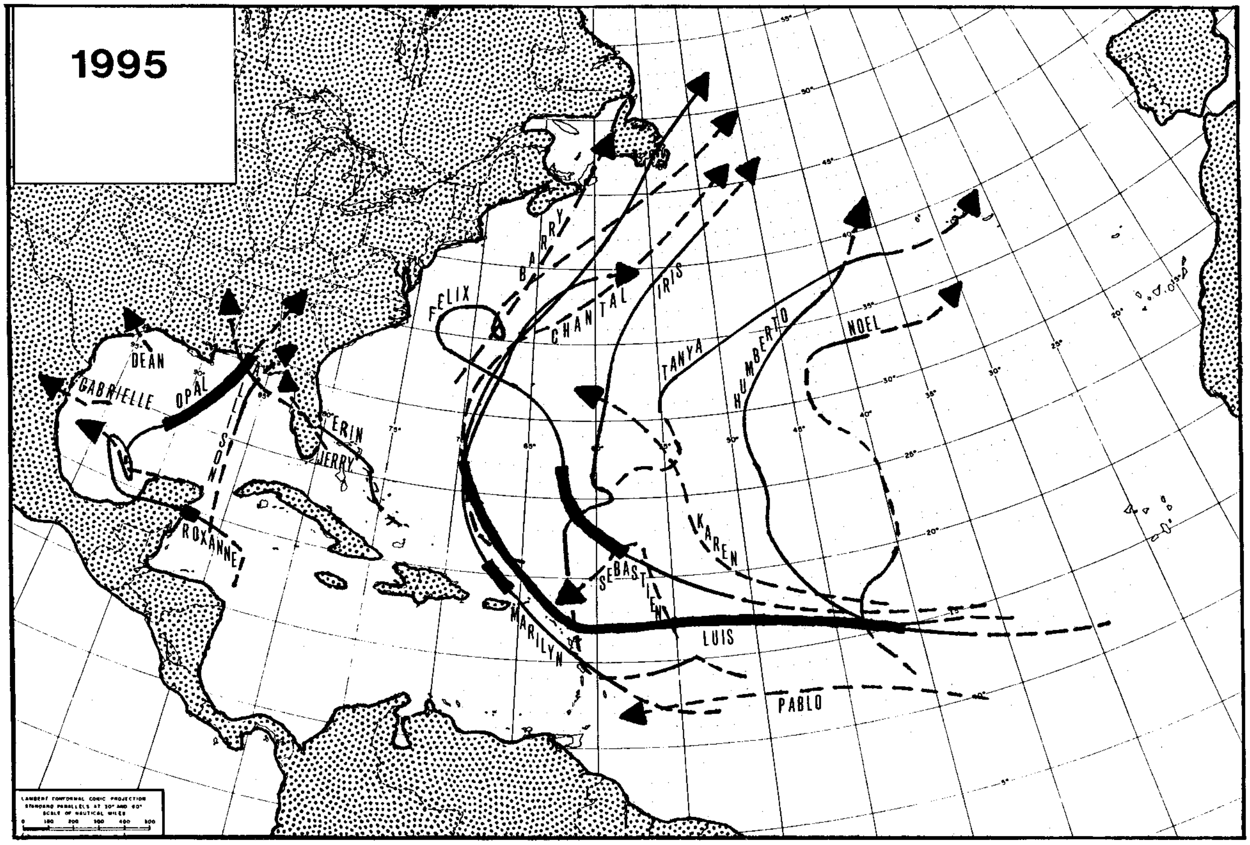


FIG. 1. Tracks of named storms in 1995. Dashed lines indicate the tropical storms (winds 18–32 m s^{-1}), thin solid lines indicate category 1–2 hurricanes (winds 33–49 m s^{-1}), and thick lines show the intense category 3–4–5 hurricanes (winds $\geq$ 50 m s^{-1}).

among other features, by the SST anomalies in the eastern and central equatorial Pacific: moderate to strong warm (cold) SST anomalies are referred to as El Niño (La Niña) events. The interannual variability of vertical shear over the Atlantic basin MDR is strongly influenced by ENSO, primarily through its influence on the upper-level flow. Increased (decreased) 200-mb westerlies and vertical wind shear accompany El Niño (La Niña). Thus one typically observes reduced hurricane activity during E1 Niño and enhanced hurricane activity during La Niña (Gray 1984a; Shapiro 1987; Goldenberg and Shapiro 1996).

2) Atlantic basin sea level pressure (SLP) variations also influence tropical cyclone activity, below (above) normal pressures typically associated with more (less) active Atlantic hurricane seasons (Shapiro 1982; Gray 1984b). In general, below-(above-) normal SLP in the MDR in combination with near-normal pressures within 10° of the equator, loosens (tightens) the meridional pressure gradient and weakens (strengthens) the easterly trade winds and contributes to decreased (increased) vertical shear (Gray et al. 1993, 1994).

Gray et al. (1993) have suggested that abnormally low SLP in the MDR reflects a poleward shift and/or a strengthening of the intertropical convergence zone (ITCZ). Both of these situations contribute to less subsidence and drying in the MDR through which easterly waves move. An enhanced ITCZ also provides more large-scale low-level cyclonic vorticity to incipient tropical cyclones, thereby creating an environment that is more favorable for tropical cyclogenesis (Gray 1968). Knaff (1997) also indicates that abnormally low SLP is accompanied by a deeper moist boundary layer and a weakened trade wind inversion. In contrast, above-normal SLP tends to be associated with opposite conditions that are unfavorable for tropical cyclogenesis.

3) SSTs in the MDR likely have a direct thermodynamic effect on tropical cyclones through their influence on moist static stability and through the evaporation–wind feedback (Malkus and Riehl 1960) with warmer (cooler) than normal waters enhancing (suppressing) convection. There is evidence that the direct thermodynamic SST effects upon interannual variations of tropical cyclones is a second-order effect compared to vertical shear variations (Shapiro and Goldenberg 1998). However, SST can also indirectly influence the vertical shear through its strong inverse

relationship with surface pressures in the tropical Atlantic (Shapiro 1982; Gray 1984b). In particular, above-normal SSTs are usually accompanied by below-normal SLP, and thus, weaker trade winds and reduced shear. In contrast, below-normal SSTs are usually accompanied by above-normal SLP, stronger trade winds, and increased shear.

4) Year-to-year changes in total precipitable water (TPW) have not yet been identified explicitly as a mechanism for hurricane activity variability. However, as suggested above, the underlying SSTs and the local SLP field are strongly coupled to the lower-tropospheric moisture fields. Thus systematic changes in TPW may influence the frequency of tropical cyclogenesis and the rate of tropical cyclone intensification (Miller 1958; Malkus and Riehl 1960; Emanuel 1986), with wetter (drier) conditions enhancing (suppressing) the ability to sustain deep convection.
5) The stratospheric quasi-biennial oscillation (QBO) is an east–west oscillation of stratospheric winds that encircles the globe near the equator (Wallace 1973). The oscillation is asymmetric in time. The west phase at 30 mb typically lasts for 13–16 months, followed by a slow transition to the 12–15-month east phase, and then a relatively quick return to the west phase. Climatologically, easterly winds uniformly dominate the lower stratosphere over the MDR during the hurricane season. Thus the QBO west phase actually manifests itself as weak easterly winds at 30 and 50 mb (0 to -5 m s^{-1}), while the east phase produces strong easterly winds (-20 to -30 m s^{-1}) (Gray et al. 1992a). The west phase corresponds with increased Atlantic basin tropical cyclone activity and the east phase with reduced activity (Gray 1984a; Shapiro 1989). While the exact mechanism of the stratospheric QBO's influence on Atlantic tropical cyclones is uncertain, it has been hypothesized that upper-tropospheric static stability changes (Knaff 1993) and/or upper-tropospheric to lower-stratospheric vertical shear variations (Gray et al. 1992b) are responsible for its effect on tropical cyclone activity.
6) Over the past century, June–September rainfall in Africa's western Sahel has shown a very close association with Atlantic hurricane activity, particularly for intense hurricane activity (Reed 1988; Gray 1990; Landsea and Gray 1992; Landsea et al. 1992). Wet years in the western Sahel (e.g., 1988 and 1989) are accompanied by dramatic increases in the incidence of intense hurricanes, while drought years (e.g., 1990–93) are accompanied by a decrease in intense hurricane activity. Variations in tropospheric vertical shear and African easterly wave intensity have been hypothesized as the physical mechanisms that link the two phenomena (Gray 1990; Landsea and Gray 1992), although Goldenberg and Shapiro (1996) have demonstrated that changes in the vertical shear probably dominate. They note that wet years are associated with smaller wind shear, due to both weaker than average trade winds and reduced upper-tropospheric westerlies throughout the MDR. Conversely, dry years are associated with higher vertical shear, due to both stronger trade wind flow and enhanced 200-mb westerlies.

The primary purpose of this paper is to describe and diagnose the large-scale local environmental conditions that contributed to the active 1995 Atlantic hurricane season, and to assess qualitatively the influence of known remote factors such as ENSO and western Sahel precipitation on these conditions. During 1995, all of the above factors with the exception of western Sahel rainfall favored enhanced Atlantic basin tropical cyclone formation. In contrast, nearly all of these factors were unfavorable during the 1991–94 period. The datasets are briefly described in section 2. A summary of Atlantic basin tropical cyclone activity is then presented in section 3. The precursor and concurrent environmental conditions during the 1995 hurricane season are described in sections 4 and 5, respectively. Contrasts of the quite different 1994 and 1995 hurricane seasons are presented in section 6. The intraseasonal variability of tropical cyclogenesis during 1995 is then described in section 7. In section 8, the preponderance of recurving tropical cyclones is described and reasons for its occurrence discussed. A verification of the 1995 seasonal forecasts is then presented (section 9), followed by a summary and discussion of results (section 10).

2. Data

The Atlantic basin tropical cyclone ''best track'' data are provided by the U.S. Tropical Prediction Center/National Hurricane Center in the form of 6-h positions and intensities of all tropical cyclones reaching named storm status. Documentation of this database is found in Jarvinen et al. (1984), with discussion of its strengths and weaknesses in Neumann et al. (1993) and Landsea (1993).

Sea surface temperature data are obtained from the high-resolution dataset of Reynolds and Smith (1995). The data are derived from an optimal interpolation of in situ ship and buoy data supplemented by satellite SST retrievals on a 2° grid spacing. Deviations from long-term means are computed with respect to a 1950–79 base period.

Station rainfall, sea level pressure, and wind data are those available in real time from the global telecommunications system, and are typically compared against long-term (1950–90) average values as described in Gray et al. (1994) and Landsea and Gray (1992). Additionally, gridded (2.5° interval) fields of sea level pressure, wind, and height are utilized from the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis project (Kalnay et

TABLE 2. Summary of the 1995 Atlantic basin seasonal hurricane activity and comparison with average conditions.

Forecast parameter	Climatology (1950–90)	1995	1995 in percent of climatology
Named storms (NS)	9.3	19	204%
Named storm days (NSD)	46.6	121	260%
Hurricanes (H)	5.8	11	190%
Hurricane days (HD)	23.9	60	251%
Intense hurricanes (IH)	2.3	5	217%
Intense hurricane days (IHD)	4.7	11.75	250%
Hurricane destruction potential (HDP)	71.2	172	241%
Net tropical cyclone activity (NTC)	100%	229%	229%

al. 1996). Tropospheric vertical shear is calculated as the vector difference of 200 minus the 850-mb flow field vectors at each grid point. Anomalies are calculated with respect to the 1979–95 base period monthly means.

Finally, monthly estimates of total precipitable water were obtained from the National Environmental Satellite, Data, and Information Service (NESDIS)/Office of Research and Applications (Ferraro et al. 1996). These estimates are derived from passive microwave measurements of the 22-GHz channel from the Special Sensor Microwave/Imager. Anomalies are calculated with respect to the 1987–95 base period monthly means.

3. Summary of 1995 Atlantic tropical cyclone activity

The 1995 Atlantic hurricane season began with the development of Hurricane Allison on 3 June and ended with the dissipation of Hurricane Tanya on 1 November. The total number of named storms (NS) was 19, yielding 121 named storm days (NSD) (Table 1, Fig. 1). Eleven of these storms reached hurricane (H) strength, yielding 60 hurricane days (HD) during the season. Five of these hurricanes reached intense hurricane (IH) status, yielding 11.75 intense hurricane days (IHD). For the season as a whole, all but one of the designated tropical cyclone activity parameters were *more than twice* the long-period (1950–90) means (Table 2). Additional details on individual tropical cyclones during 1995 can be found in Lawrence et al. (1998).

Though extremely active, the 1995 hurricane season is not unprecedented. Ten other hurricane seasons in the last 110 years have had comparable activity (i.e., nearly equivalent or greater activity in at least one of the tropical cyclone parameters listed in Table 2) (Table 3), with a very active season occurring approximately once every 10–15 years. The record number of named storms observed is 21 during the 1933 season.[1] The 1995 and 1887[2] seasons each had 19 named storms, followed by the 1969 and 1936 seasons, in which 17 named storms were recorded. The 11 hurricanes recorded during 1995 were second only to the 12 observed in 1969, and was tied with the 1950 and 1916 seasons. The total of five intense hurricanes during 1995 was exceeded in 1950 (7) and 1961, 1926, and 1916 with six each. Hurricane destruction potential (HDP)—a combined measure of hurricane intensity and duration—reached a total of 172, almost two and a half times the long-term average.

The parameter ''net tropical cyclone'' (NTC) activity is useful for characterizing how active the season has been overall in terms of the total cyclone frequency, intensity, and duration (Gray et al. 1994). NTC combines six measures of tropical cyclone activity (NS, NSD, H, HD, IH, IHD) into an average percentage value compared with the 1950–90 climatology. The NTC value for 1995 was 229%, and was the largest value recorded since 1950 (243%). NTC during 1995 was also exceeded in 1926 (237%) and 1893 (250%). The active years of 1961 and 1933 recorded NTC values of 222% and 215%, respectively.

The upsurge in hurricane activity during 1995 was most dramatic in the latitudes equatorward of 25°N ex-

[1] The Atlantic tropical cyclone record before 1944 is likely incomplete since storms may have been missed or their intensity misclassified due to lack of satellite and aircraft monitoring (Neumann et al. 1993; Landsea 1993).

[2] Recent reanalysis by Fernández-Partagás and Diaz (1996) has identified that 1887 had at least 19 named storms—making it as active as 1995's busy season in terms of named storms. Only the named storm count for 1887 in Table 3 has been updated; the remaining values are the original best track data.

TABLE 3. Comparison of 1995 hurricane activity with the 10 most active hurricane seasons during the last 110 yr. Numbers of all of the parameters are less reliable before the mid-1940s (Neumann et al. 1993; Landsea 1993). Following Landsea (1993), the 1944–69 values of IH, IHD, HDP, and NTC are adjusted slightly downward to account for an overestimation of the tropical cyclone best track winds. Underlined values show seasonal totals for a particular parameter that were greater than or equal to the values for 1995.

Forecast parameter	1995	1969	1961	1955	1950	1933	1926	1916	1906	1893	1887
Named storms (NS)	19	17	11	12	13	21	11	14	11	12	19
Named storm days (NSD)	121	84	71	82	98	136	87	88	89	111	106
Hurricanes (H)	11	12	8	9	11	7	8	11	6	10	10
Hurricane days (HD)	60	40	48	47	60	50	55	47	44	72	55
Intense hurricanes (IH)	5	3	6	5	7	5	6	6	4	3	2
Intense hurricane days (IHD)	11.75	2.75	20.75	13.75	15.75	10.50	23.00	10.75	11.25	25.00	8.25
Hurricane destruction potential (HDP)	172	110	170	158	200	152	197	143	137	230	158
Net tropical cyclone activity (NTC)	229%	156%	222%	198%	243%	215%	237%	203%	168%	250%	179%

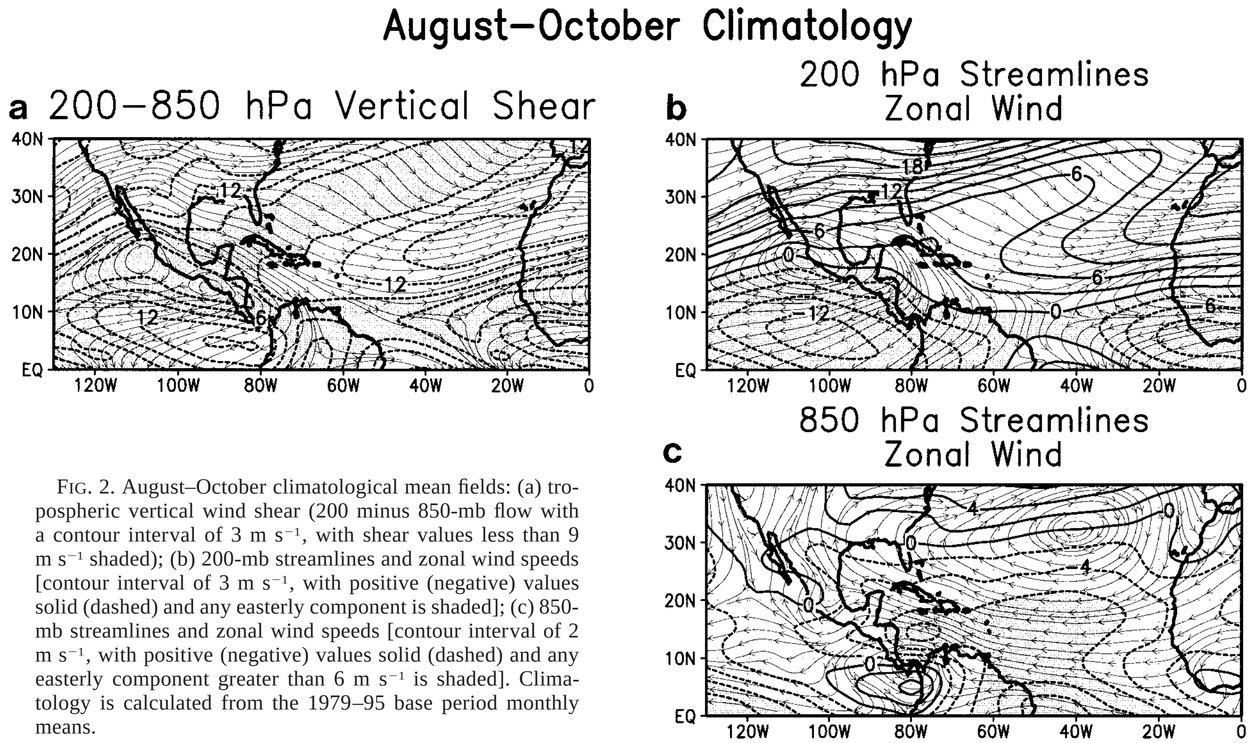


FIG. 2. August–October climatological mean fields: (a) tropospheric vertical wind shear (200 minus 850-mb flow with a contour interval of 3 m s^{-1}, with shear values less than 9 m s^{-1} shaded); (b) 200-mb streamlines and zonal wind speeds [contour interval of 3 m s^{-1}, with positive (negative) values solid (dashed) and any easterly component is shaded]; (c) 850-mb streamlines and zonal wind speeds [contour interval of 2 m s^{-1}, with positive (negative) values solid (dashed) and any easterly component greater than 6 m s^{-1} is shaded]. Climatology is calculated from the 1979–95 base period monthly means.

cluding the Gulf of Mexico, where seven hurricanes developed compared to only one during the entire 1991–94 period (Hurricane Chris in 1993). The Caribbean countries were struck by three of these hurricanes (two intense—Luis and Roxanne), after experiencing a record five years with no hurricanes at all.

Hurricane Luis was of particular interest during 1995 because of its long duration at IH status and its destructiveness in the Caribbean. Typically, intense hurricanes remain so for an average of just 2–3 days. Luis maintained that status for 8.25 days. This is the third longest duration of an intense hurricane observed in the period of reliable records (i.e., since 1944), exceeded only by Hurricanes Donna in 1960 (9.0 IHD) and Esther in 1961 (8.5 IHD).

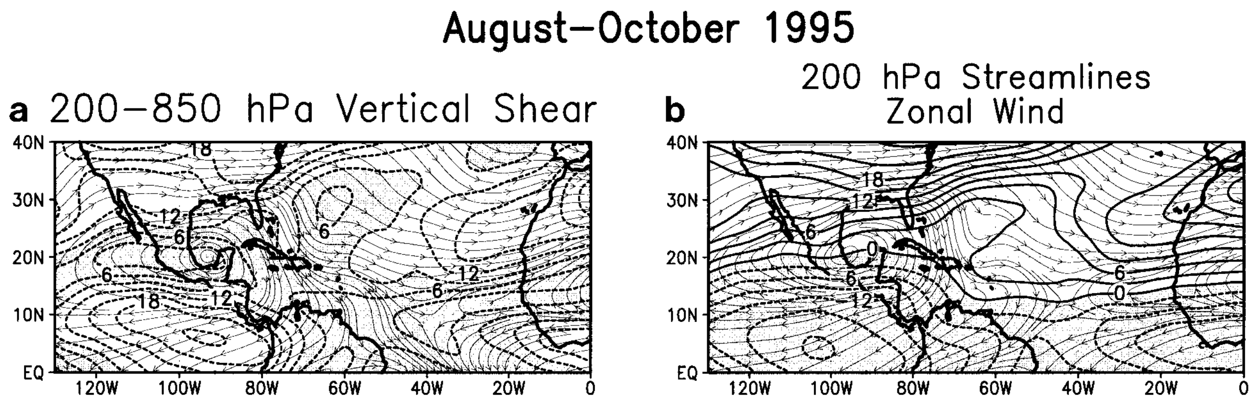
4. Local environmental conditions associated with the active 1995 hurricane season

Several persistent local factors combined to produce the extremely active 1995 hurricane season. These were 1) reduced vertical wind shear; 2) below-normal sea level pressure; 3) abnormally warm ocean waters with correspondingly large amounts of lower-tropospheric water vapor; and 4) a strong west phase of the stratospheric QBO. These favorable conditions allowed for an abnormally large number (89%, or 17 of 19) of tropical cyclones to develop from African easterly waves (Pasch et al. 1998). Typically, an average of only 61% of the tropical cyclones form from easterly waves in a given season. In fact, during three weeks in August, six of the eight easterly waves that moved from North Africa through the MDR developed into a tropical cyclone. It is also possible that the active hurricane season was due in part to stronger than normal easterly waves originating from Africa as suggested in section 1. However, high quality data at a dense enough network to capture interannual variations in the over-ocean easterly wave structure differences is not available at this time. Thus we are unable at this time to further test this hypothesis.

a. Vertical wind shear

During August–October, vertical wind shear the Atlantic basin's MDR normally exhibits a strong westerly component and exceeds the critical 7.5–10 m s^{-1} threshold for tropical cyclone formation (Fig. 2a). This large shear results from a combination of upper-level (200 mb) westerly winds averaging 3–6 m s^{-1} (Fig. 2b), in association with a mean tropical upper-tropospheric trough (or TUTT; Sadler 1976; Fitzpatrick et al. 1995), and low-level (850 mb) easterly trade winds averaging 6–7 m s^{-1} (Fig. 2c). Thus, very active hurricane seasons require that the vertical wind shear in this region be substantially reduced from the climatological mean.

During August–October 1995, the magnitude of the vertical shear over the North Atlantic decreased to 2–6 m s^{-1} throughout the MDR (Fig. 3a), approximately 3–5 m s^{-1} below the climatological mean (Fig. 4a). This decrease reflected a nearly complete elimination of the normal pattern of westerly shear over much of the region, and resulted from a combination of 1) reduced



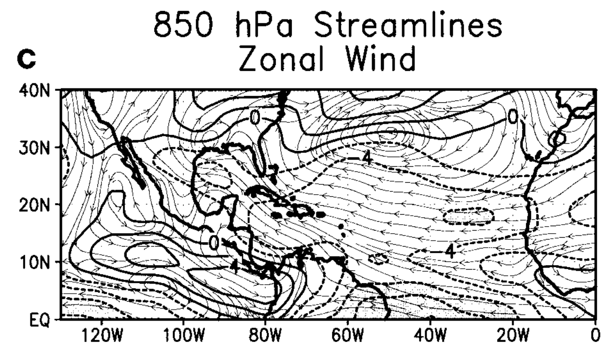


FIG. 3. Same as Fig. 2 except the analyses depict August–October 1995.

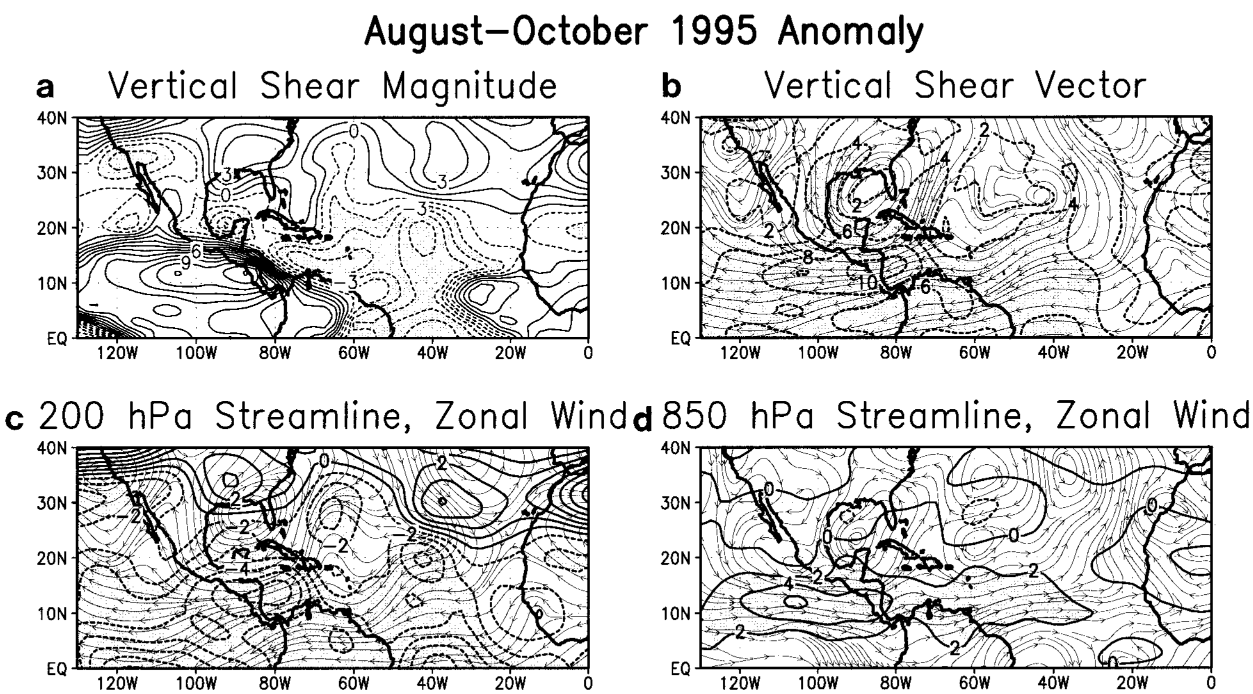


FIG. 4. August–October anomaly values of (a) the vertical shear magnitude [contour interval is 1.5 m s^{-1}, with weaker (stronger) than average shear values dashed (solid) and shear that is at least 3 m s^{-1} weaker than climatology is shaded]; (b) the vertical shear vector (contour interval is 2 m s^{-1}, with values larger than 4 m s^{-1} shaded); (c) the 200-mb streamlines and zonal wind speeds [contour interval is 2 m s^{-1}, with positive (negative) values solid (dashed) and any easterly component greater than 2 m s^{-1} is shaded]; and (d) the 850-mb streamlines and zonal wind speeds [contour interval is 2 m s^{-1}, with positive (negative) values solid (dashed) and any westerly component greater than 2 m s^{-1} is shaded]. Anomalies are departures from the 1979–95 base period monthly means.

TABLE 4. 1995 Caribbean 200-mb zonal wind anomalies (ZWA) in meters per second and sea level pressure (SLP) anomalies in millibars for the base period 1950–1990. ZWA is computed from the four stations of Kingston (18°N), Curacao (12°N), Barbados (13.5°N), and Trinidad (11°N). SLP anomalies are computed by two indices: the Caribbean (San Juan, Barbados, Trinidad, Curacao, and Cayenne) and the Caribbean–Gulf of Mexico (Brownsville, Miami, Merida, San Juan, Curacao, and Barbados).

	April	May	June	July	August	September	October
Average ZWA (m s^{-1})	−2.5	−0.5	−1.6	−4.3	−7.0	−4.1	−0.8
Caribbean SLP anomalies (mb)	−0.9	+0.5	−0.2	−1.2	−1.3	+0.3	−0.2
Caribbean–Gulf of Mexico SLP anomalies (mb)	−1.4	−0.4	−0.8	−1.2	−2.9	−0.3	−1.4

upper-level westerlies (Figs. 3b, 4c, and Table 4), with an actual reversal to upper-level easterlies throughout the Caribbean Sea eastward to approximately 60°W (Figs. 3b and 5); and 2) weaker than normal low-level easterlies across the tropical North Atlantic. Farther north, the westerly vertical shear observed in the region poleward of approximately 25°N averaged near normal to slightly above normal during August–October. Similar regional variations in vertical shear have also been noted during other active hurricane seasons (Goldenberg and Shapiro 1996). Together, this pattern of vertical shear strongly delineated the observed sites of tropical cyclogenesis during 1995, with 16 tropical storms forming south of 25°N including all of the Gulf of Mexico (Fig. 1) compared to the 1950–90 average of 6.9 storms, and three tropical storms forming north of 25°N compared to an average of 2.4 storms.

The large-scale pattern of upper-tropospheric easterly anomalies and lower-tropospheric westerly anomalies that contributed to reduced vertical shear over the tropical North Atlantic during 1995 also extended well westward to the tropical northeast Pacific. However, in this latter region, these anomalies produced a sharp increase in vertical shear to 9–20 m s^{-1} (Fig. 4a), which is 6–9 m s^{-1} larger than the typically low values observed in association with the climatological mean 200-mb subtropical ridge (Figs. 3a,b). This increase in vertical shear contributed to a marked decrease in northeast Pacific cyclone activity during 1995 (Rappaport et al. 1998), contrasting with the quite numerous tropical cyclones normally observed in that region. It is interesting that the same anomalous forcing in the Atlantic and northeast Pacific tropical cyclone basins produces such a dichotomous response because of the differences in background climatological flow.

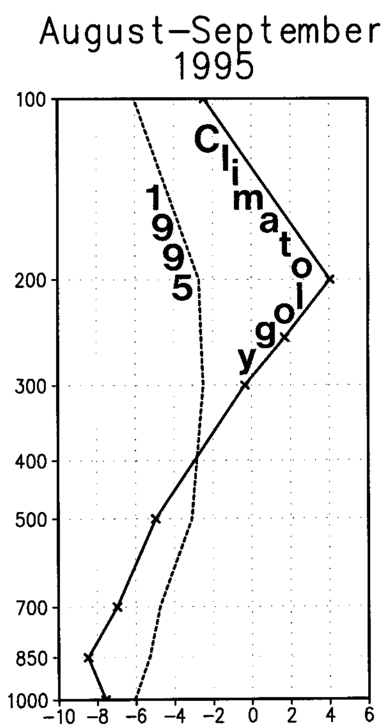


FIG. 5. August–September vertical profiles of the mean zonal wind for the Caribbean strip at 70°W along 10°–20°N for 1995 (dashed lines) and for the 1979–95 climatology (solid line).

The circulation anomaly patterns first appeared over the MDR during February and March 1995 (Fig. 6b), and reflected a reversal from the anomalous cyclonic circulation and anomalous westerly shear patterns observed over the region during December 1994–January 1995 (Fig. 6a). By April–May, easterly shear anomalies dominated the entire tropical North Atlantic (Fig. 6c), as the anomalous anticyclonic circulation center moved poleward to approximately 28°N. These conditions then continued during June and July (Fig. 6d) and subsequently persisted through the remainder of the hurricane season. The large spatial scale and extreme persistence of these anomalies since early 1995 strongly suggests that they were a cause, rather than an effect, of the active 1995 hurricane season.

b. Sea level pressure (SLP)

A second contributing factor to the extremely active 1995 hurricane season was a persistent pattern of below-normal sea level pressure throughout the tropical North Atlantic (Fig. 7c, Table 4). During August–October, a large-scale pattern of negative SLP anomalies dominated the North Atlantic, the United States, and Central America, with SLPs averaging up to 2 mb below normal throughout the northern portion of the MDR, and more than 2.5–3 mb below normal throughout the Gulf of Mexico. These conditions are consistent with the pattern of low-level wind anomalies and vertical shear described previously (Fig. 4d).

Below-normal SLPs also began to cover the tropical North Atlantic during April–May 1995 (Fig. 7a). By

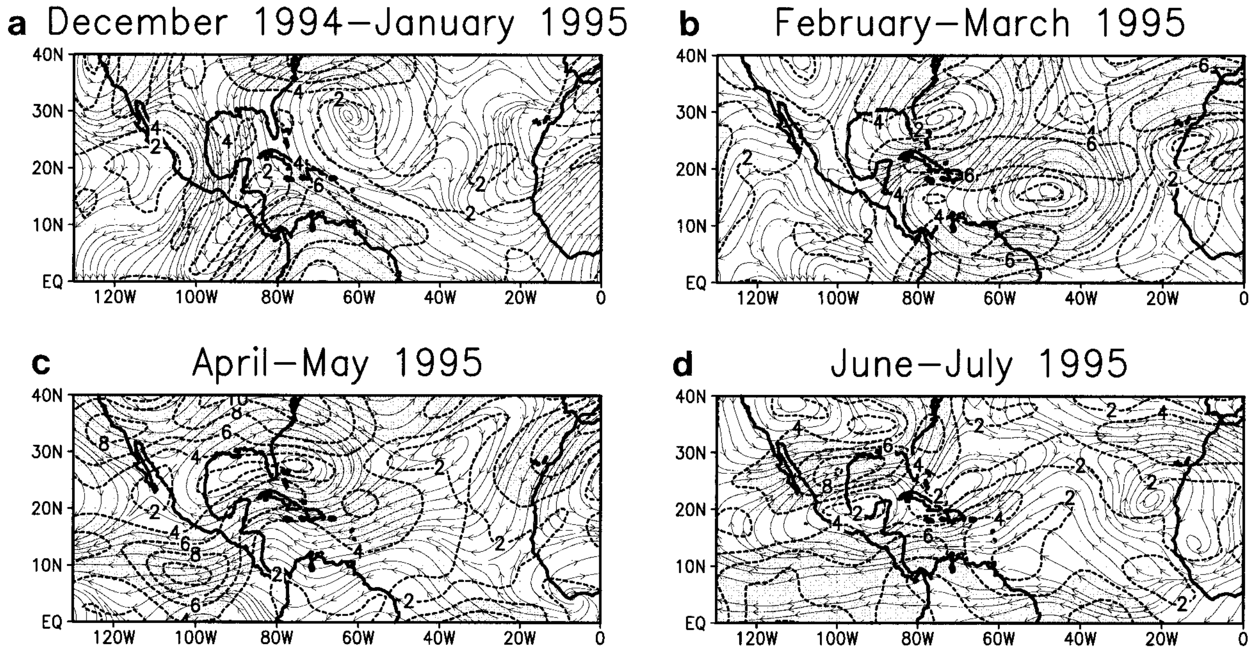


FIG. 6. Same as Fig. 4b except for (a) December 1994–January 1995, (b) February–March 1995, (c) April–May 1995, (d) June–July 1995.

June–July the entire tropical North Atlantic was dominated by below-normal SLP, which subsequently persisted through the remainder of the hurricane season (Fig. 7c). Again, the large spatial scale and extreme persistence of these negative SLP anomalies since early 1995 suggests that they were also a contributing factor to, rather than an effect of, the active 1995 hurricane season.

c. Atlantic sea surface temperature (SST)

A third contributing factor to the active 1995 hurricane season was a persistent, large-scale pattern of above-normal SSTs (0.5°C warmer than average) across the MDR during August–October (Fig. 8c). Above-normal SSTs first developed over large portions of the tropical North Atlantic during April–May (Fig. 8a), with anomalies exceeding +0.5°C. This pattern expanded during June–July (Fig. 8b), as anomalies increased to more than +1.0°C throughout the region. This persistent pattern of above-normal SSTs is consistent with the large-scale pattern of negative SLP anomalies during the period, and also supports the interpretation that favorable environmental conditions were in place well prior to the onset of the active August–October period.

d. Atlantic total precipitable water (TPW)

An additional likely contributor to the development and growth of the Atlantic tropical cyclones during August–October was above-normal total precipitable water across the tropical North Atlantic, the Caribbean Sea, and the Gulf of Mexico (Fig. 9c). These conditions are consistent with the overall tendency for above-normal SSTs and below-normal SLPs throughout the region. The more humid than normal TPW values became established throughout the MDR (Fig. 9b), following a period of abnormally dry TPW values during April–May (Fig. 9a).

e. The stratospheric quasi-biennial oscillation (QBO)

During the 1995 Atlantic hurricane season, the stratospheric zonal winds at both 30 mb and 50 mb were easterly with an amplitude of 2.5–5 m s^{-1} (Fig. 10a), indicating only weak vertical wind shear between these two levels. At both levels, these easterlies were much weaker than normal, consistent with the westerly phase of the stratospheric quasi-biennial oscillation (Fig. 10b). As discussed in section 1, the westerly phase of the stratospheric QBO tends to promote active hurricane seasons (Gray 1984a; Shapiro 1989). Thus these stratospheric conditions also favored an active hurricane season during 1995.

5. Remote environmental conditions contributing to the active 1995 hurricane season

The local environmental conditions that favor tropical cyclone development over the North Atlantic exhibit substantial interannual variability, which is influenced by at least two remote climate phenomena: the ENSO cycle, and western Sahel rainfall. These phenomena also

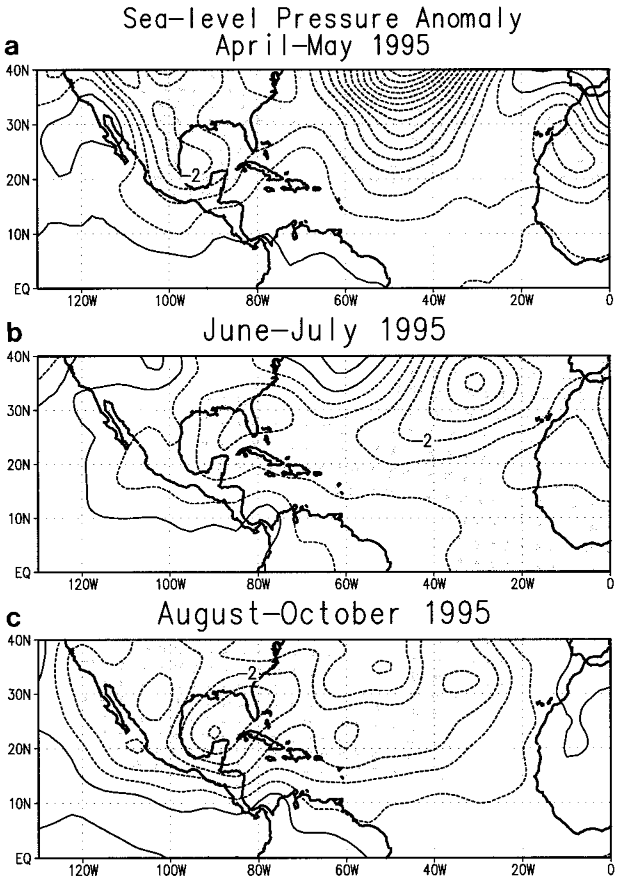


FIG. 7. SLP anomalies (mb) for (a) April–May 1995, (b) June–July 1995, and (c) August–October 1995. Contour interval is 0.5 mb, with positive (negative) values shown solid (dashed). Anomalies below −1.0 mb are shaded. Anomalies are departures from the 1979–95 base period monthly means.

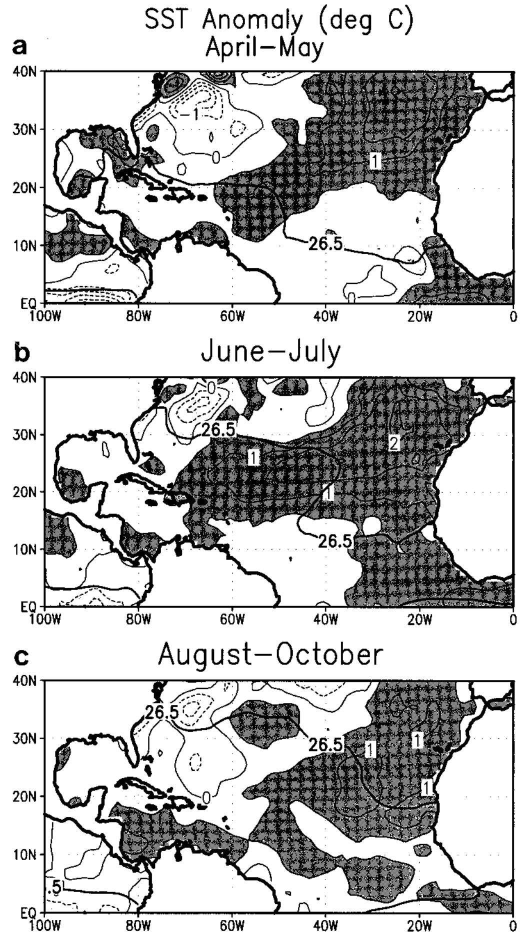


FIG. 8. SST anomalies (°C) for (a) April–May 1995, (b) June–July 1995, and (c) August–October 1995. Contour interval is 0.5°C, with positive (negative) anomalies shown solid (dashed). Values greater than 0.5°C are shaded dark, and values less than −0.5°C are shaded light. The 26.5°C SST contour is also drawn. Anomalies are departures from the 1950–79 base period monthly means.

contribute to a surprisingly strong long-range predictive signal for Atlantic basin seasonal tropical cyclone activity up to 11 months in advance (Gray et al. 1992, 1993, 1994).

a. *The 1995 transition from warm episode (El Niño) to cold episode (La Niña) conditions*

The late 1990–early 1995 period was dominated by warm episode (El Niño) conditions in the tropical Pacific (Trenberth and Hoar 1996). During this period, tropical cyclone activity over the North Atlantic averaged the lowest on record since the beginning of reliable archives in the mid-1940s (Landsea et al. 1996). These warm episode conditions culminated during the 1994/95 winter season (Fig. 11a) with return to mature phase of warm ENSO conditions for the third time in four years (Halpert et al. 1996).

Following January 1995, SSTs over the tropical Pacific began a rapid decline toward normal. By April–May, the area of positive SST anomalies had disappeared from the tropical Pacific east of the date line (Fig. 11b) and below-normal SSTs had developed over much of the eastern equatorial Pacific. During August–October 1995, below-normal SSTs spread westward to cover the entire tropical Pacific east of the date line, with the largest negative anomalies observed over the east central equatorial Pacific (Fig. 11c). Accompanying this transition to cold episode (La Niña) conditions, the pattern of anomalous tropical convection also reversed, with suppressed convective activity near the date line and enhanced convective activity over Indonesia (Halpert et al. 1996). Collectively, these conditions reflected a reversal from the atmospheric and oceanic anomaly patterns that had dominated the tropical Pacific since late 1990. This evolution matches the persistent pattern (since February) of easterly shear anomalies over the tropical North Atlantic. It also corresponds well with the dramatic decrease in the magnitude of the vertical

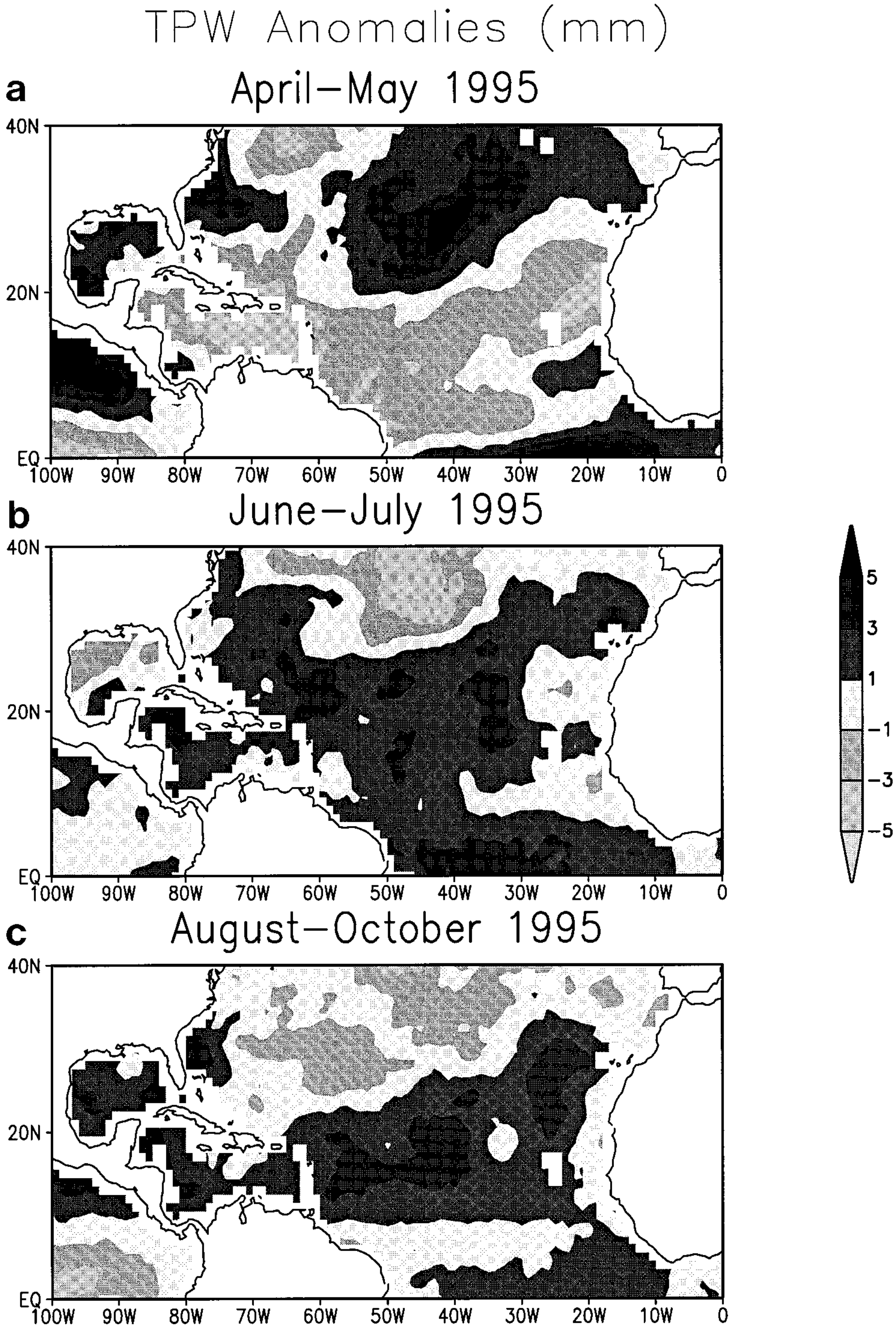


FIG. 9. Total precipitable water (TPW) anomalies (mm) for (a) April–May 1995, (b) June–July 1995, (c) August–October 1995. White areas (near or over land) indicate no analysis possible. Negative anomalies are shaded moderately dark through lightly shaded and positive anomalies are shaded dark. The anomalies are departures from the July 1987–October 1994 base period monthly means.

shear during the peak of the 1995 Atlantic hurricane season (Figs. 4a and 5), compared to the relatively high shear conditions that prevailed during the past four hurricane seasons (Landsea et al. 1996).

b. Western Sahel rainfall

Rainfall totals during June–September 1995 were near normal to moderately dry over much of the African

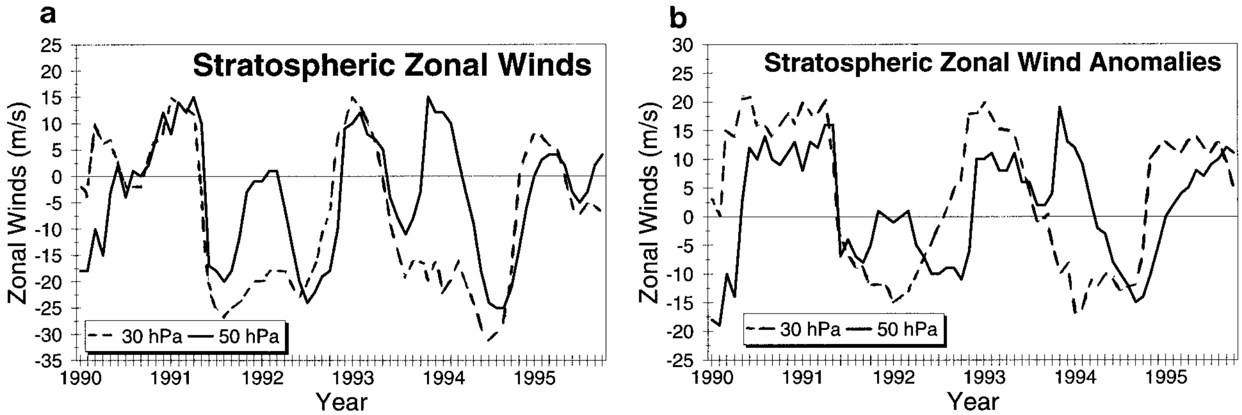


FIG. 10. Time series of (a) stratospheric zonal winds and (b) anomalies averaged between Curacao (12°N), Barbados [13°N and Trinidad (11°N)]. Values at 50 mb (30 mb) are shown by solid (dashed) curves. Units are meters per second. Anomalies are calculated from the 1950–90 base period monthly means.

Sahel, defined as the region from Senegal to Sudan roughly between 10° and 20°N (Fig. 12a). Overall the western Sahel, the area with the strongest concurrent association with Atlantic intense hurricane activity (Landsea and Gray 1992), had near-average rainfall during the June–September 1995 rainy season, with an area-averaged precipitation amount of −0.20 standardized deviations below the long-term mean (Fig. 12b).[3] This value is within the middle quintile of rainfall years since 1950 (i.e., within the one-fifth of all years closest to the long-term mean) and is significantly wetter than most the previous 25 years, which averaged −0.57 standardized deviations. Overall, these observations do suggest that the western Sahel rainfall was not a major contributor to the active 1995 Atlantic hurricane season.

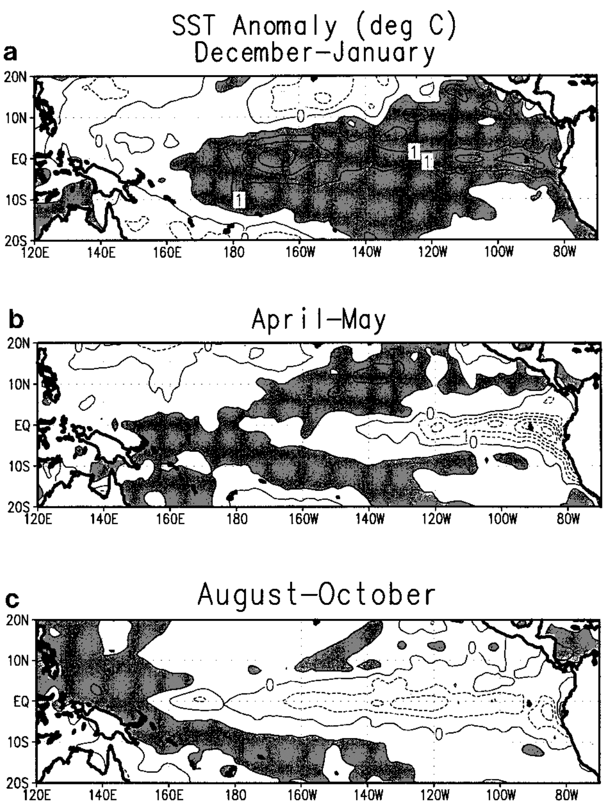


FIG. 11. Tropical Pacific SST anomalies (°C) for (a) December 1994–January 1995, (b) April–May 1995, and (c) August–October 1995. Contour interval is 0.5°C, with positive (negative) anomalies shown solid (dashed). Values greater than 0.5°C are shaded dark, and values less than −0.5°C are shaded light. Anomalies are departures from the 1979–95 base period monthly means.

6. Contrast of the 1994 and 1995 hurricane seasons

There could not be two hurricane seasons more different than 1994 and 1995. Nine hurricanes were observed during August–October 1995, compared to only one hurricane during the same three months of 1994 (Table 5), values well above and well below the climatological mean of five hurricanes expected during these months, respectively. All other tropical cyclone parameters currently used to summarize a given hurricane season also highlight the dramatic differences between the extremely active 1995 season and the inactive 1994 season during the traditional August–October period peak of activity (Table 5).

While the juxtaposition of conducive environmental conditions led to a busy 1995 hurricane season, August–October 1994 hurricane activity was suppressed by a combination of inhibiting conditions: abnormally strong upper-level westerlies and enhanced vertical wind shear,

[3] This rainfall index is based upon a slightly modified region with a reduced number of stations from that presented in Landsea and Gray (1992). This new index is designed to better take into account the area's identified spatial variability (see Nicholson and Palao 1993; Moron 1994) and to utilize stations that have reliable long-term records that are also readily accessible in real time. See Landsea et al. (1997) for details.

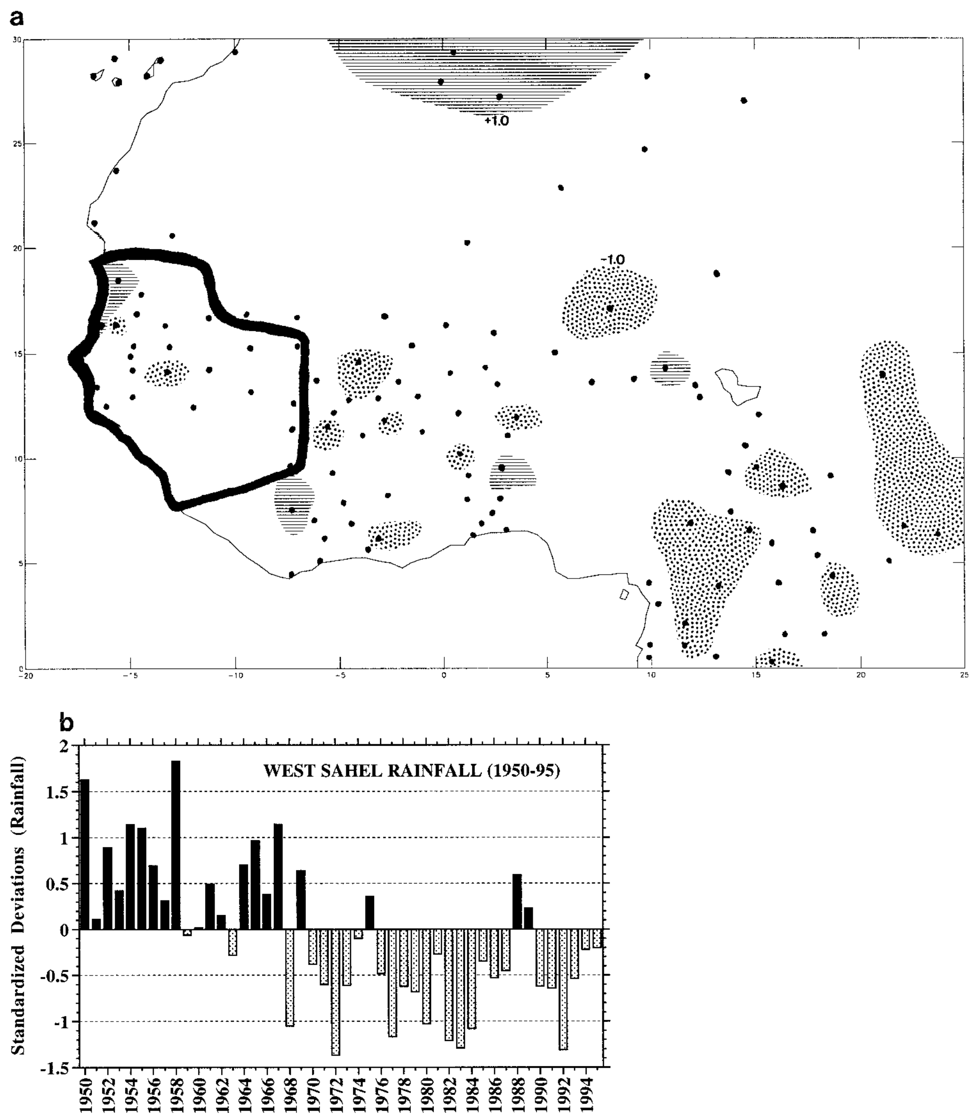


FIG. 12. Standardized anomalies of June–September precipitation from the base period of 1950–90: (a) over North Africa during 1995 and (b) averaged over the western Sahel for each of the 1950–95 seasons. In panel (a) horizontal hatching indicates totals exceeding one standard deviation above normal, and dotted shading indicates totals more than one standard deviation below normal. Station locations are indicated by the dots. The dark curve indicates the Western Sahel region (Landsea et al. 1997). Yearly values in panel (b) are the average of the available station anomalies from a possible 7 stations.

abnormally high SLP and abnormally cool SSTs over the MDR, along with a moderate El Niño and a strong easterly phase of the QBO (Table 5). Notably, the western Sahel rainfall was near normal during both years (Fig. 12b).

7. Intraseasonal variations of 1995 hurricane activity

The season began when Hurricane Allison formed over the eastern Gulf of Mexico in early June, followed by two tropical storms (Barry and Chantal) during the first half of July (Fig. 13). Subsequently, tropical cyclone formation occurred primarily during two month-long periods, 30 July–29 August and 27 September–27 October, separated by the inactive period of 30 August–26 September. This clustering of tropical cyclone activity over 20–30-day periods interspersed with 20–30-day quiet periods is typical of other active Atlantic hurricane seasons as well, as was observed during the 1950, 1955, 1985, and 1990 seasons.

In fact, Gray (1979) noted a clustering of tropical cyclogenesis on the timescales of a few weeks in both the Northern and Southern Hemispheres. In the Indian and western Pacific, this clustering is often forced by the Madden–Julian oscillation (MJO), with more than

TABLE 5. August–October values and differences for 1994 and 1995. Tropical cyclone parameters are shown in the top portion of the panel and environmental factors are shown in the bottom portion.

	Tropical cyclone parameters							
	NS	H	IH	NSD	HD	IHD	HDP	NTC
1995	14	9	5	104	57	11.75	165	206%
1994	4	1	0	11	2	0	4	15%
1995–94	10	8	5	93	55	11.75	161	191%

	Environmental parameters					
	Caribbean 200-mb zonal wind anomalies ($m\ s^{-1}$)	Caribbean/Gulf of Mexico SLP anomalies (mb)	Tropical Atlantic SST anomalies (5°–20°N, 30–60°W) (°C)	Niño 3.4 SST anomalies (°C)	Caribbean 30-mb zonal wind anomalies (m s°)	Western Sahel rainfall anomalies (std. devs.)
1995	−4.0	−1.5	+0.5	−0.6	−6	−0.22
1994	+1.1	+0.7	−0.3	+0.6	−25	−0.20
1995–94	−5.1	−2.2	+0.8	−1.2	+19	+0.02

twice as many cyclones forming in the "wet" MJO phase than in the "dry" MJO phase (Liebmann et al. 1994). Shapiro and Goldenberg (1993) has shown, however, that the MJO is negligible in amplitude during the summer months over the Atlantic MDR. This suggests that the MJO may not be responsible for the intraseasonal variations in Atlantic tropical cyclones, though it does not discount the possibility that other intraseasonal variations in the atmospheric circulation may be tied to the "clustering" of Atlantic tropical cyclogenesis.

During 1995, nine named storms (Dean, Erin, Felix, Gabrielle, Humberto, Iris, Jerry, Karen and Luis) formed during the 31 days between 30 July and 29 August. This is equivalent to the formation of a new named storm just over every three days. Of these nine storms, five became hurricanes (Erin, Felix, Humberto, Iris, and Luis) and two became intense hurricanes (Felix and Luis). The first three weeks of September define the climatological peak of the hurricane season (Neumann et al. 1993). However, between 29 August when Luis was named and 27 September when Noel was named, only one new system formed—Intense Hurricane Marilyn. On average, 4.1 named storms form in the Atlantic basin during this 28-day period. A second burst of six new named storms formed between 27 September and 27 October. Of these new storms, four became hurricanes and two became intense hurricanes (Noel—H, Opal—IH, Pablo—TS, Roxanne—IH, Sebastien—TS, and Tanya—H).

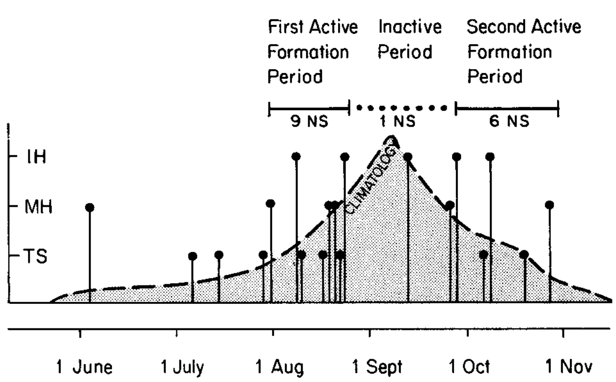


FIG. 13. Time line showing the dates when the 19 named storms of 1995 first attained tropical storm status. These storms tended to cluster during two active periods (30 July–29 August and 27 September–27 October). Note the relatively inactive period during 30 August–26 September that coincided with the normal climatological peak in activity.

The large-scale circulation changes associated with the active and inactive periods of hurricane activity during 1995 are shown in Fig. 14. During August and October, there was a large-scale pattern of anomalous cyclonic streamfunction over western Canada and anomalous anticyclonic streamfunction throughout eastern North America. This latter feature is consistent with reduced westerly flow (and actual easterly flow in some cases) at upper levels throughout the MDR, and thus with reduced vertical wind shear. In contrast, an opposite pattern of streamfunction anomalies is evident during September, with near-normal geostrophic winds observed across the tropical North Atlantic, the Caribbean, and the Gulf of Mexico. These conditions are then consistent with the observed return to near-normal values of vertical shear across the MDR during the month. Thus a large-scale change in the atmospheric circulation across North America appears to have been a primary contributor to the reduced hurricane activity observed during September.

Another contributor to the decreased tropical cyclogenesis during September was a weakening of the wide-scale warm SST anomalies and a creation of some cool anomalies in the MDR and in the North Atlantic subtropics (Fig. 15b) compared to that observed during August (Fig. 15a) and October (Fig. 15c). These cooler SSTs during September appeared directly under the late July–late August tropical cyclone tracks (Fig. 15b). Additionally, they were accompanied by a temporary return to near normal SLPs during the month (Table 4). Thus both atmospheric and oceanic conditions favored increased hurricane activity during August and October and relatively fewer hurricanes in September.

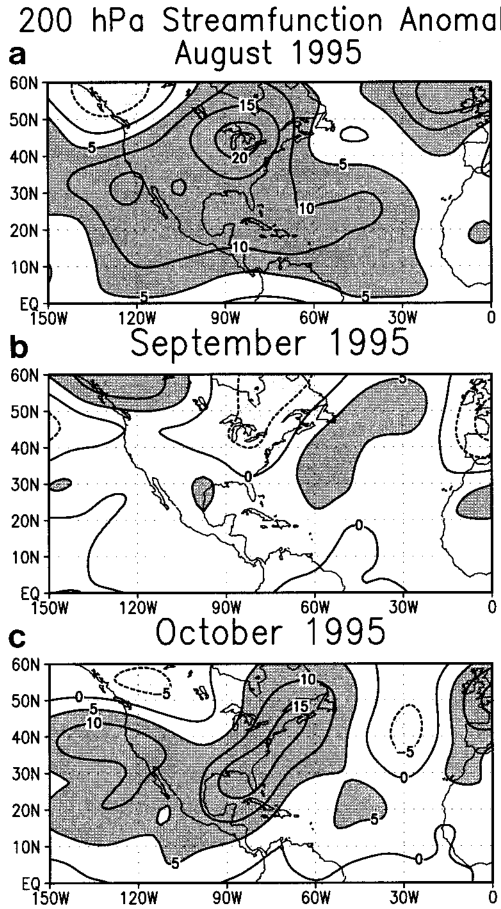


FIG. 14. The 200-mb streamfunction anomalies during (a) August, (b) September, and (c) October. The contour interval is 5×10^6 m^2 s^{-1}, with positive (negative) values dashed (solid) and values greater (less) than $5\ (-5) \times 10^6$ m^2 s^{-1} shaded dark (light). The nondivergent component of the flow is directed along the streamfunction contours with a speed proportional to the gradient. Thus, high (low) streamfunction values correspond to high (low) geopotential heights. Anomalies are departures from the 1979–95 base period means.

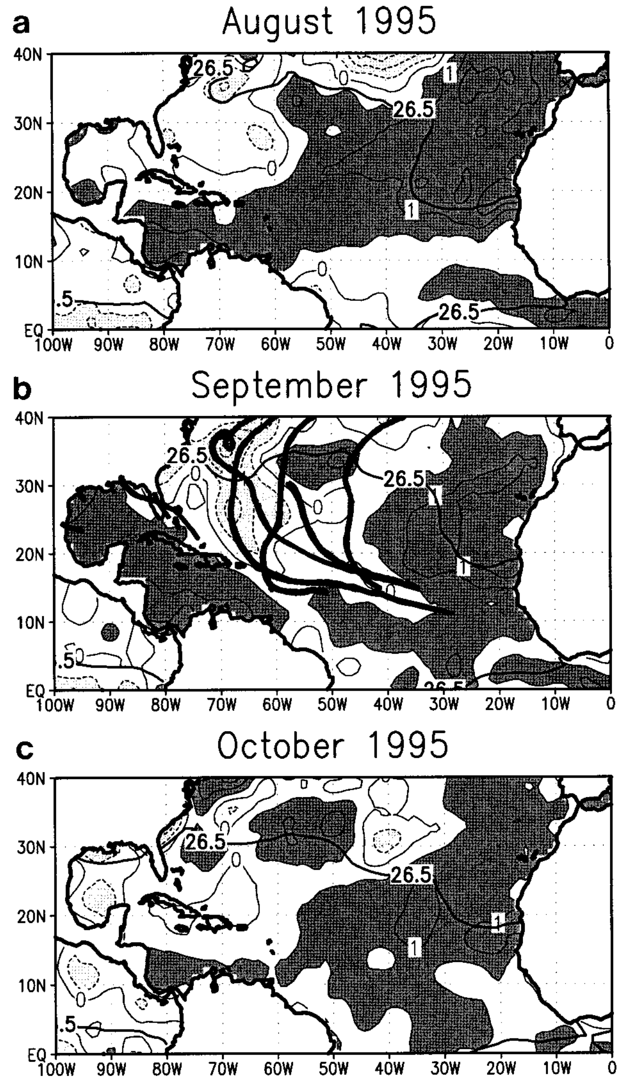


FIG. 15. Same as Fig. 8 except for (a) August, (b) September, and (c) October 1995 SSTs and SST anomalies. Solid lines in (b) indicate tracks of Atlantic tropical cyclones that formed from late July through late August.

Tropical cyclones are known to force cooling of the SST by a combination of vertical turbulent mixing and upwelling of cooler subsurface water (e.g., Shay et al. 1989). The timescale that the oceanic mixed layer takes to recover to original pre–tropical cyclone conditions can vary from a few days to a few weeks depending on the location in the basin, depth of the thermocline, and the time of year (Black 1983). It is suggested here that the tropical cyclones themselves can induce a negative feedback that operates on a monthly timescale: during a several week period of multiple tropical cyclones, the SSTs are cooled significantly, reducing the potential for tropical cyclones to develop. After a few weeks, the SSTs return to their original warm state and multiple tropical cyclones are again possible, dependent upon other genesis factors being favorable. The scenario appears to be what occurred during 1995.

8. Recurring tropical cyclone tracks

Most of the tropical storms and hurricanes during 1995 originated over the central tropical North Atlantic, moved toward the west-northwest, and then recurved back to the northeast before affecting North America or Central America (Fig. 1). In fact, of the seven named storms that developed during August and September in the MDR (Felix, Humberto, Iris, Karen, Luis, Marilyn, and Noel), only Felix crossed 70°W and threatened the continental United States. Even this system eventually recurved to the northeast without making landfall. Since 1944, three-fourths of the August–September named storms forming equatorward of 20°N and east of 55°W have recurved or dissipated over the open ocean, while 18% have made landfall along the continental United

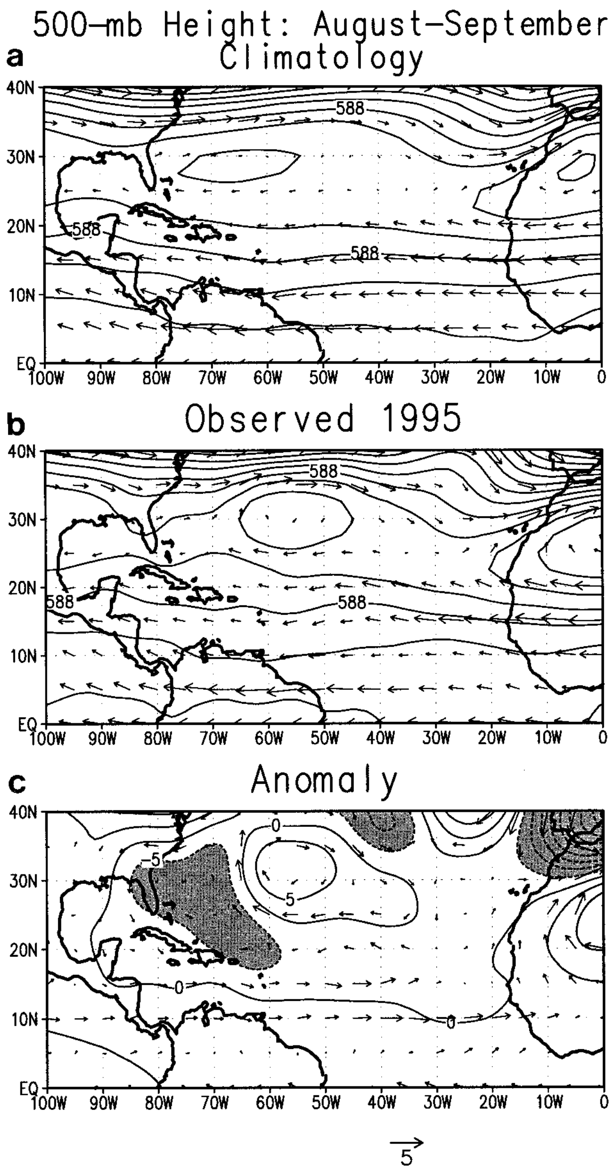


FIG. 16. August–September 500-mb heights and winds for (a) climatology (1979–95), (b) 1995 mean, and (c) 1995 anomaly. Contour interval for heights is 15 m and for height anomalies is 5 m. In panel (c), positive height anomalies are contoured solid and values greater than 5 m are shaded light. Negative height anomalies are contoured dashed and values less than −5 m are shaded dark.

States and 7% have struck Central America or Mexico. Thus, the frequency of recurving systems during 1995 is much larger than is expected to occur climatologically.

This repetition of recurving tropical cyclone tracks during 1995 is attributed to an anomalous 500-mb circulation over the western North Atlantic, the approximate steering level for hurricanes (e.g., Elsberry 1995). In particular, there was an eastward shift of the climatological mean subtropical ridge normally centered east of Florida near 65°W (Fig. 16a), to approximately 55°W during August–September 1995 (Fig. 16b), along with an amplification of the mean trough over the southeastern United States (Figs. 16b,c). This anomaly pattern was associated with enhanced southerly flow over the western Atlantic near 30°N, 65°W during August–September. This flow pattern directed the hurricanes northward into the mean westerly current, where they subsequently recurved to the northeast without making landfall. However, such anomalous steering flow variations were not present in the preceeding months, thus making anticipating such track variations difficult.

9. Verification of forecasts for the 1995 hurricane season

The seasonal hurricane forecasts for 1995, issued by Gray (1994) and Gray et al. (1995a,b) on 30 November 1994, 7 June 1995, and 4 August 1995, respectively, are given in Table 6.[4] The verification of the 4 August forecasts of upcoming August–November tropical cyclones is shown in Table 7. All of these forecasts correctly called for an above-average season, with all measures of activity above the long-term mean. However, these forecasts did not anticipate the extreme nature of the 1995 hurricane season.

Nonetheless, the forecasts successfully indicated a marked upswing in tropical cyclone activity during

[4] The third author made a qualitative adjustment to the 30 November 1994 forecast at the National Hurricane Conference in Atlantic City on 14 April 1995 (Gray 1995). This was based on a then faulty assessment of March ENSO and Atlantic sea surface temperature conditions.

TABLE 6. Verification of the 1995 seasonal hurricane predictions (Gray 1994, 1995; Gray et al. 1995a,b).

Forecast parameter	30 Nov 1994 forecast	14 Apr 1995 qualitative adjustment	7 Jun 1995 forecast	4 Aug 1995 forecast	Verification
Named storms (NS)	12	10	12	16	19
Named storm days (NSD)	65	50	65	65	121
Hurricanes (H)	8	6	8	9	11
Hurricane days (HD)	35	25	35	30	60
Intense hurricanes (IH)	3	2	3	3	5
Intense hurricane days (IHD)	8	5	6	5	11.75
Hurricane destruction potential (HDP)	100	75	110	90	172
Net tropical cyclone activity (NTC)	140%	100%	140%	130%	229%

TABLE 7. Verification of 4 August 1995 forecast for hurricane activity after 1 August.

Forecast parameter	Climatology (1950–90) after 1 Aug	Forecast activity after 1 Aug	After 1 Aug verification
Named storms (NS)	7.9	11	14
Named storm days (NSD)	42.0	49	104
Hurricanes (H)	5.2	7	9
Hurricane days (HD)	22.7	27	57
Intense hurricanes (IH)	2.2	3	5
Intense hurricane days (IHD)	4.7	5	11.75
Hurricane destruction potential (HDP)	68.4	84	165
Net tropical cyclone activity (NTC)	92.8%	107%	206%

1995, following the extremely inactive 1991–94 seasons. For example, in late November 1994, it was stated that ‘‘the 1995 season should be much more active than the four recent 1991–94 hurricane seasons, and especially in the tropical regions at latitudes south of 25°N’’ (Gray 1994). The primary factor leading to this forecast was ‘‘the anticipated dissipation of the long running equatorial Pacific warm water event, which [had then] persisted for over four consecutive years.’’ By June 1995 it was evident that ‘‘the El Niño, stratospheric QBO, West African rainfall, and Atlantic sea surface temperature anomalies [were] all coming together to promote the large-scale wind and thermal-moisture conditions which are associated with an active season’’ (Gray et al. 1995a). Additionally, it was suggested at that time that the probability of hurricane activity within the Gulf of Mexico and the Caribbean would be higher than at any time since 1989. Finally, by August 1995, most of the global and regional meteorological features known to be associated with active Atlantic hurricane seasons were evident. Gray et al. (1995b) indicated that there was ‘‘a very high statistical probability that 1995 will experience a very active hurricane season.’’

10. Summary and discussion

The 1995 Atlantic hurricane season featured 19 named storms (the average is 9.3), with 11 of these systems reaching hurricane status (the average is 5.8). This is the second largest number of named storms observed in any hurricane season (June–November) since 1871, and the second largest number of hurricanes observed in any season since 1886. Of these 11 hurricanes, 5 reached intense hurricane status (the average is 2.3)—the most observed in the Atlantic basin since 1964. This active hurricane season followed four consecutive years (1991–94) of extremely low Atlantic tropical cyclone activity. During the 1995 Atlantic hurricane season an abnormally large fraction of the named storms (89%, or 17 of 19) developed from African easterly waves. As with most seasons, the majority of the storms developed during the August–October period, although there was a relative lull in formation from late August through late September in 1995, during the climatological peak of the season. Seven of the hurricanes formed south of 25°N excluding the Gulf of Mexico, compared to only one hurricane, which formed in this region during the entire 1991–94 period. Additionally, all named storms that formed in the tropical North Atlantic during 1995 exhibited strongly recurving tracks, which prevented their landfall on the east coast of the United States. This extreme repetition of recurving hurricane tracks resulted from a systematic eastward displacement of the midtropospheric subtropical ridge position to near 55°W, and the development of southerly flow to the west of the mean ridge axis over the western North Atlantic.

Perhaps the primary factor for the increased hurricane activity during 1995 can be attributed to a favorable, large-scale pattern of extremely low vertical wind shear throughout the MDR. This reduced vertical shear actually reflected a large-scale pattern of anomalous easterly (westerly) winds at upper- (lower-) tropospheric levels extending from Africa to approximately 140°W. These same anomalies extended across the northeast Pacific tropical cyclone basin and—due to a different climatological mean flow in that region—resulted in increased shear and substantially reduced tropical cyclone activity during the 1995 season. These large-scale conditions first appeared in February and March 1995 and subsequently persisted throughout the hurricane season. This extreme persistence and large spatial scale of these anomalous wind and shear patterns indicates that they were a cause, rather than an effect, of the active 1995 hurricane season.

In addition to changes in the large-scale flow fields, the enhanced Atlantic hurricane activity has also been linked to below-normal sea level pressure, abnormally warm ocean waters, and very humid values of total precipitable water. These favorable conditions all developed by the start of the hurricane season in June. Our results suggest a positive interplay between the anomalously warm SSTs, low SLPs, and humid TPW values over the tropical North Atlantic during 1995, which ultimately favored tropical cyclogenesis and intensification. Qualitatively (Fig. 17a), the abnormally warm SSTs over the MDR help to lower surface pressures

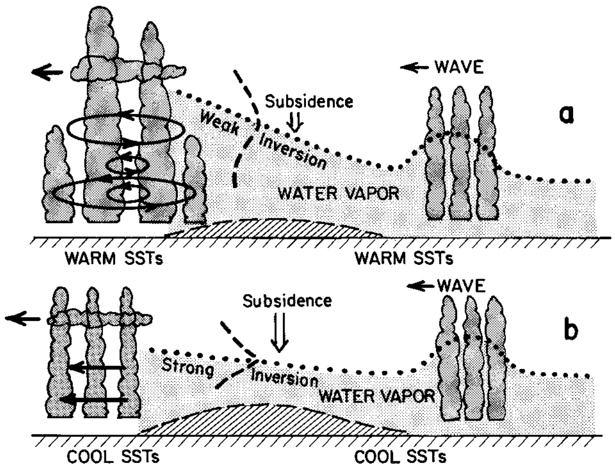


FIG. 17. Idealized schematic of an Atlantic easterly wave disturbance moving westward from Africa into the central and western Atlantic Ocean near 15°N during late summer. In the top diagram (a) only weak surface pressure, warm SSTs, and weak subsidence drying conditions exist. A weak trade wind inversion is present. The top of the moisture level is high enough such that the wave's upward vertical motion is able to overcome the subsidence drying and a tropical cyclone is able to form. In the bottom diagram (b) surface pressure and subsidence are stronger than normal, the SSTs are cooler than normal, the height of the moist level is lower than normal, and the trade wind inversion is stronger. The wave's upward vertical motion cannot overcome these adverse influences. The westward moving easterly wave disturbance of diagram (b) is not able to transform itself into a tropical cyclone and continues to move to the west as a cloud cluster.

hydrostatically by directly warming the lower troposphere.[5] The reduced meridional pressure gradient of the modified SLP acts to reduce the low-level trade wind easterlies, thereby contributing to a further warming of the ocean temperatures via reduced oceanic upwelling (Enfield and Mayer 1997). Finally, the TPW is increased due to less subsidence drying and increased moisture flux from the ocean surface associated with the lowered SLP and increased SST, respectively. In contrast, opposite conditions of abnormally cool SSTs, high SLPs, and dry TPW values (Fig. 17b) are more typical of inactive hurricane seasons.

An additional local environmental factor that likely contributed to the active 1995 hurricane season was the westerly phase of the stratospheric quasi-biennial oscillation (QBO). This westerly phase of the QBO enhances Atlantic basin hurricane activity, while the easterly phase is typically associated with suppressed hurricane activity.

Remote climate factors can significantly affect the interannual variability of Atlantic basin hurricane activity, primarily through their low-frequency modulation of the distribution of vertical shear. These same factors provide the main long-range forecast signal for seasonal hurricane activity up to 11 months in advance. During 1995, the most important of these climate factors appears to have been a dramatic transition from the prolonged late 1991–early 1995 warm episode (El Niño) to cold episode (La Niña) conditions during February–August. This transition contributed to the extreme duration of the atmospheric circulation anomalies over the North Atlantic during 1995, and to the dramatic reversal in these anomaly patterns from those which dominated during the last four hurricane seasons. This strongly reduced vertical shear in the MDR (and slightly above-normal shear north of 25°N) during 1995 is consistent with conditions observed during previous La Niña events (Goldenberg and Shapiro 1996).

A second remote climate factor previously identified as a contributor to increased Atlantic basin hurricane activity is enhanced western Sahel precipitation. However, we find that near-normal rainfall was observed throughout the western Sahel during 1995. Thus this effect was likely a neutral contributor to the observed increase in Atlantic hurricane activity this year. This near-normal value of western Sahel rainfall was a surprise, however, considering the strong and very stable correlations shown in other studies (e.g., Landsea and Gray 1992; Landsea et al. 1992; Goldenberg and Shapiro 1996) between June–September rainfall and Atlantic tropical cyclone activity.

Despite the lack of positive contribution of Sahelian rainfall toward the 1995 Atlantic hurricane season, the combined conducive effects of low vertical wind shear, low SLPs, warm SSTs, humid TPW, a westerly phase of the stratospheric QBO moderate, and a La Niña event allowed for the 1995 hurricane season to be extremely active. In strong contrast to 1995, the 1994 hurricane season had very quiet conditions especially during the traditional peak in activity during August–October. The same factors that promoted increased activity in 1995 were shown to be in an opposite, inhibiting state during 1994.

The correct anticipation of two factors, the end of the long running Pacific warm episode and the onset of the westerly phase of the QBO, led to successful forecasts of an active hurricane season as early as late November 1994. These long-range forecasts are also significant, in that they indicated a reversal from the suppressed hurricane activity observed during the previous four years, and thus were a marked departure from both ''persistence'' and ''climatology.''

Finally, there was substantial intermonthly variability in tropical cyclone activity during the 1995 season, with named storms forming primarily during two one-month periods: 30 July–29 August and 27 September–27 October. The downturn in activity during September likely resulted from a return to near-normal vertical shear over the Gulf of Mexico and western Caribbean, caused by a series of large amplitude troughs propagating across

[5] This negative relationship of SLP and SST anomalies in the tropical North Atlantic is not uniform around the Tropics. Weisberg and Wang (1997) show that many regions of the Tropics show no consistent SLP–SST relationship or even an in-phase association.

the eastern United States and the northern Gulf of Mexico. In contrast the Caribbean and Gulf of Mexico regions were dominated by very low vertical shear values during August and October, caused by a persistent upper-level ridge that extended southward from the eastern United States to the Yucatan peninsula. These observations highlight the sometimes important contribution to the short-term variability of Atlantic basin tropical cyclone activity from slowly evolving, midlatitude weather systems. A second effect that likely also contributed to the reduction of September tropical cyclones was cooler SSTs throughout the MDR that were produced by the tropical cyclones that passed through the area the previous month. By October, the SSTs had recovered to their originally favorable warm anomaly state.

Some have asked (e.g., Begley 1996) whether the increase in hurricanes during 1995 is related to the global surface temperature increases that have been observed over the last century, some contribution of which is often ascribed to increases in anthropogenic ''greenhouse'' gases (Houghton et al. 1996). We conclude that such an interpretation is not warranted, particularly in light of the large-scale patterns of oceanic and atmospheric conditions that can be linked coherently and tangibly to the observed interannual variability of hurricane activity. Additionally, Atlantic hurricane activity has actually decreased significantly in both frequency of intense hurricanes and mean intensity of all named storms over the past few decades (Landsea et al. 1996). This holds true even with the inclusion of 1995's Atlantic hurricane season. It is likely that this multidecadal variability (Landsea et al. 1992; Gray et al. 1997) is primarily of natural origin, and is partly related to the sometimes large interdecadal variability of the Sahel rainfall (Nicholson 1989), Southern Oscillation (Quinn et al. 1987), and to known atmospheric circulation patterns that control the distribution of vertical shear over the tropical North Atlantic.

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