Atlantic Tropical Systems of 1994 and 1995: A Comparison of a Quiet Season to a Near-Record-Breaking One

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ABSTRACT

Totals of 70 and 63 tropical waves (also known as African or easterly waves) were counted in the Atlantic basin during the 1994 and 1995 hurricane seasons. These waves led to the formation of 9 of the 12 total number of tropical cyclones in 1994 and 19 of the 21 total number of tropical cyclones in 1995. Tropical waves contributed to the formation of 75% of the eastern Pacific tropical cyclones in 1994 and 73% in 1995. Upper- and lower-level prevailing wind patterns observed during the below-normal season of 1994 and the very active one of 1995 are discussed. Tropical wave characteristics between the two years are compared.

1. Introduction

The importance of westward-propagating disturbances, referred to as tropical waves (also called African or easterly waves), has been recognized for more than half a century (Dunn 1940). These disturbances, which are usually traced back to Africa, can lead to the formation of tropical cyclones over the Atlantic and eastern Pacific basins. Typically, the strongest Atlantic hurricanes of the year originate from tropical waves (e.g., Landsea 1993).

Initially, the waves were detected as series of centers of falling and rising sea level pressure moving from east to west across the islands of the Caribbean Sea. When upper-air observations became available, it was noted that those pressure centers were accompanied by a cyclonic wind shift (typically from northeast to southeast) that was largest near the 700-mb level. Currently, satellite images are an extremely valuable supplement to surface and upper-air data for tracking tropical waves.

Tropical waves have been the focus of research for a long time. Riehl (1945, 1954) first described the dynamics of easterly waves, and a more detailed analysis and compilation began in 1967 by Simpson et al. (1968). Carlson (1969a,b) carried out synoptic analyses describing the characteristics of tropical waves over west Africa and the tropical Atlantic. Burpee (1972) studied the origin and structure of tropical waves in the lower troposphere of North Africa. In addition, several papers about the structure and properties of tropical waves were published after the Global Atmospheric Research Project (GARP) Atlantic Tropical Experiment (GATE) (e.g., Thompson et al. 1979; Burpee and Reed 1982). Furthermore, there have been some attempts to analyze and forecast tropical waves using global models (e.g., Reed et al. 1988).

This article is primarily concerned with operational analysis of tropical waves. The main purpose here is to tabulate and summarize certain weaker synoptic-scale systems of 1994 and 1995, namely, tropical waves and tropical depressions. Nature has provided the unique opportunity to compare some prevailing meteorological conditions between a nonactive 1994 season and a very active or near-record 1995 season.

2. Data and analysis

Tropical waves were identified and tabulated using satellite imagery, surface observations, and upper-air data across the Tropics from Africa to Central America. In general, vertical time sections were constructed with the available 0000 and 1200 UTC upper-air data from 1 May to 30 November. The time sections were prepared for several stations and, in conjunction with daily satellite imagery, are used to locate the waves. The presence of a lower-tropospheric cyclonic wind shift, a notable 24-h surface pressure change, and/or the propagation of an organized and distinct cloud mass are the primary parameters used in locating the wave axis. Figure 1 is a vertical time section of the wind for Trinidad for 1–15 September 1994 and 1995.

Since some tropical waves have very poor cloud definition, it is difficult to track such waves across the data-sparse oceanic areas, and there is a certain amount of noise in their identification and positioning. In general, when deep convection was minimal or absent and the

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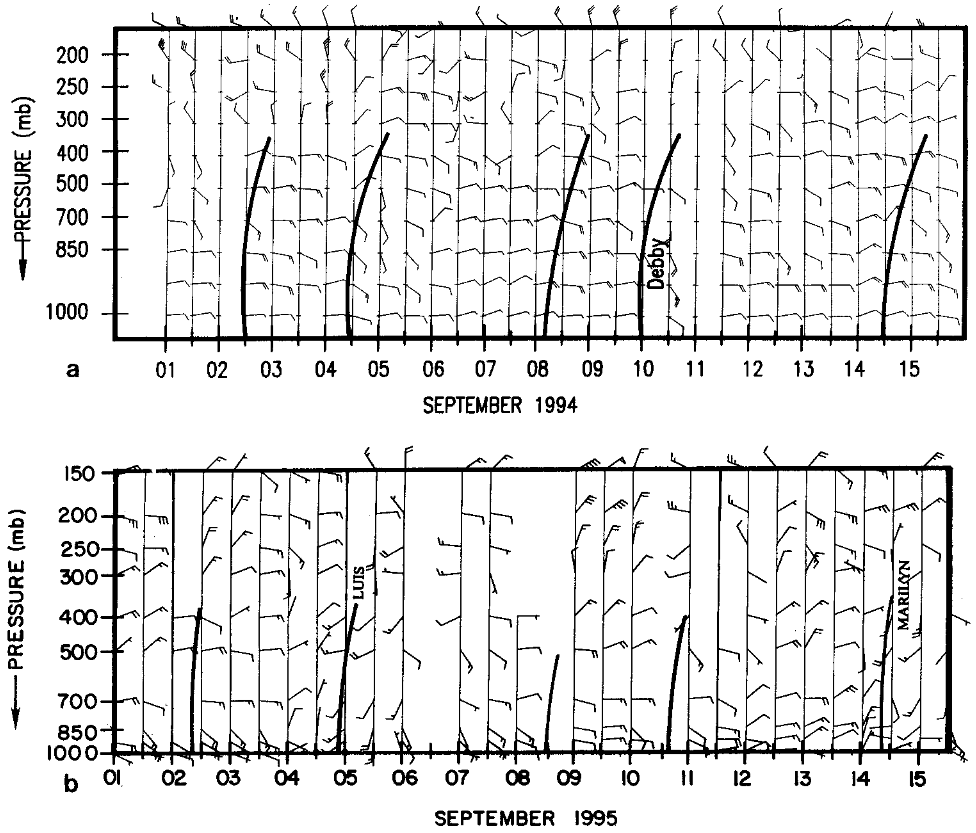


FIG. 1. Vertical time section of the wind at Trinidad from (a) 1–15 September 1994 and (b) September 1995. Winds plotted every 12 h according to convention with each full barb and half-barb denoting 5.1 and 2.6 m s^{-1}, respectively, and the solid flag denoting 25.7 m s^{-1}. Thick lines indicate the positions of the tropical wave axes. The names denote tropical storms or hurricanes that crossed the longitude of Trinidad.

cloud pattern was not well defined, the position of such waves was simply extrapolated.

Over the past few years, improvements in the analysis and initialization in global models have made it possible to depict more accurately the westward propagation of lower- to middle-tropospheric vorticity centers along the tropical belt. Longitude versus time (Hovmöller) diagrams of the meridional component of the wind were sometimes used to depict the (U.S. Environmental Modeling Center) Medium Range Forecast Model's representation of tropical waves. This was also used as complementary information to track the waves.

3. Census and comparison of the 1994 and 1995 Atlantic systems

Tropical cyclone activity in the Atlantic was below normal in 1994. The season featured a total of seven named tropical cyclones, three of which became hurricanes. None of the hurricanes hit the United States but the combination of Alberto, Beryl, and Gordon at tropical-storm strength caused $1 billion in damage. Torrential rains associated with the remnants of Alberto caused 30 fatalities in Alabama and Georgia. Rainfall and mud slides associated with Gordon during its tropical storm stage killed 1122 people in Haiti.

In contrast to 1994, tropical cyclone activity was near a record in 1995. There were 19 named storms, 11 of which became hurricanes. Three tropical storms and two hurricanes made landfall in the continental United States. Tropical cyclones in the Atlantic basin were responsible for an estimated 123 deaths, and U.S. damages were over one billion dollars each in Hurricane Marilyn and Hurricane Opal. In addition, it is estimated that non-U.S. damages of $2.5 billion occurred in the Caribbean from Hurricane Luis and $1.5 billion occurred in Mexico from the combination of Roxanne and Opal. Detailed summaries of the 1994 and 1995 hurricane seasons are included in Avila and Rappaport (1996) and Lawrence et al. (1998), respectively.

In addition, there were five tropical depressions that did not intensify into tropical storms in 1994 and two in 1995. Only those depressions are described here. In 1994, three tropical depressions formed from disturbances of nontropical origin (e.g., cold fronts, upper lows) and nine developed from tropical waves. In 1995, 19 of the 21 total number of tropical depressions developed from tropical waves.

In terms of tropical depression frequency, 1994 was below average with a total of only 12 tropical depressions. On the other hand, in 1995 the total number of tropical depressions jumped to 21. The average for the period of 1967–94 is 19. In both years, there were tropical depressions in every month of the season. In 1994, September was the most active month with five tropical depressions, but only two intensified to tropical storms and none reached hurricane status. In 1995, August was the most active month with eight tropical depressions, and only one failed to become a tropical storm. Four of the tropical storms reached hurricane status. Figures 2a and 2b show the Atlantic tropical depression tracks for 1994 and 1995, respectively.

a. Tropical depressions of 1994

1) TROPICAL DEPRESSION TWO

Tropical Depression Two formed from a weather system of nontropical origin. A broad upper-tropospheric trough, related to the climatological summertime mid-Atlantic trough, had an axis extending east-northeastward for several hundred miles from the Bahamas in mid-July. Cloudiness and thunderstorms increased within this trough, over an area just to the north of the Bahamas on 18 July. Although surface pressures were relatively high over the area, a weak surface low gradually developed a couple hundred miles southeast of the coast of the Carolinas by 19 July. The system was poorly organized, with most of the convection situated south of the center. Surface observations suggest that a tropical depression formed around 0600 UTC 20 July.

Just 6 h after its formation, as the depression center neared the coast of South Carolina, reconnaissance aircraft data showed that the low-level circulation had become much better defined. Convection had also increased significantly over the center by that time. Moving northwestward, the center of the depression crossed the coast near Georgetown, South Carolina, at 1400 UTC 20 July as shown in Fig. 3. Myrtle Beach, South Carolina, experienced wind gusts to 19 m s^{-1} a few hours after the depression made landfall.

The depression moved northwestward to northward, weakening over land. By 0600 UTC 21 July, the system was dissipating in the vicinity of Charlotte, North Carolina. Some locally heavy rains, totaling 50–75 mm, attended the remnant low as it moved northward over North Carolina and Virginia. The remnants of the depression accelerated northward to northeastward and became indiscernible late on 21 July.

Because of the threat posed by heavy rains, flash flood watches were posted over portions of the eastern United States during the depression's passage. However, this system apparently did not cause any casualties or significant damage.

2) TROPICAL DEPRESSION FIVE

The development of Tropical Depression Five was associated with a tropical wave that was tracked from Africa since 17 August. It was not until the wave reached the western Caribbean Sea on 26 August that the convection became organized and surface pressures began to fall. A reconnaissance plane was dispatched to the area and found a well-defined midlevel circulation but only a wind shift at the surface. The wave moved westward across the Yucatan peninsula and on 29 August became a tropical depression when a reconnaissance plane found a low-level circulation center of 1007 mb and 23 m s^{-1} winds at a flight level of 460 m in the Bay of Campeche. Figure 4 shows the developing tropical depression in that area.

The depression moved on a general west-northwest track with some potential for development. The central pressure dropped to 1005 mb on 30 August, but the winds did not increase in strength. A tropical storm watch then was issued for the coast of Mexico from Nautla to La Pesca at 0300 UTC 30 August. Tropical storm warnings were issued from Nautla to Tampico at 1200 UTC 30 August and then extended northward to La Pesca as the depression approached the coast. The expected intensification did not materialize and the depression moved inland near Tampico in the early morning of the 31st. Watches and warnings were then discontinued. The tropical depression dissipated later on 31 August, but its remnants continued over northeast Mexico for a couple of days. Totals between 50 and 100 mm of rain associated with the tropical depression were recorded over the area but no reports of damage were received at the National Hurricane Center.

3) TROPICAL DEPRESSION EIGHT

Satellite imagery showed a concentrated area of deep convection over the southwest Caribbean Sea on 19 September. This area persisted for several days and slowly moved toward the northwest to the northeast coast of Honduras by 23 September. Based on postanalysis of satellite data, it is estimated that Tropical Depression Eight formed near 1200 UTC 24 September centered just off the northeast coast of Honduras as indicated in Fig. 5. An Air Force Reserve unit aircraft found a poorly organized low-level circulation with 1007-mb central pressure at 2045 UTC on this date. The depression moved generally toward the west about 4 m s^{-1} until the center moved over the southern coast of Belize near 1800 UTC 25 September. Surface reports from Belize as well as aircraft reconnaissance reports from about 460-m elevation just off the coast of Belize indicated that the surface and low-level center moved inland. At landfall the tropical cyclone looked better organized on satellite pictures and the central pressure had fallen to 1004 mb based on reconnaissance aircraft reports. Peak winds reported from Belize were 15 m s^{-1} just prior to landfall. The depression slowed its westward motion and is estimated to have dissipated over Guatemala on the following day.

Locally heavy rains accompanied the depression over Belize and the Yucatan peninsula. Even after the surface circulation dissipated, there was evidence in satellite imagery of a midlevel circulation remaining near the coast of Belize. The satellite imagery suggested that some of the moisture from the remnants of Tropical Depression Eight merged with another disturbance that became Tropical Depression Ten near the western tip of Cuba on 29 September.

4) TROPICAL DEPRESSION NINE

Tropical Depression Nine formed from a well-defined cloud circulation that moved off the coast of Africa on 26 September. It was upgraded to a depression at 1200 UTC 27 September, while centered about 280 km southeast of the Cape Verde Islands in the far eastern tropical Atlantic Ocean, when a banding-type cloud pattern was evident on Meteosat satellite imagery depicted in Fig. 6. Also, a ship located just west of the circulation center reported northwesterly winds at 11 m s^{-1} this time.

The depression moved toward the north and then northwest for the next 36 h at less than 5 m s^{-1} while losing its deep convection. The center of the depression moved close to Sal in the Cape Verde Islands late on the 28 September and then dissipated.

5) TROPICAL DEPRESSION TEN

An area of disturbed weather partially related to the remnants of Tropical Depression Eight persisted for several days over the northwestern Caribbean Sea and the Yucatan peninsula. A tropical wave moved into the area, causing an increase in cloudiness and showers. The convective activity gradually became organized while an upper-level anticyclone developed in the region. Surface observations indicated that pressures dropped and that a circulation began to develop just east of Cozumel, Mexico. Based on that information, it is estimated that a tropical depression formed near 0600 UTC 29 September about 280 km south-southwest of the western tip of Cuba. Later on that day, a reconnaissance plane could not close off a circulation due to the cyclone's proximity to land, but surface observations placed the broad center of the depression near Cape San Antonio on the western tip of Cuba. Figure 7 shows the cloud pattern associated with the depression. Ships in the area reported winds of 15–18 m s^{-1} mainly in squalls.

The depression was becoming better organized and meteorological conditions (upper-level outflow, surface inflow) appeared to be favorable for intensification. However, a large and nontropical low pressure system, which was developing over the south-central Gulf of Mexico at that time, became the dominant meteorological feature. Once Tropical Depression Ten moved into the southeastern Gulf of Mexico, it was absorbed into the much larger circulation of the nontropical system by 1800 UTC 30 September.

A large convective mass was associated with the tropical depression. This activity moved northward over Cuba, southern Florida, and the Florida Keys producing heavy rains. Giron, in central Cuba, reported 305 mm of rain in 24 h.

b. *Tropical depressions of 1995*

1) TROPICAL DEPRESSION SIX

A tropical wave emerged from the west coast of Africa on 22 July. The northern portion of this system developed into Tropical Storm Erin on 31 July. However, the southern portion of the wave, which moved westward over the Caribbean Sea, produced sea level pressure falls over eastern Cuba and Jamaica. Surface data suggested the presence of a low pressure area and an extremely weak cyclonic circulation over the northwest Caribbean Sea by 1 August. This system moved slowly westward across the Yucatan peninsula on 2–3 August, and entered the Bay of Campeche by 4 August.

On 4 and 5 August, as the low moved slowly over the southwestern Gulf of Mexico, the associated shower activity increased. Reports from an Air Force Reserve Hurricane Hunter aircraft investigating the area on 5 August indicate that a tropical depression had developed. Deep-layer mean high pressure to the north of the depression steered the tropical cyclone west-northwestward to westward at 3–4 m s^{-1}, and the center moved across the coast of Mexico, roughly midway between Tampico and Tuxpan, around 2300 UTC 6 August. Figure 8 is a satellite picture of Tropical Depression Six shortly before landfall. Upper-level winds over the system favored anticyclonic outflow, but further development of the depression was prevented by landfall. Data from a Hurricane Hunter plane just before the depression moved ashore showed that maximum winds at the 460-m flight level were 20 m s^{-1}. Thus, assuming some reduction of this wind speed at the surface, Tropical Depression Six was likely just below the threshold of a tropical storm. Satellite intensity estimates concur with this inference. After moving inland, the depression quickly dissipated over the mountains of Mexico.

No reports of casualties or damage have been brought to the attention of the National Hurricane Center. It is possible that some localized flooding may have occurred near the path of the depression over Mexico.

2) TROPICAL DEPRESSION FOURTEEN

Tropical Depression Fourteen developed from a distinct tropical wave that exited the coast of Africa on 4 September. The system gradually organized and became a tropical depression at 1200 UTC 9 September. Figure 9 is a satellite picture of the depression a little later that

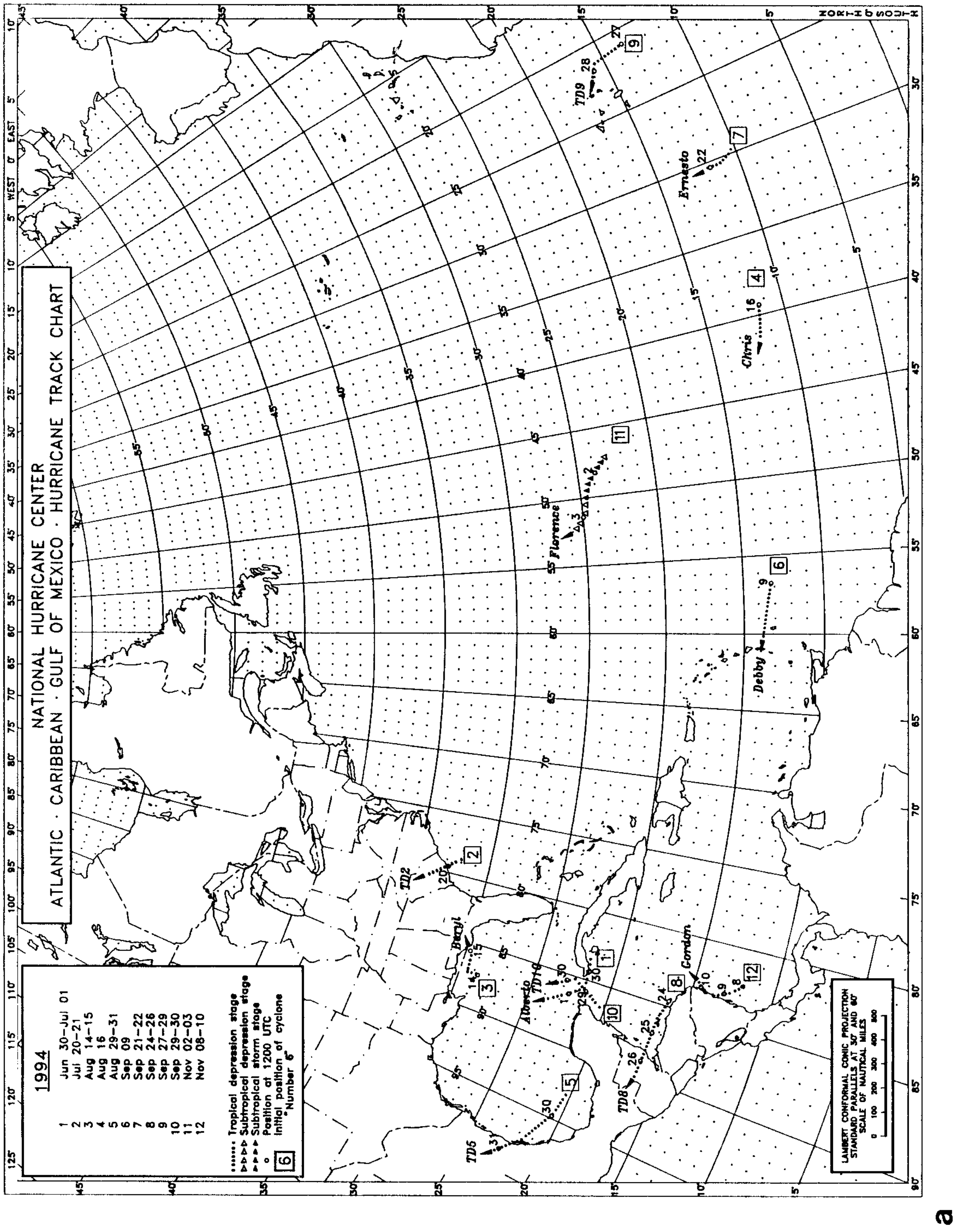
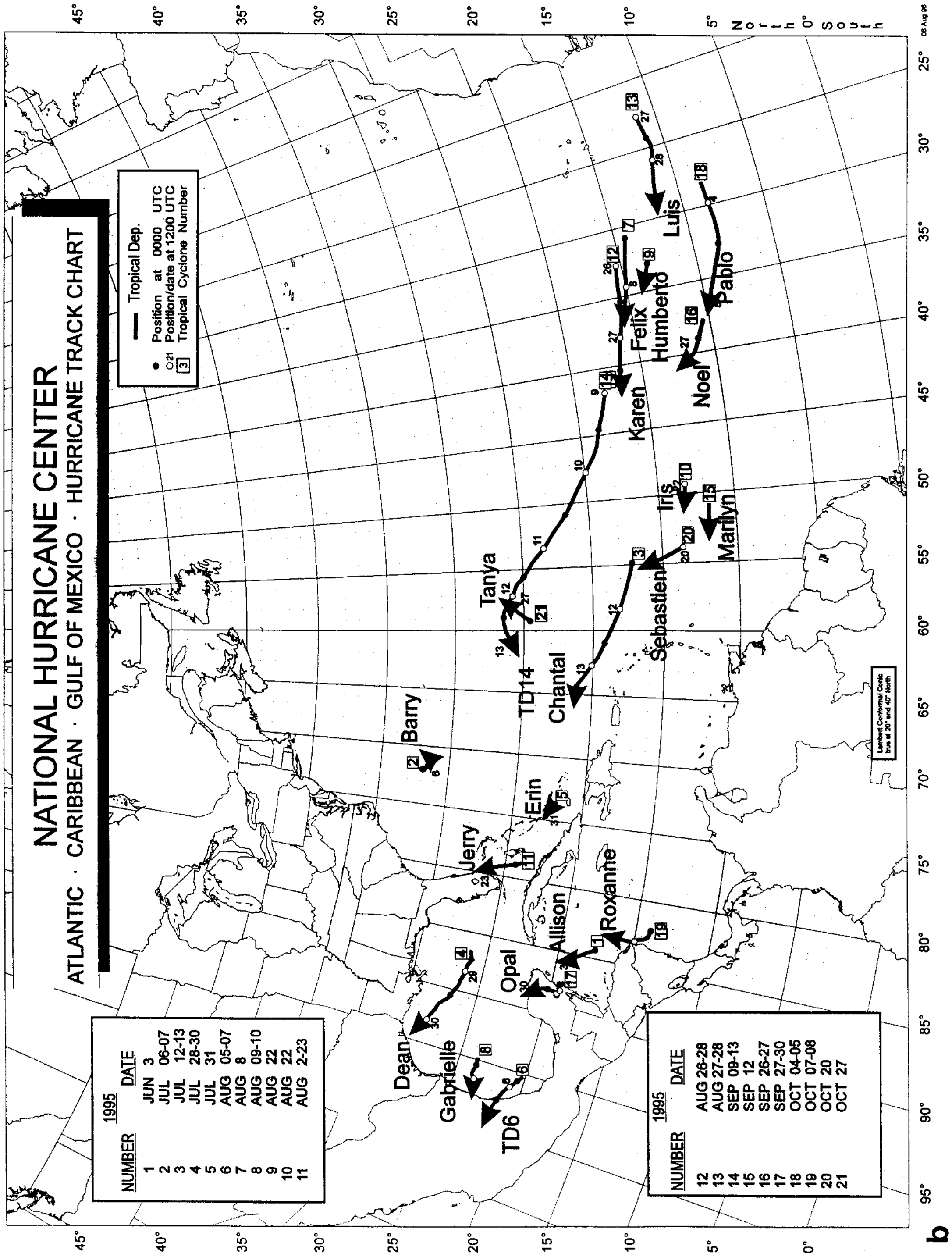


FIG. 2. Tropical depression tracks for (a) 1994 and (b) 1995.



NUMBER	1995 DATE
1	JUN 3
2	JUL 06-07
3	JUL 12-13
4	JUL 28-30
5	JUL 31
6	AUG 05-07
7	AUG 8
8	AUG 09-10
9	AUG 22
10	AUG 22
11	AUG 2-23

NUMBER	1995 DATE
12	AUG 26-28
13	AUG 27-28
14	SEP 09-13
15	SEP 12
16	SEP 26-27
17	SEP 27-30
18	OCT 04-05
19	OCT 07-08
20	OCT 20
21	OCT 27

FIG. 2. *(Continued)*

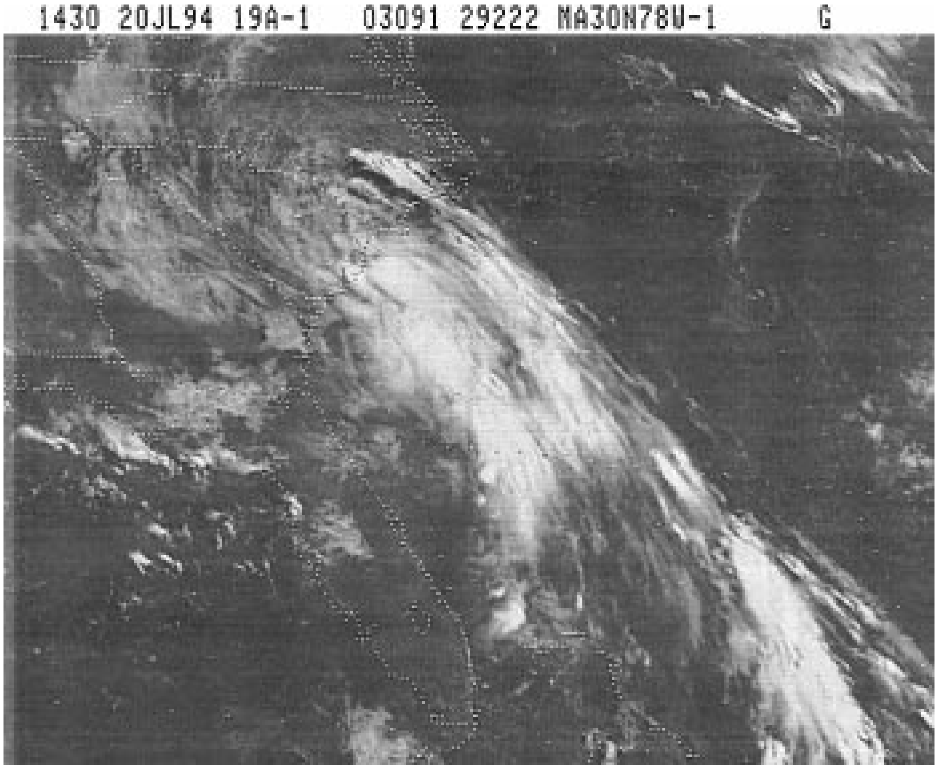


FIG. 3. *GOES-7* visible satellite picture of Tropical Depression Two at 1430 UTC 20 July 1994. The center is moving over the South Carolina coast.

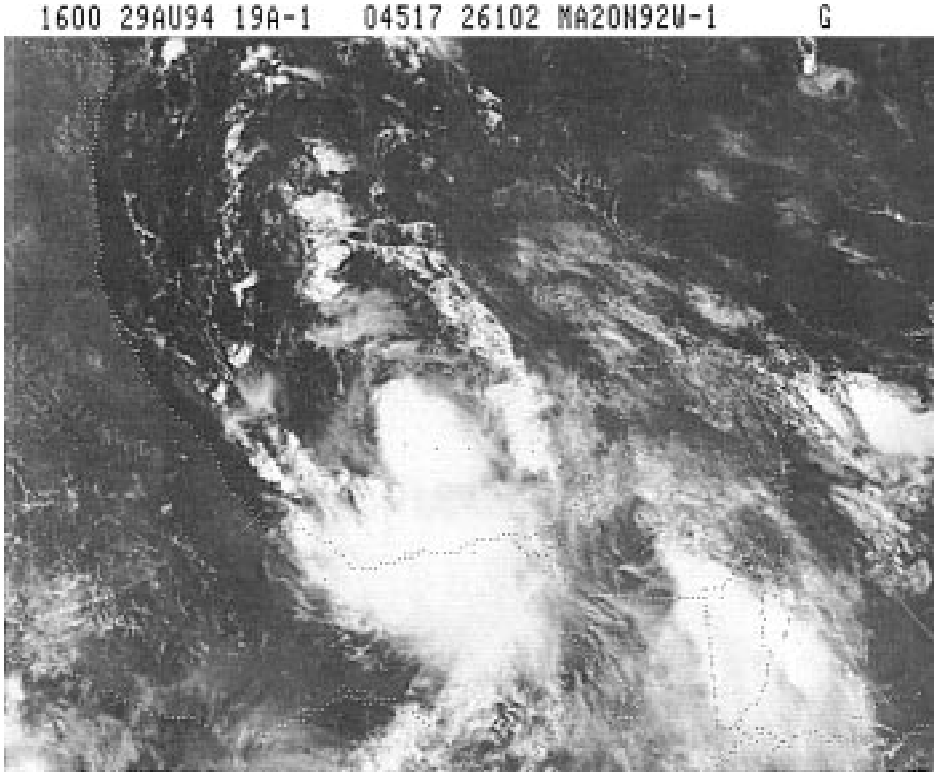


FIG. 4. *GOES-7* visible satellite picture at 1600 UTC 29 August 1994 of developing Tropical Depression Five.

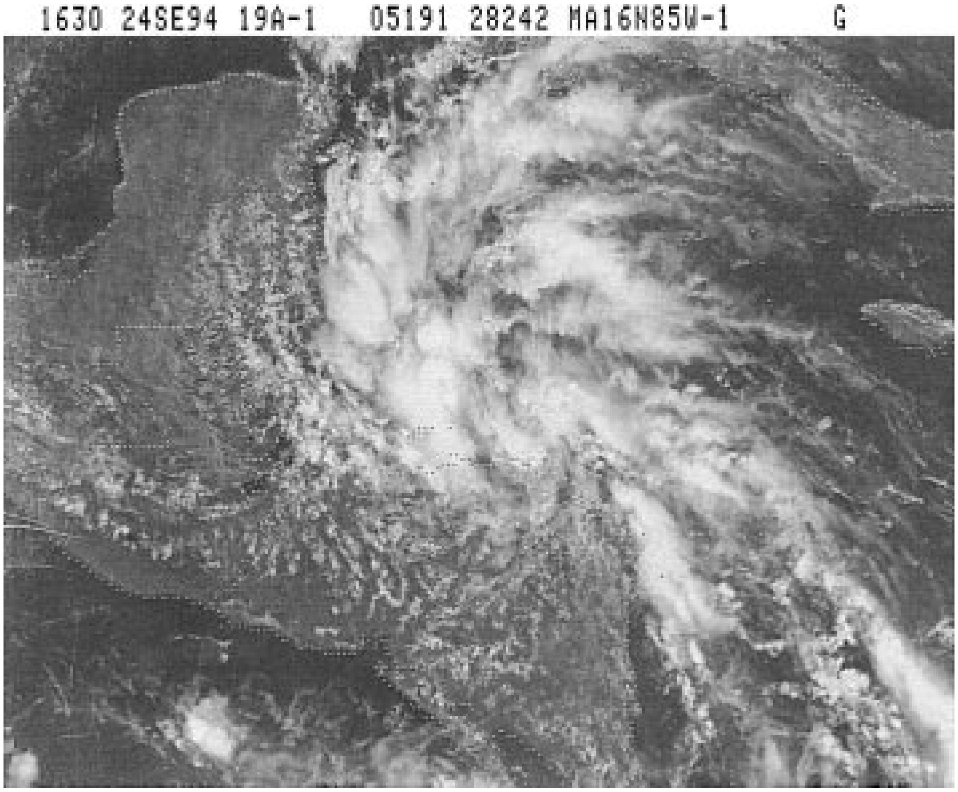


FIG. 5. *GOES-7* visible satellite picture at 1630 UTC 24 September 1994 of Tropical Depression Eight.

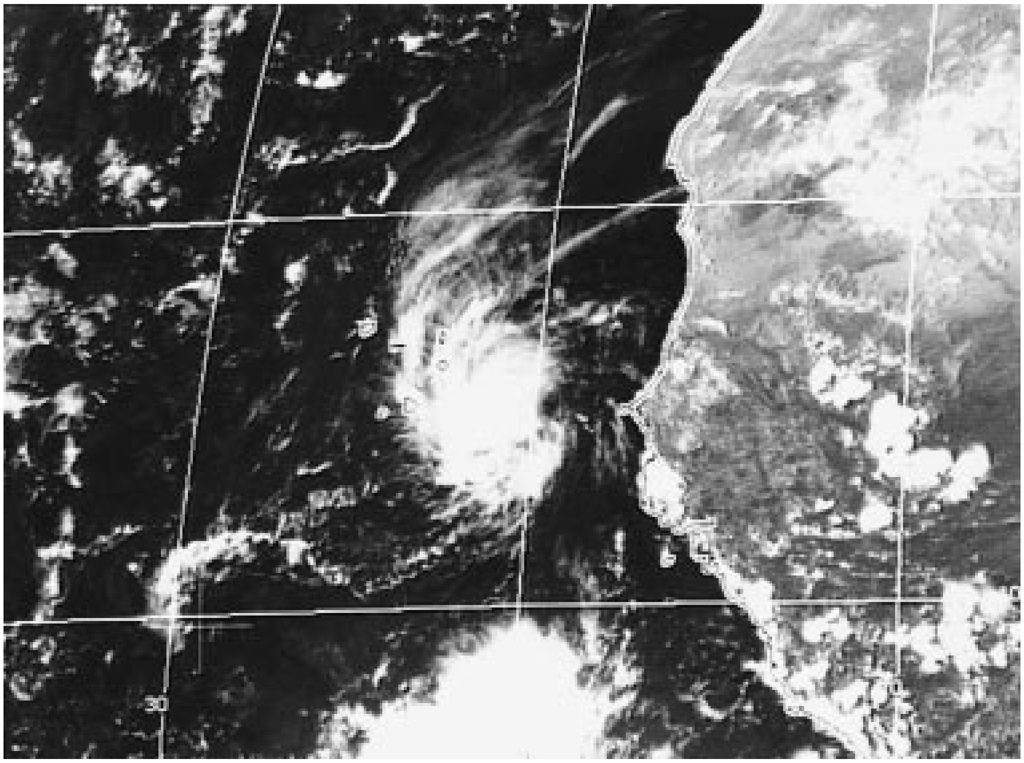


FIG. 6. Meteosat visible satellite picture at 1200 UTC 27 September 1994 of Tropical Depression Nine.

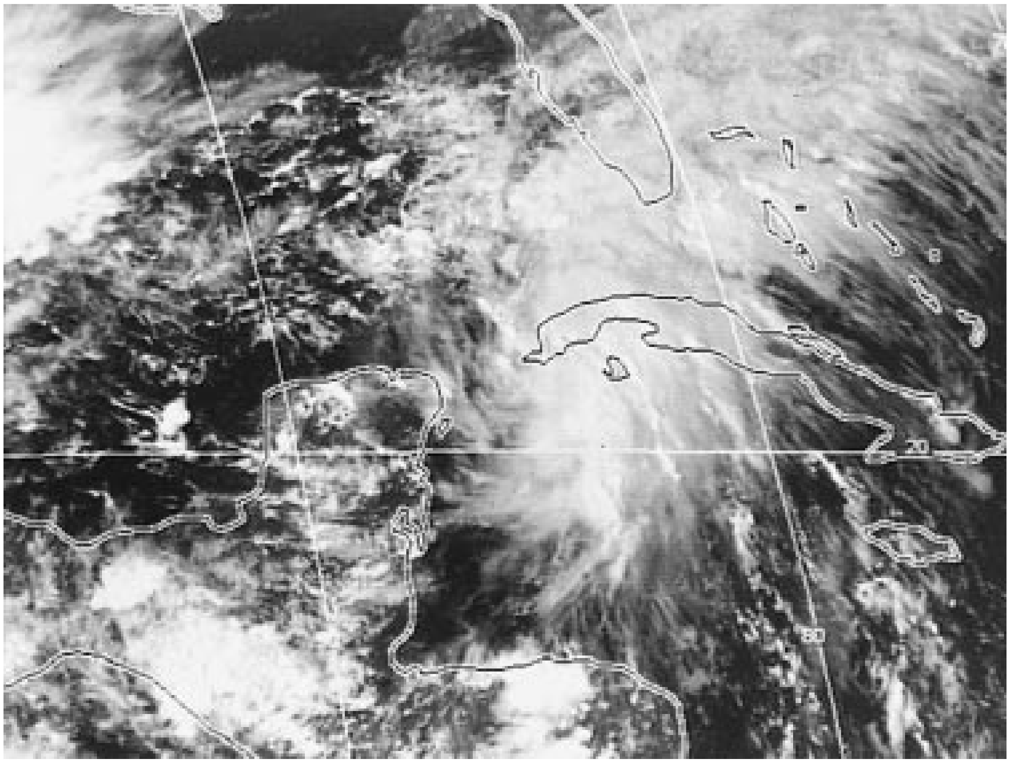


FIG. 7. *GOES-7* visible satellite picture at 2030 UTC 29 September 1994 of Tropical Depression Ten.

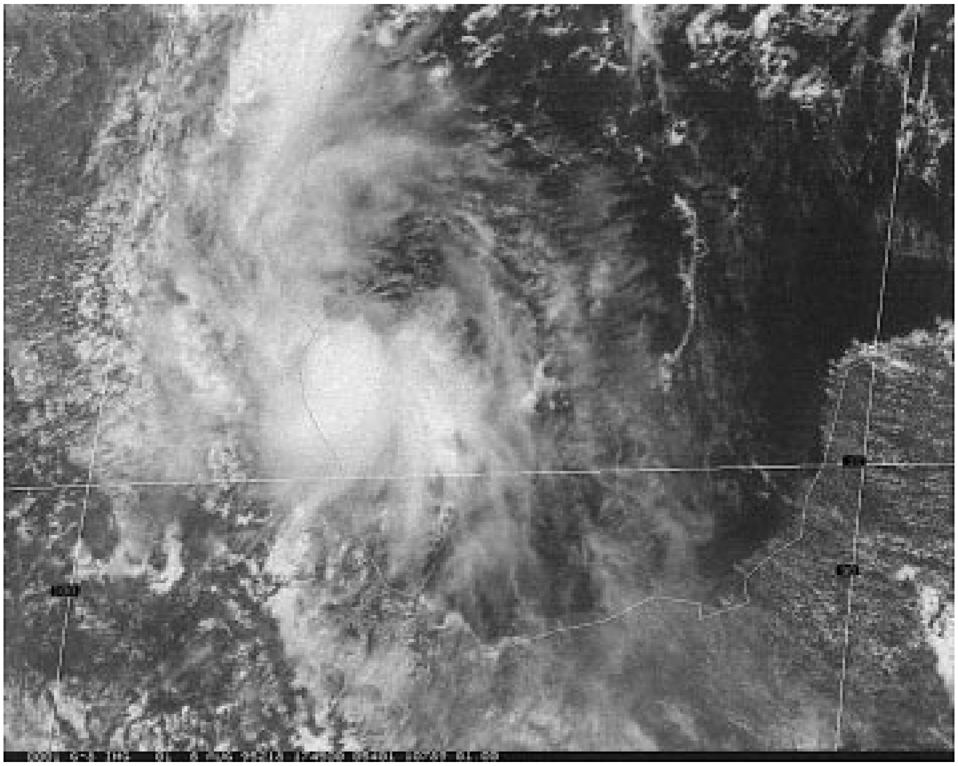


FIG. 8. *GOES-8* visible satellite picture at 1745 UTC 6 August 1995 of Tropical Depression Six.

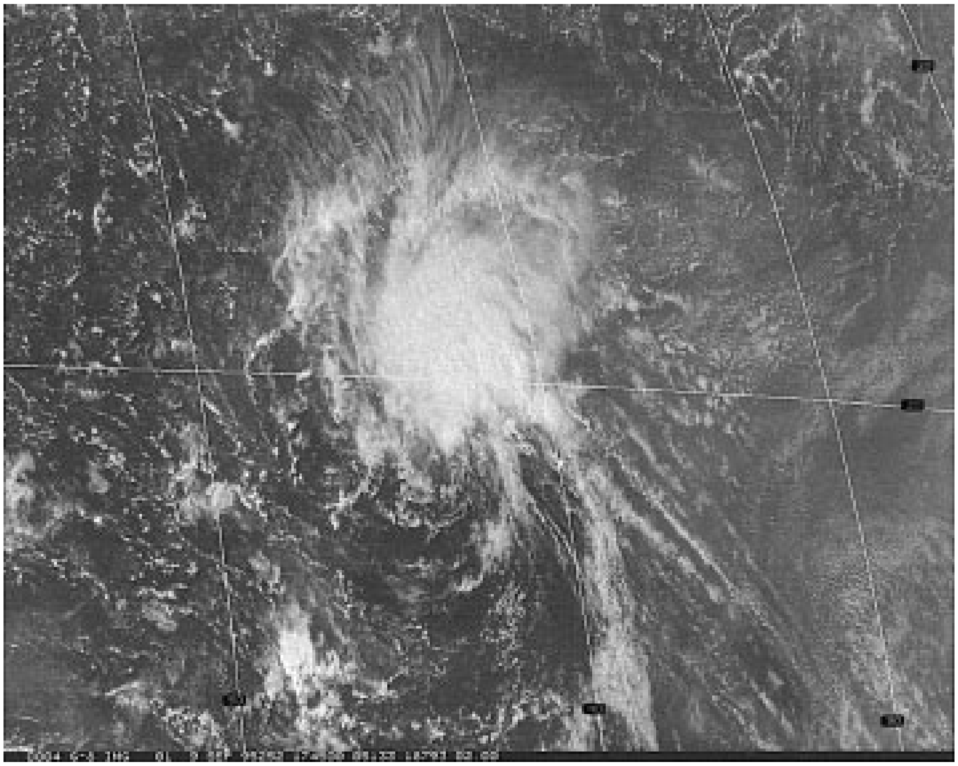


FIG. 9. *GOES-8* visible satellite picture at 1745 UTC 9 September 1995 of Tropical Depression Fourteen.

same day. The depression moved toward the northwest and encountered strong upper-level winds, which removed the convection from the low-level center. The depression dissipated on 13 September but its remnants meandered for a few more days over the north Atlantic.

4. Tropical waves and their environment during 1994 and 1995

Figures 10a and 10b show that during 1994 and 1995 70 and 63 tropical waves crossed the northwest coast of Africa and moved westward over the tropical Atlantic, the Caribbean, Central America, and appeared to move into the eastern Pacific. The average period of the waves in 1994 was 3.0 days, which is very similar to the period that was observed during the previous three years. The first tracked wave exited Africa on 2 May and the last one crossed Dakar during late November. In 1995, the first wave was counted on early May and the last one on the middle of November. The average period of the 1995 waves was 3.4 days.

Tropical waves in 1994, as in the previous three years, appeared to be poorly defined in the wind and cloud fields relative to other years wherein large amplitude waves were observed to move off the coast of Africa (e.g., Simpson et al. 1968). Vertical time sections from several rawinsonde stations consistently showed that the wind shifts associated with the waves were not significantly marked. In general the convective clusters propagating westward on satellite images were not really distinct. For example, one can notice in Fig. 11a, a sequence of daily satellite images from late August through September of 1994, that the tropical wave associated with Debby was the only easily discernible system on satellite images during that climatologically most active period. In Fig. 1a, one can also detect that with the exception of the tropical wave associated with Debby on 10 September, only small cyclonic wind shifts were observed at Trinidad associated with the other waves during that period. The low amplitude of the waves observed since 1991 may partially explain the lack of tropical cyclone activity in the deep Tropics.

In contrast with 1994, during 1995, tropical waves were characterized by their large amplitude and impressive cloud representation on satellite images. In fact, by the time some tropical waves exited the coast of Africa, there was already a low- to middle-level circulation and/or a surface low associated with the waves. If time sections for Trinidad during 1994 and 1995 are compared, one can see that during 1995 the wind shifts associated with tropical waves were distinct. The maximum wind change occurred at the low and middle levels and one could imply from the data that these waves already had an embedded vortex. In addition, one can observe that the upper-level winds (250 mb and above) were predominantly from the east (Landsea et al. 1997),

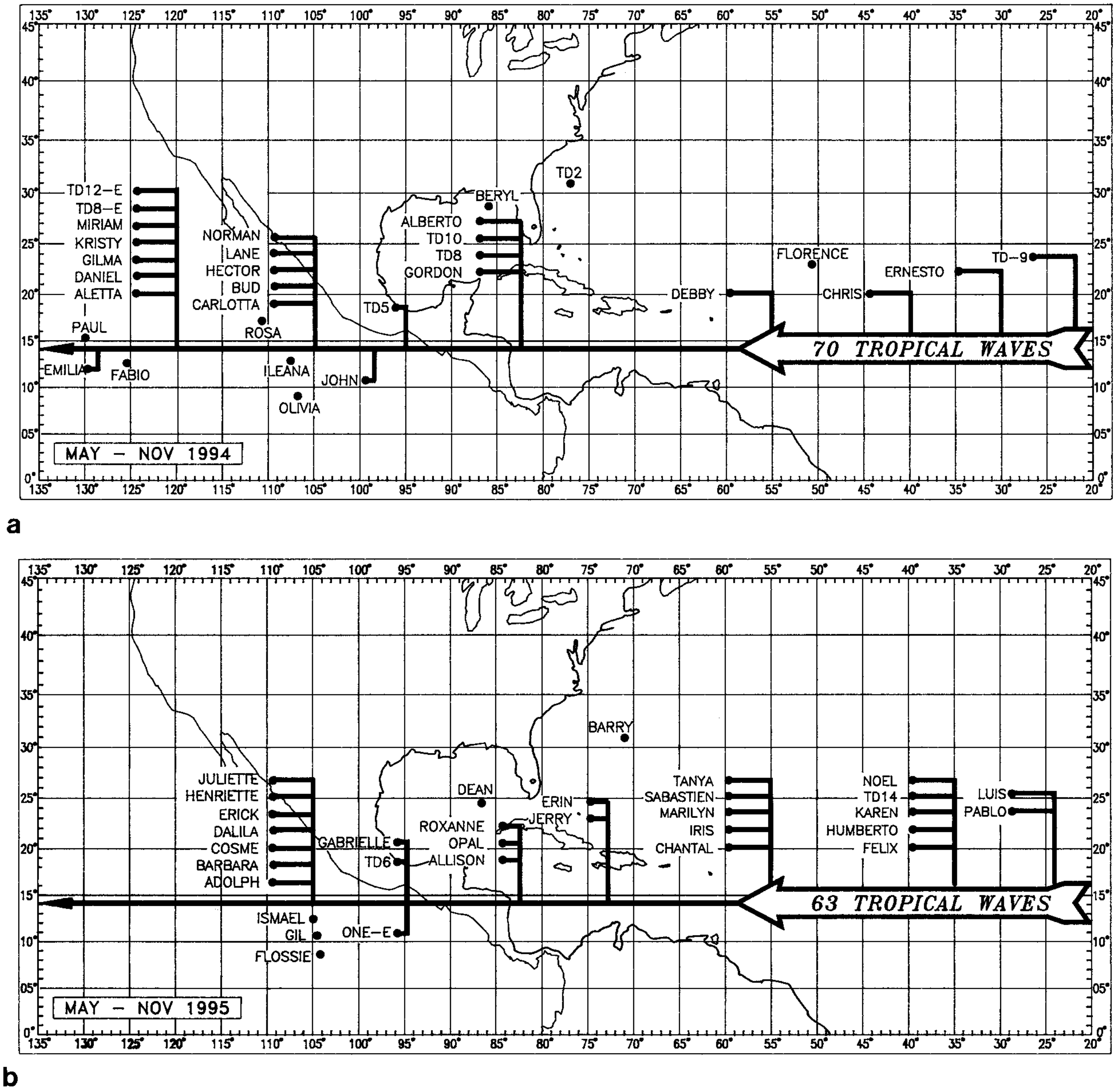


FIG. 10. Total number of waves that maintained their identities while traveling the Atlantic, Caribbean, the Gulf of Mexico, and the eastern Pacific during (a) 1994 and (b) 1995. The figure highlights the longitude bands in which tropical cyclones developed. Separate dots denote the approximate locations of tropical cyclone formation from disturbances other than tropical waves.

whereas in 1994 these winds were in general from the west and northwest. This suggests that the 1995 waves were moving through an environment of prevailing low vertical wind shear. Indeed, the cloud pattern for the tropical Atlantic during September of 1995 (Fig. 11b) shows that many of the waves had already spawned tropical cyclones.

Since tropical waves appeared to be so active and spawned so many more tropical cyclones over the Atlantic in 1995 as compared to 1994, one could ask the question: ‘‘Were these waves stronger over west Africa in 1995 in comparison to the previous year?’’ A clue to this may be found by considering the dynamics of the waves. It has been established that tropical waves have cold cores in the lower troposphere and warm cores aloft (e.g., Reed et al. 1977). As long as the waves produce deep convection not far from the trough axis, as they typically do over west Africa, the loss of energy from the lifting of cooler air at low levels is compensated by heating and lifting aloft. However, once these waves enter the tropical Atlantic, if deep convection is suppressed, there will be a sink of energy and the systems will weaken. Based on satellite images, fields of outgoing longwave radiation during 1994 and 1995 (Cli-

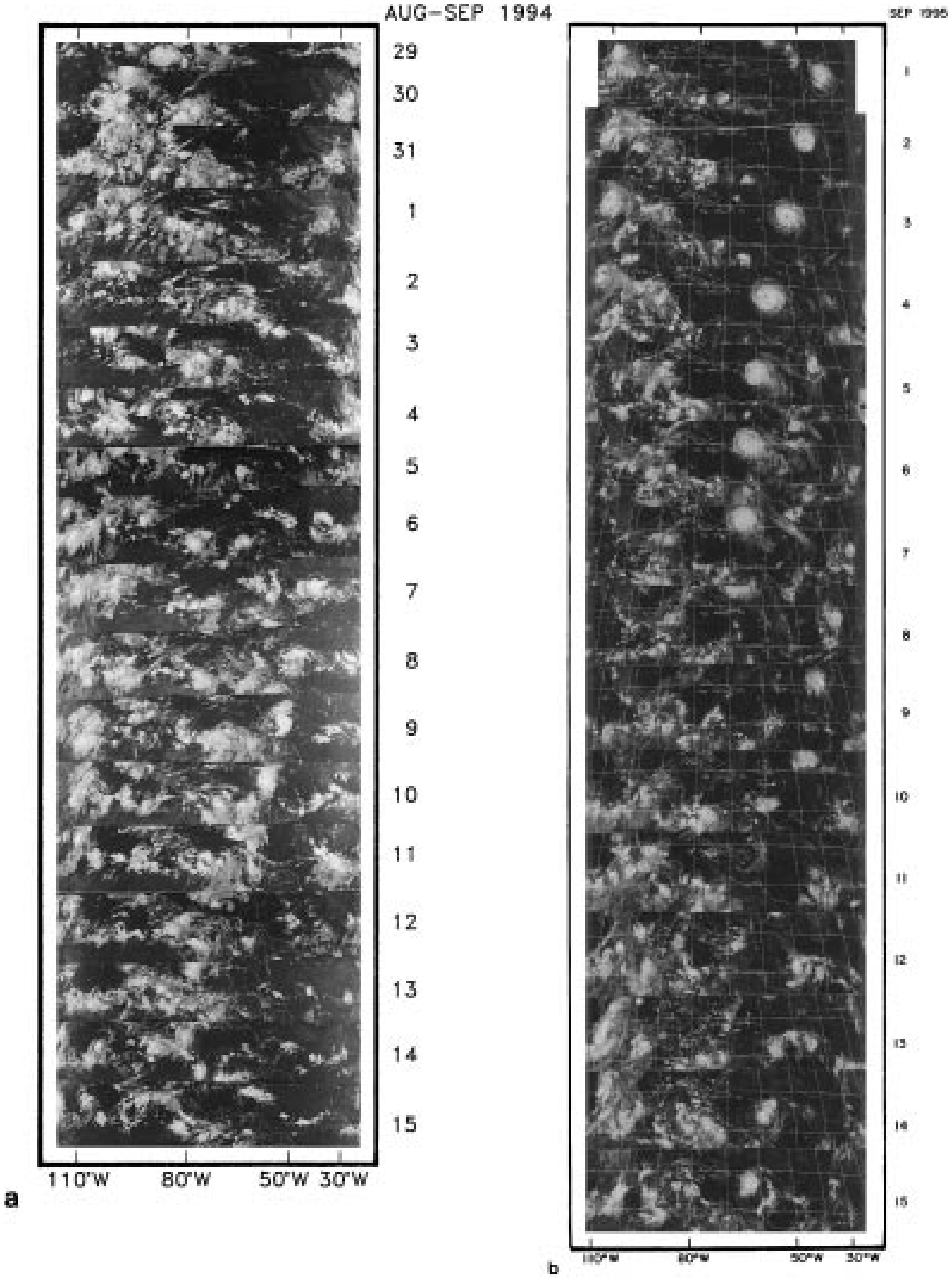


FIG. 11. Time sequence of Meteosat infrared images taken once a day at 1200 UTC from 29 August to 15 September 1994 (a) and from 1 to 15 September 1995 (b). The latitude belt is roughly 5°–25°N. Note the sequence of distinct cloud masses spreading westward from the Atlantic through the Caribbean and into the eastern Pacific associated with tropical waves and/or tropical cyclones.

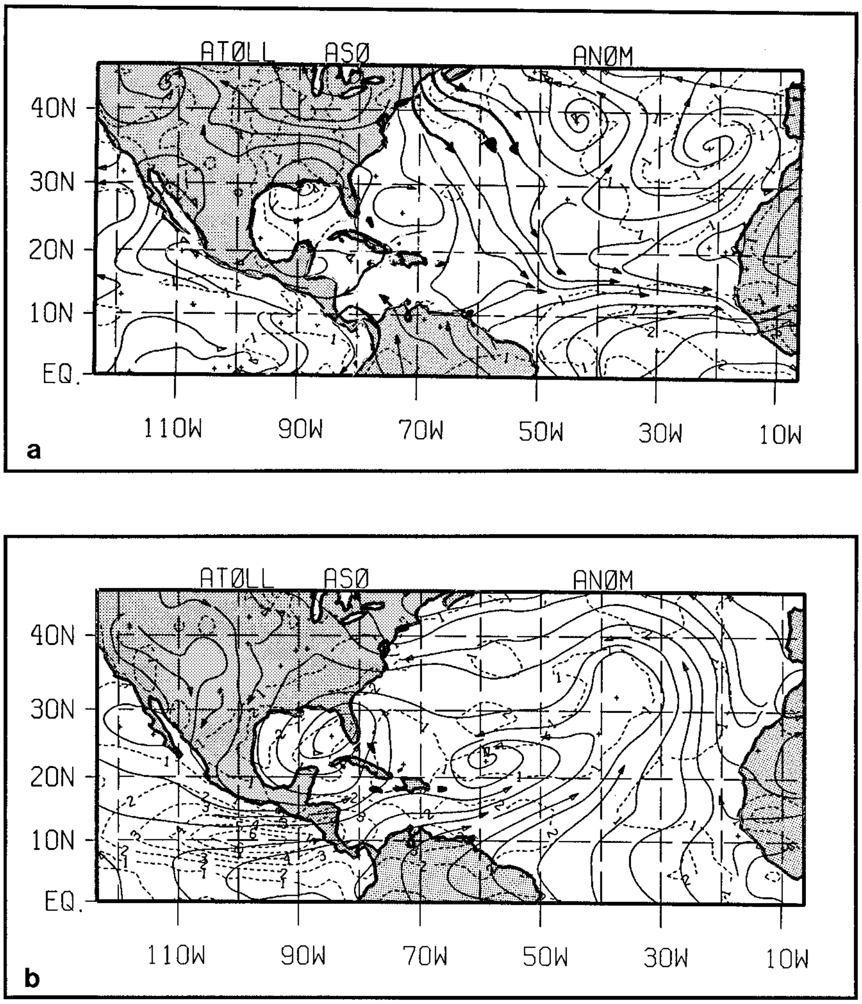


FIG. 12. Average low-level (approximately 900 mb) wind anomalies for August, September, and October 1994 (a) and for the same months of 1995 (b). Anomalies are taken from the 1975–94 average. Units are meters per second. The acronym ATOLL refers to analysis of the tropical oceanic lower layer.

mate Analysis Center 1994, 1995), and rainfall data (Landsea 1996, personal communication), the waves were not more active in terms of the amount of deep convection or associated rainfall over west Africa in 1995 as compared to 1994. However, over the eastern tropical Atlantic, the amount of deep convection appeared to be greater in late summer of 1995 as compared to the previous year, which implies a less stable atmosphere during 1995. This decreased stability is also consistent with positive sea surface temperature anomalies over the eastern Atlantic during the summer of 1995 (Landsea et al. 1998) and negative anomalies over the comparable region and period of 1994 (Avila and Rappaport 1996).

Some characteristics of the lower-tropospheric environment of the waves during 1994 and 1995 can be inferred from Figs. 12a,b, which depict the average low-level (approximately 900 mb) wind anomalies (from the 1974–94 mean) for August, September, and October (ASO) of 1994 and 1995, respectively. In 1994 (Fig. 12a), as occurred in 1993, an anomalous monsoon-type flow extended northward across the tropical Atlantic to near 17°N, where a large anomalous cyclonic flow prevailed. More significantly, there was an intrusion of anomalous northwesterly (and, presumably, dry) flow over the western Atlantic into the Tropics, and also an equatorward branch of anomalous flow feeding air from a stable region of the subtropics into the monsoonal region of west Africa. These also could have been inhibiting factors. The region of anomalous cyclonic flow centered along approximately 18°N from 50°W to Africa in Fig 12a is probably related to the primary path of the vorticity maximum associated with the waves during the period. Since the region of anomalous cyclonic flow was located over relatively cool sea surface temperatures (Avila and Rappaport 1996), the development of

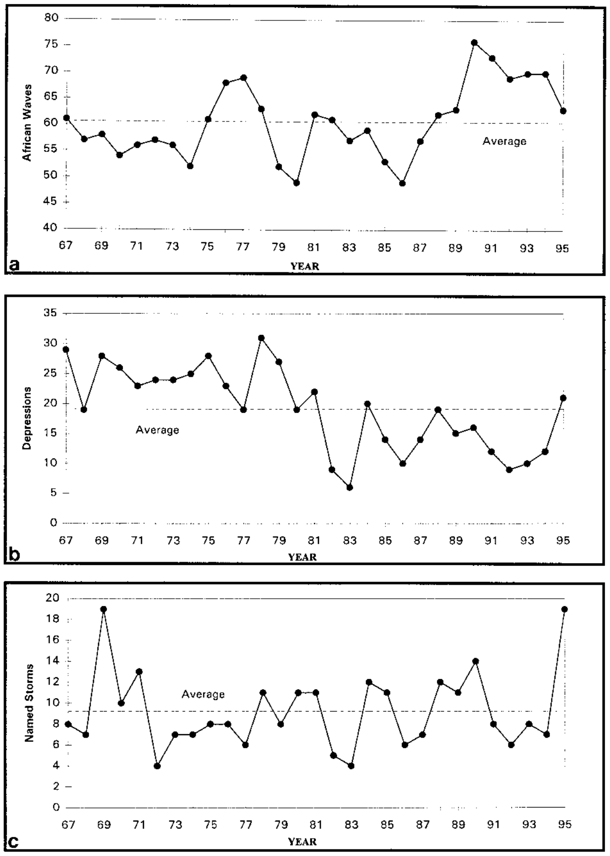


FIG. 13. (a) Total number of tropical waves from 1967 to 1995. Horizontal dashed line represents the average for the 1967–95 period. (b) Total number of tropical depressions from 1967 to 1995. Horizontal dashed line represents the average for the 1967–95 period. (c) Total number of named storms from 1967 to 1995. Horizontal dashed line represents the average for the 1967–95 period.

deep convection associated with the waves moving through that area was very limited (this reiterates what was discussed earlier from a static stability point of view). Only the few systems that moved westward through lower latitudes were able to produce deep convection (e.g., Debby). In general those systems that propagated westward over low latitudes (between 5° and 10°N), moved over South America and did not have the opportunity to develop.

In 1995, the pattern of wind anomalies for ASO (Fig. 12b) changed from 1994. In 1995, there was a significant intrusion of moist tropical air from the eastern Pacific into the Caribbean Sea and into the tropical Atlantic. Contrasting with 1994, the monsoonal flow prevailing in 1995 was over a region where the ocean was warmer than normal, primarily over the eastern Atlantic. In 1994, the eastern Atlantic was cooler than normal, as noted above. In addition, in ASO 1995, there were two large low-level cyclonic wind gyres, one centered just to the northeast of Puerto Rico and the other over the eastern Gulf of Mexico. These gyres were superimposed by a large area of anticyclonic flow and diffluence aloft. This persistent pattern of anomalous low-level confluence, upper-level diffluence, and warm ocean probably favored the waves to develop. Moreover, the southwesterly anomalies in the low-level flow pattern over the tropical Atlantic basin during ASO 1995 would also correspond to weaker northeast trade winds. This would contribute to a weaker vertical shear, since the easterlies typically decrease with height and become westerlies in the upper troposphere over that area. The weaker shear over the Atlantic basin during 1995 has been confirmed by Landsea et al. (1998); this decreased shear favored the development of more storms from waves in 1995.

It may be argued that the existence of the large low-level anomalous gyres in ASO of 1995 was due to the presence of a number of Atlantic hurricanes. Whereas this may be partially true, one can see, in Fig. 12b, that there is a flow of air, on a very broad scale, feeding from low latitudes into the gyres. This is suggestive of a large-scale circulation anomaly that favored cyclogenesis from tropical waves in the Atlantic basin during the peak months of the 1995 Atlantic season.

Nine of the 12 tropical cyclones in 1994 and 19 of 21 in 1995 developed from tropical waves over the Atlantic basin. Those tropical cyclones are represented in Figs. 10a,b by lines attached to the main ''stream'' of waves. Note that only Chris attained hurricane strength south of 21°N in 1994. In 1995, several of the systems reached hurricane strength in the deep Tropics. Moreover, four of them reached category 3 or higher intensity on the Saffir–Simpson hurricane scale (Simpson 1974) along that belt.

The development of eastern Pacific tropical cyclones from tropical waves has been suggested previously by Frank and Clark (1980). During the summer months it is typical for weak vertical shear and monsoonal-type flow to prevail over the warm Pacific waters to the south of Mexico. Therefore, tropical cyclogenesis in this region is frequently favored. In 1994 as well as 1995, it is likely that tropical waves again played a significant role in the formation of many of the eastern Pacific tropical storms (Pasch and Mayfield 1996). These waves usually take more than a week to traverse the Atlantic and Central America after emerging from west Africa. In Figs. 11a,b, one can observe the westward propagation of the convection associated with some of the tropical waves crossing Central America from the Caribbean into the eastern Pacific, leading to the development of some of the tropical cyclones in the latter basin. For example, in 1995 (Fig. 11b) there was a westward progression of an area of cloudiness across Central America on 11–12 September. This same system, which can be seen crossing 100°W on 14 September, later developed into east Pacific Hurricane Juliette.

Figure 10 shows two longitude bands centered along 105°W and 120°W, where tropical waves contributed to the formation of several of the eastern Pacific tropical cyclones in 1994. The formation along 120°W during 1994 represented a westward shift from the climatolog-

TABLE 1. Atlantic tropical system statistics for 1967–95.

		Total			African			Ratio		
Year	Waves	TD	TS	H	TD	TS	H	African TD / Total TD	African TS / Total TS	African H / Total H
1967	61	29	8	6	14	5	5	0.48	0.63	0.83
1968	57	19	7	4	8	4	2	0.42	0.57	0.50
1969	58	28	18	12	16	10	8	0.57	0.56	0.66
1970	54	26	10	5	16	7	3	0.82	0.70	0.60
1971	56	23	13	6	12	6	2	0.52	0.56	0.33
1972	57	24	4	3	6	1	1	0.25	0.25	0.33
1973	56	24	7	4	10	4	2	0.42	0.57	0.50
1974	52	25	7	4	12	5	4	0.48	0.71	1.00
1975	61	28	8	6	14	5	5	0.50	0.63	0.83
1976	68	23	8	6	10	5	5	0.43	0.63	0.83
1977	69	19	6	5	7	3	2	0.37	0.50	0.40
1978	63	31	11	5	18	6	4	0.58	0.55	0.80
1979	52	27	8	5	20	8	5	0.74	1.00	1.00
1980	49	19	11	9	14	8	6	0.78	0.73	0.66
1981	62	22	11	7	17	6	6	0.77	0.55	0.85
1982	61	9	5	2	6	3	2	0.67	0.60	1.00
1983	57	6	4	3	3	1	1	0.50	0.25	0.33
1984	59	20	12	5	8	5	1	0.40	0.42	0.20
1985	53	14	11	7	9	8	5	0.64	0.73	0.71
1986	49	10	6	4	6	3	2	0.60	0.50	0.50
1987	57	14	7	3	11	5	2	0.79	0.71	0.66
1988	62	19	12	5	16	9	4	0.84	0.75	0.80
1989	63	15	11	7	14	11	7	0.93	1.00	1.00
1990	76	16	14	8	12	10	5	0.75	0.71	0.62
1991	73	12	8	4	7	3	0	0.58	0.38	0.00
1992	69	9	6	4	4	2	1	0.44	0.33	0.25
1993	70	10	8	4	9	8	4	0.90	1.00	1.00
1994	70	12	7	3	9	5	2	0.75	0.71	0.66
Average	61	19	9	5	11	6	3	0.61	0.62	0.65
1995	63	21	19	11	19	17	11	0.90	0.89	1.00

TD: Tropical depression.
TS: Tropical storm.
H: Hurricane.

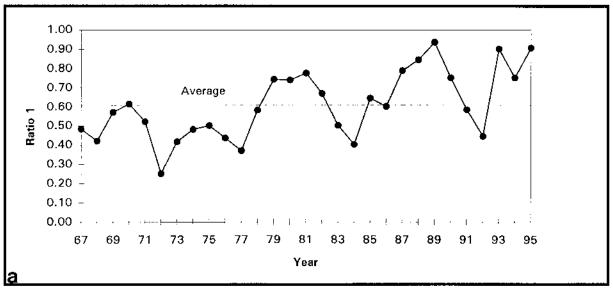
ical longitude of development. In some cases, particularly for those eastern Pacific tropical cyclones that formed closer to Central America, it is possible that the orographic effects of the adjacent mountainous landmass can aid in their formation, as theorized by Zehnder (1991). In 1995 the tropical cyclone activity in the eastern Pacific was rather limited, and development was clustered in a small region centered along 110°W. Rappaport et al. (1998) gave a possible explanation for the below average activity in this basin during 1995. Even though there was considerably less tropical cyclone activity in the eastern Pacific during 1995 compared to 1994, an inspection of Fig. 10 reveals that the percentage of cyclones that developed from tropical waves was about 75% in both years.

As noted above, there are some cases (in 1994, 1995, or other years) where eastern Pacific tropical cyclogenesis could not be traced back to a tropical wave, and the source of the preexisting disturbance was not clear. Typically these were situations in which the development occurred from a disturbance that was first detected within the ITCZ over the eastern north Pacific.

5. Comparison with other years

Figure 13a and Table 1 show the number of tropical waves from 1967 through 1995. In 1994, the number of waves (70) was somewhat higher than the average (61) but very similar to the previous four years. In 1995, the number of waves (63) was close to the average. It is emphasized that year to year variations in the total number of waves are probably not significant. Since the process of identifying tropical waves has not been uniformly applied over the years, one must be careful in interpreting the total number of such events especially when we are dealing with weak systems. However, this was not the case in 1995 since the waves were well represented in the wind and cloud fields and obviously the counting was more accurate.

Table 1 indicates that peaks in the number of tropical waves do not coincide with peaks in the number of tropical storms. This reaffirms Frank's (1975) statement that the number of waves is not related to the total number of tropical storms. The large-scale atmospheric and oceanic environment exercises the largest control



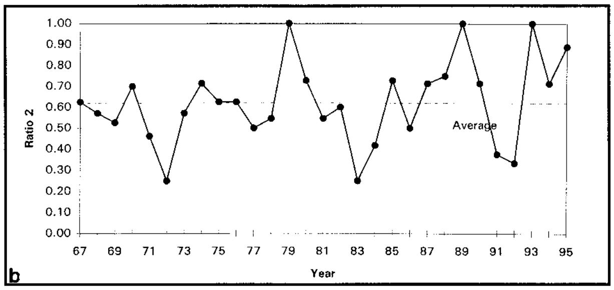


FIG. 14. (a) Ratio of the number of tropical depressions of African origin to the total number of depressions (ratio 1), annually from 1967 to 1995. Horizontal dashed line represents the average for the 1967–95 period. (b) Ratio of the number of named storms of African origin to the total number of named storms (ratio 2), annually from 1967 to 1995. Horizontal dashed line represents the average for the 1967–95 period.

on the yearly variation in the number of tropical storms forming from tropical waves.

Table 1 and Figs. 13b and 13c show the seasonal totals of tropical depressions and storms since 1967. A trend toward fewer tropical depressions per year began around 1980, as indicated by Avila and Pasch (1992). In 1994, that trend continued with a total of only 12 depressions. This number is well below the more recent 1980–94 average of 15. In 1995, there were 21 depressions. This number is even higher than the long-term average and definitely much higher than the average observed since 1980 when the trend of having fewer depressions began. During the 1967–80 period, some nontropical cyclones may have been classified as tropical depressions. Examples of such cases have been documented by Pasch and Avila (1994). However, the number of tropical depressions in 1995 was realistic since these depressions were well documented with surface data, satellites, and reconnaissance aircraft.

Figure 14a displays the ratio of the number of tropical depressions of African origin to the total number of tropical depressions per year (ratio 1). Low values of ratio 1 indicate that a high number of depressions originated from upper-tropospheric cold lows or along frontal zones—that is, from nontropical ‘‘seedling’’ disturbances (Frank 1975). In 1994, ratio 1 was 0.8, a number that is similar to 1993 but substantially higher than that observed in 1991 or 1992, when many depressions originated from nontropical sources. In 1995, ratio 1 was 0.9.

The ratio between the number of tropical storms of African origin to the total number of tropical storms (ratio 2) has been found to be a useful parameter to describe the overall character of the hurricane season (Avila and Clark 1989). Figure 14b and Table 1 display the values of ratio 2 since 1967. The 1967–94 average contribution from tropical waves to the total number of storms is 0.61. In 1994, ratio 2 was 0.71, a value just above average, while in 1995, ratio 2 jumped to 0.89, a value much above normal.

Typically, tropical waves are the main source of hurricanes for the Atlantic basin. There have been exceptions, namely the 1971, 1972, 1977, 1983, 1984, 1991, and 1992 seasons, when tropical waves induced only a few hurricanes. In 1994, for the first time in three years, a tropical wave spawned a hurricane (Chris) at low latitudes. However, it was a hurricane only for a few hours. Table 1 shows that on average, 65% of the hurricanes in the Atlantic basin develop from tropical waves. In 1994, two of the three hurricanes developed from waves. However, although Gordon originated from a tropical wave, it underwent a quasi-subtropical transformation before reaching hurricane status at high latitudes. In 1995, all of the hurricanes were spawned by tropical waves.

It is of interest to note that 1991, 1992, 1993, and 1994 have been designated as years of generally moderate El Niño conditions, based on equatorial Pacific sea surface temperatures and atmospheric indices (Climate Analysis Center 1994). During those years, tropical

TABLE 2. Comparison of African, non-African, and average years with season-averaged hurricane destruction potential (HDP) and major hurricanes (MH). African years: Ratio of the number of tropical storms of African origin to the total number of storms is higher or equal to 0.70. Non-African years: Ratio of the number of tropical storms of African origin to the total number of storms is lower or equal to 0.50. Average years: Ratio of number of tropical storms of African origin to the total number of tropical storms is less than 0.70 and higher than 0.50. HDP: Sum of the square of each hurricane's maximum wind for each 6-h period of its existence (Gray et al. 1992) scaled by 10^{-4}. MH: Total number of major hurricanes [category 3 or higher on the Saffir–Simpson scale (Simpson 1974)] during those years.

													HDP	MH
African years	1970	1974	1979	1980	1985	1987	1988	1989	1990	1993	1994	1995	65	24
Non-African years	1971	1972	1977	1983	1984	1986	1991	1992					30	7
Average years	1967	1968	1969	1973	1975	1976	1978	1981	1982				55	17

waves, although prevalent, induced only a few storms and hurricanes. Gray (1984) speculated that a hostile environment, induced by El Niño episodes, prevented many of the waves from developing over the deep Tropics in the Atlantic basin.

Avila and Clark (1989) arbitrarily used ratio 2 to quantify the relative contribution to tropical storm development by tropical waves. Years in which ratio 2 is greater than or equal to 0.7 are termed African years. Non-African years are those for which ratio 2 is less than or equal to 0.5. Intermediate values correspond to average years. Ratio 2 for 1994 was 0.71, indicating that it was a borderline African year. However, hurricanes were not intense. In fact, of the African years, only 1987 produced fewer intense hurricanes. Ratio 2 was 0.89 in 1995 and there were several intense hurricanes. This is a more typical characteristic of an African year. Obviously, there are exceptions to the rule that African years feature a relatively large number of intense hurricanes. It appears that these exceptions often coincide with El Niño conditions, as alluded to above.

While ratio 2 provides information about tropical cyclone origin, the hurricane destruction potential (HDP) measures a hurricane's potential for wind and storm surge destruction. The HDP is defined as the sum of the square of each hurricane's maximum wind speed for each 6-h period of its existence (Gray et al. 1992). Table 2 summarizes the African, non-African, and average years, including the HDP and the total number of major hurricanes (category 3 or higher on the Saffir–Simpson hurricane scale). The average HDP of African years for the 1967–94 period was substantially larger than (more than double) the average HDP of the non-African years. The HDP for 1994 was only 15, which is a very low number for an African year, but for 1995, the HDP increased dramatically to 158.

This study again supports the concept that tropical waves play a dominant role as the precursors to major hurricanes, and that many of eastern Pacific tropical cyclones can likely be traced back to these waves. The significance of tropical waves is further highlighted by the fact that these systems are largely responsible for the enhancement of rainfall in the Caribbean area (Riehl 1954). Thus the two well-established climatological seasons (namely, wet and dry) in the tropical Atlantic basin can be attributed to the presence of (typically) stronger, rain-producing tropical waves during the summer and fall months. Therefore, it is important to continue to monitor and to study these systems.

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