SUMMARY OF 1999 ATLANTIC TROPICAL CYCLONE ACTIVITY AND VERIFICATION OF AUTHORS' SEASONAL ACTIVITY PREDICTION

A Very Active Hurricane Season and a Successful Seasonal Forecast

(as of 24 November 1999)

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[This and past forecasts are available via the World Wide Web:
http://tropical.atmos.colostate.edu/forecasts/index.html] — also,

David Weymiller and Thomas Milligan, Colorado State University Media Representatives (970-491-6432) are available to answer questions about this forecast.

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Colorado State University Hurricane Forecast Team

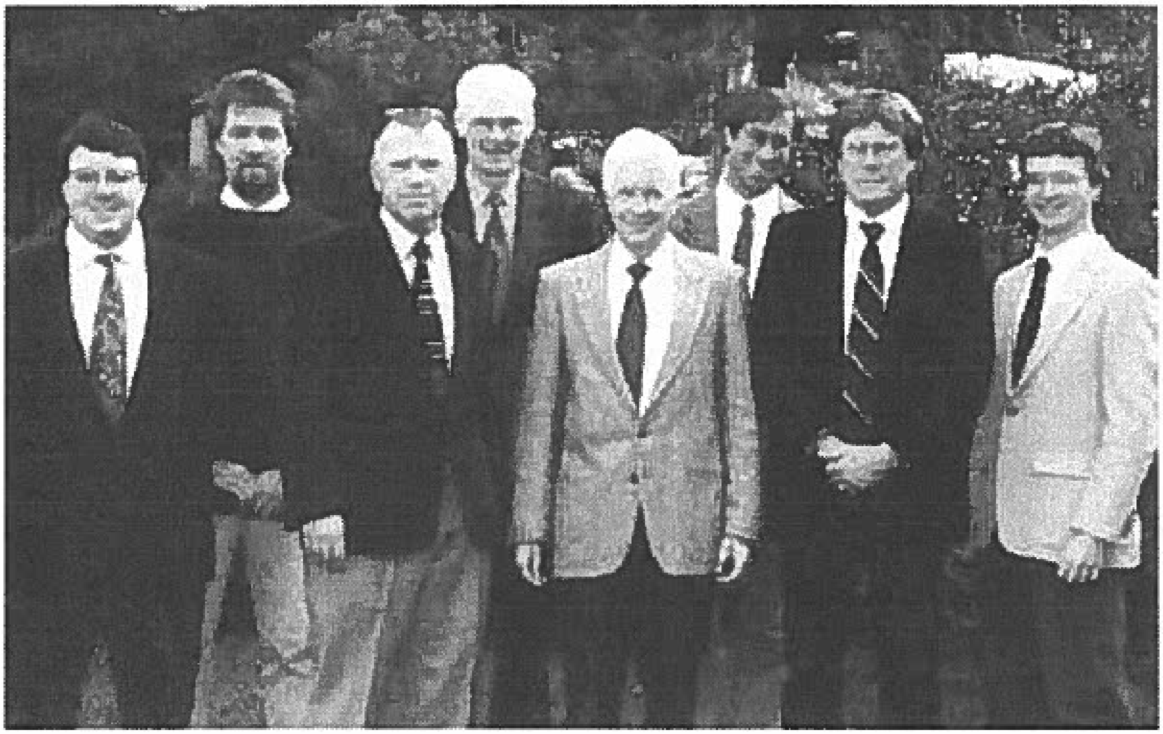

Figure 1: Colorado State University Hurricane Forecast Team

Front Row - left to right: John Knaff, Ken Berry, Paul Mielke, John Sheaffer, Rick Taft. Back Row - left to right: Bill Thorson, Bill Gray, and Chris Landsea. Missing members include Todd Kimberlain and Eric Blake.

SUMMARY OF 1999 SEASONAL FORECASTS AND VERIFICATION

Tropical Cyclone Seasonal Parameters (1950-90 Ave.)	Sequence of Forecast Updates 4 Dec 98 Forecast	7 Apr 99 Forecast	4 Jun 99 Forecast	6 Aug 99 Forecast	Observed Totals
Named Storms (NS) (9.3)	14	14	14	14	12
Named Storm Days (NSD) (46.9)	65	65	75	75	77
Hurricanes (H)(5.8)	9	9	9	9	8
Hurricane Days (HD)(23.7)	40	40	40	40	43
Intense Hurricanes (IH) (2.2)	4	4	4	4	5
Intense Hurricane Days (IHD)(4.7)	10	10	10	10	15
Hurricane Destruction Potential (HDP) (70.6)	130	130	130	130	145
Maximum Potential Destruction (MPD) (61.7)	130	130	130	130	114
Net Tropical Cyclone Activity (NTC)(100%)	160	160	160	160	193

VERIFICATION OF 1999 PROBABILITY OF MAJOR HURRICANE LANDFALL

	Forecast Probability and Climatology (in parentheses)	Observed
1. Entire United States Coastline	72% (50%)	1
2. Florida Peninsula and East Coast	54% (31%)	0
3. Gulf Coast	40% (30%)	1
4. Caribbean and Bahama Land Areas	72% (51%)	2
5. East Coast of Mexico	28% (18%)	0

DEFINITIONS

Atlantic Basin - The area including the entire North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico.

El Niño - (EN) A 12-18 month period during which anomalously warm sea surface temperatures occur in the eastern half of the equatorial Pacific. Moderate or strong El Niño events occur irregularly, about once every 3-7 years or so on average.

Hurricane - (H) A tropical cyclone with sustained low level winds of 74 miles per hour (33 ms^{-1} or 64 knots) or greater.

Hurricane Day - (HD) A measure of hurricane activity, one unit of which occurs as four 6-hour periods during which a tropical cyclone is observed or estimated to have hurricane intensity winds.

Hurricane Destruction Potential - (HDP) A measure of a hurricane's potential for wind and storm surge destruction defined as the sum of the square of a hurricane's maximum wind speed (in 10^4 knots^2)for each 6-hour period of its existence.

Intense Hurricane - (IH) A hurricane which reaches a sustained low level wind of at least 111 mph (96 kt or 50 ms^{-1}) at some point in its lifetime. This constitutes a category 3 or higher on the Saffir/Simpson scale (also termed a "major" hurricane).

Intense Hurricane Day - (IHD) Four 6-hour periods during which a hurricane has intensity of Saffir/Simpson category 3 or higher.

MATL - Sea surface temperature anomaly in the sub-tropical Atlantic between 30-50°N, 10-30°W

MPD - Maximum Potential Destruction - A measure of the net maximum destruction potential during the season compiled as the sum of the square of the maximum wind observed (in knots) for each named storm. Values expressed in 10^3kt.

Named Storm - (NS) A hurricane or a tropical storm.

Named Storm Day - (NSD) As in HD but for four 6-hour periods during which a tropical cyclone is observed (or is estimated) to have attained tropical storm intensity winds.

NATL - Sea surface temperature anomaly in the Atlantic between 50-60°N, 10-50°W

NTC - Net Tropical Cyclone Activity - Average seasonal percentage mean of NS, NSD, H, HD, IH, IHD. Gives overall indication of Atlantic basin seasonal hurricane activity (see Appendix B).

ONR - previous year October-November SLPA of subtropical Ridge in eastern Atlantic between 20-30°W.

QBO - Quasi-Biennial Oscillation - A stratospheric (16 to 35 km altitude) oscillation of equatorial east-west winds which vary with a period of about 26 to 30 months or roughly 2 years; typically blowing for 12-16 months from the east, then reverse and blowing 12-16 months from the west, then back to easterly again.

Saffir/Simpson (S-S) Category - A measurement scale ranging from 1 to 5 of hurricane wind and ocean surge intensity. One is a weak hurricane whereas 5 is the most intense hurricane.

SLPA - Sea Level Pressure Anomaly - The deviation of Caribbean and Gulf of Mexico sea level pressure from observed long term average conditions.

SOI - Southern Oscillation Index - A normalized measure of the surface pressure difference between Tahiti and Darwin.

SST(s) - Sea Surface Temperature(s).

SSTA(s) - Sea Surface Temperature(s) Anomalies.

Tropical Cyclone - (TC) A large-scale circular flow occurring within the tropics and subtropics which has its strongest winds at low levels; including hurricanes, tropical storms, and other weaker rotating vortices.

Tropical Storm - (TS) A tropical cyclone with maximum sustained winds between 39 (18 ms^{-1} or 34 knots) and 73 (32 ms^{-1} or 63 knots) miles per hour.

TATL - Sea surface temperature anomaly in Atlantic between 6-22°N, 18-80°W.

ZWA - Zonal Wind Anomaly - A measure of upper level ($\sim$ 200 mb) west to east wind strength. Positive anomaly values mean winds are stronger from the west or weaker from the east than normal.

1 knot = 1.15 miles per hour = .515 meters per second.

ABSTRACT

This report summarizes tropical cyclone (TC) activity which occurred in the Atlantic Basin during 1999 and verifies the authors' seasonal forecasts of this activity which were initially issued on 4 December 1998, with updates on 7 April, 4 June and 6 August of this year. The 1999 hurricane season was characterized by enhanced levels of tropical cyclone activity and extensive flooding in North Carolina due to Hurricane Floyd. A total of 12 named storms (average is 9.3) and 8 hurricanes (average is 5.8) occurred and persisted for a total of 43 hurricane days (average is 24). There were 5 major hurricanes of Saffir/Simpson intensity category 3-4-5 (average is 2.3) with 15 intense hurricane days (average is 4.7). The seasonal total of named storm days was 77 which is 165 percent of the long-term average. Net tropical cyclone (NTC) activity was 193 percent of the 1950–1990 average and 306 and 257 percent of the annual average NTC for the periods between 1990–94 and 1970–94, respectively. Late season major hurricane Lenny is only the third such late season intense hurricane on record. It is also the only recorded tropical cyclone to move eastward across the Caribbean Sea.

1 Introduction

The Atlantic basin (including the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico) experiences more season-to-season hurricane variability than occurs in any of the other global tropical cyclone basins. The number of Atlantic basin hurricanes per season in recent years has ranged as high as 12 (as in 1969), 11 (as in 1950 and 1995), 10 (as in 1998) and 9 (as in 1955, 1980, 1996), and as low as 2 (as in 1982) and 3 (1997, 1994, 1987, 1983, 1972, 1962, 1957). Until the mid 1980s there were no objective methods for predicting whether forthcoming hurricane seasons were likely to be active, inactive, or near normal. Recent ongoing research by the authors (see Gray, 1984a, 1984b, 1990; Landsea, 1991; Gray *et al.*, 1992, 1993a, 1994) indicates that there are surprisingly skillful 3-to-11 month (in advance) predictive signals for Atlantic basin seasonal hurricane activity. This research now allows us to issue extended-range forecasts in early December of next years Atlantic Basin hurricane activity with updates in early April, early June, and early August. The purpose of this end of season report is to compare these forecasts with actual observed hurricane activity during the 1999 hurricane season.

2 Factors Known to be Associated With Atlantic Seasonal Hurricane Variability

Our forecasts which are issued at several lead times prior to each hurricane season are based on the currently available values of indices derived from various global and regional scale predictive factors which the authors have shown to be related to subsequent seasonal variations of Atlantic Basin hurricane activity. Figures 1-3 provide a summary of the locations of the various forecast parameters. Our forecast methodology emphasizes studying past years of oceanic and atmospheric precursor conditions which are observed to be associated with amount of hurricane activity during the following season. These predictors include the following:

(a) El Niño-Southern Oscillation (ENSO): El Niño is characterized by warm sea surface temperature anomalies in the eastern equatorial Pacific areas of Nino 1-2, 3, 3.4 and 4 (Fig. 1),

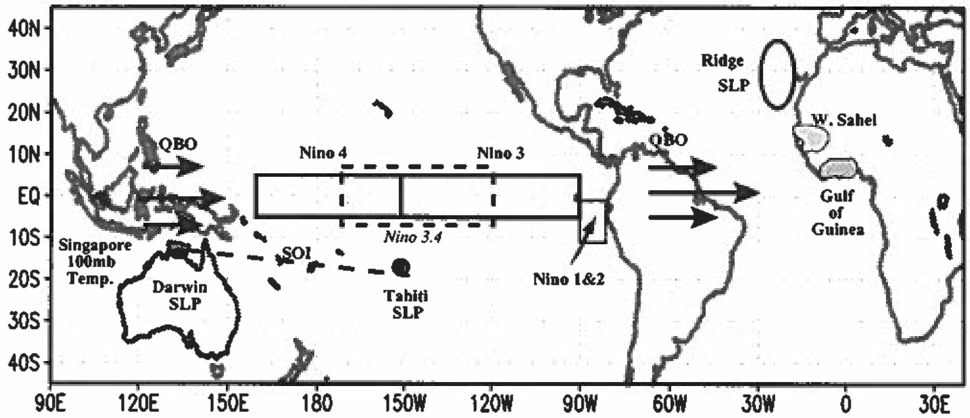

Figure 1: Meteorological parameters used in our various seasonal forecasts.

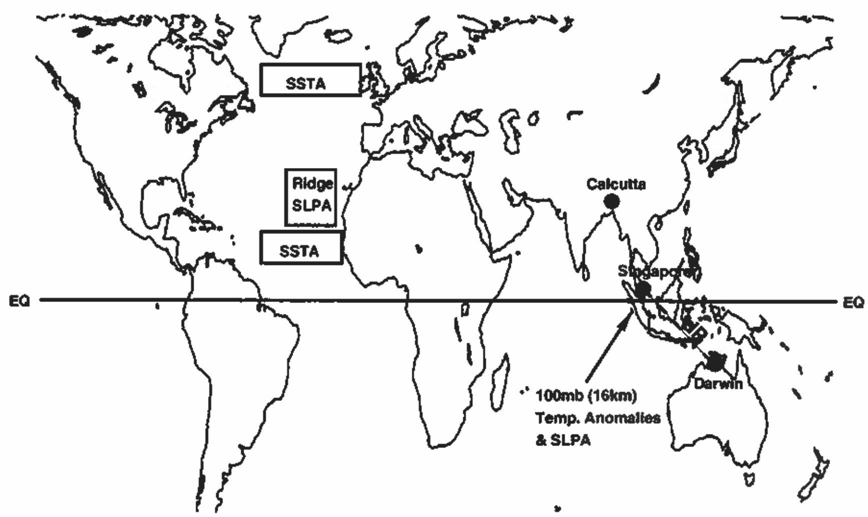

Figure 2: Additional predictors which relate to our Atlantic season hurricane forecasts.

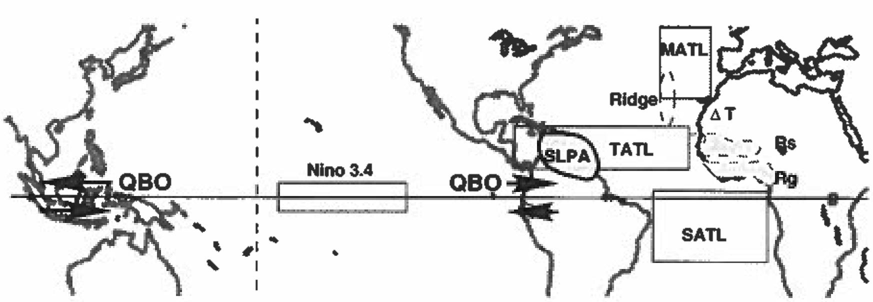

Figure 3: Some additional meteorological parameters which are now used in our reformulated early June and early August forecast.

a negative value of the Tahiti minus Darwin surface pressure gradient and enhanced equatorial deep convection near the Dateline. These conditions cause disruptions of the global atmospheric circulation fields contributing to anomalous upper-level westerly winds over the Atlantic basin. The effects of a moderate or strong El Niño event are, typically, to reduce Atlantic basin hurricane activity. Conversely, during La Niña seasons, anomalously cold sea surface temperatures are present together with high values of Tahiti minus Darwin surface pressure difference and reduced deep equatorial convection near the Dateline are associated with enhanced Atlantic basin hurricane activity.

(b) The stratospheric Quasi-Biennial Oscillation (QBO). The QBO refers to the variable east–west oscillating stratospheric winds which encircle the globe near the equator. Other factors being equal, there is more intense (category 3-4-5) Atlantic basin hurricane activity during those seasons when equatorial stratospheric winds at 30 mb and 50 mb (23 and 20 km altitude, respectively) are from a westerly (versus easterly) direction.

(c) African Rainfall (AR): The incidence of intense Atlantic hurricane activity is enhanced when rainfall during years when prior August-September Western Sahel region is above average and when August-November Gulf of Guinea region during the prior year is also above average. The June-July rainfall is also a predictor for the immediate following August through October hurricane activity. Other factors being equal, hurricane activity is typically suppressed if the rainfall in the prior year (or season) in these two regions is below average.

(d) Prior Year October-November and March northeast Atlantic Subtropical Ridge Strength (ONR). When this pressure ridge is anomalously weak during the prior autumn and spring periods, eastern Atlantic trade winds are weaker. A weak ridge condition is associated with decreased mid-latitude cold water upwelling and advection off the northwest African coast, as well as to decreased evaporative cooling rates in this area of the Atlantic. In this way, a weak ridge leads to warmer sea surface temperatures which typically persist into the following summer period and contribute (other factors being constant) to greater seasonal hurricane activity. Conversely, less hurricane activity occurs when the October-November and spring pressure ridge is anomalously strong.

(e) Atlantic Sea Surface Temperature Anomalies (SSTA) in the three regions [(MATL; 30-50°N, 10-30°N and TATL; 6-22°N, 18-82°W) during April through June] and [NATL; 50-60°N, 10-50°W and TATL during January through March]: [See Fig. 3 (bottom) for the location of these areas]. Warmer SSTAs in these areas enhance deep oceanic convection and, other factors aside, provide conditions more conducive for Atlantic tropical cyclone activity; cold water temperatures the reverse.

(f) Caribbean Basin Sea Level Pressure Anomaly (SLPA) and upper tropospheric (12 km) Zonal Wind Anomaly (ZWA): Spring and early summer SLPA and ZWA have moderate predictive potentials for hurricane activity occurring during the following August through October months (Fig. 3). Negative anomalies (i.e., low pressure and easterly zonal wind anomalies) imply enhanced seasonal hurricane activity (easterly 200 mb) while positive values imply suppressed hurricane activity (westerly 200 mb shear).

(g) Influence of West Africa west-to-east surface pressure and temperature gradients (Δ PT): Anomalously strong west-to-east surface pressure and temperature gradients across West Africa between February and May are typically correlated with the hurricane activity which follows later in the year.

Our various lead-time forecast schemes are created by maximizing the pre-season forecast skill from a combination of the above predictors, for the period 1950–1997. We also use an analog methodology whereby we choose those years with precursor climate signals most similar to the current forecast year. This empirical methodology has the great advantage that one does not have to understand the myriad complicated aspects of the ocean and atmosphere and its interaction but only the observable large-scale parameter associations.

3 Statistical Summary of 1999 Atlantic Tropical Cyclone Activity

The 1999 Atlantic hurricane season officially ends on 30 November. To date, there have been eight hurricanes and 43 hurricane days during the 1999 season. The total named storms (i.e., the number of hurricanes plus tropical storms) was 12, yielding 77 named storm days. There were five major hurricanes this season. All designated tropical cyclone activity parameters exceeded the long-term average. Figure 4 and Table 1 show the tracks and give statistical summaries, respectively, for the 1999 season. Table 2 characterizes 1999 seasonal tropical cyclone activity in terms of long-term average annual percentages for the 1950-1990, 1970–94 and 1990–94 periods. Note that 1999 hurricane activity was much above the typical seasonal averages for these earlier periods. Figure 5 shows the U.S. landfalling named storms of 1999.

1999 ATLANTIC HURRICANE SEASON

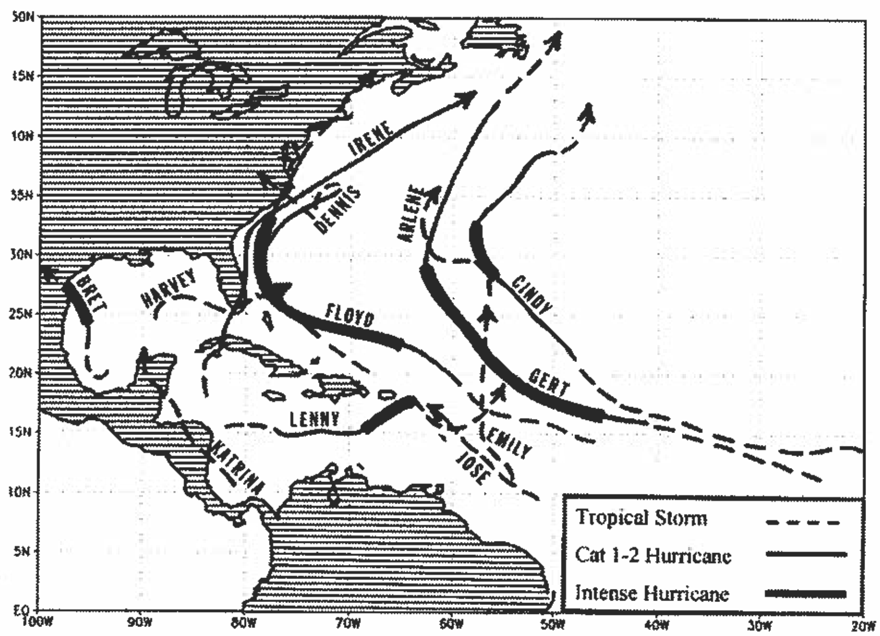

Figure 4: Tracks of the 12 named tropical cyclones of 1999. Dashed lines indicate the tropical storm intensity stage, thin solid lines indicate the Saffir/Simpson hurricane category 1-2 stage, and the thick lines show the intense (or major) hurricane category 3-4-5 hurricane stage.

By all measures, 1999 was a very active hurricane year. Ranking seasons since 1950 by Net Tropical Cyclone (NTC)[5] only 1950, 1955, 1961, 1995 and 1996 seasons were more active than

[5]Average of the percentage of the long term mean of the six seasonal number of Named Storms (NS), Named Storm Days (NSD), Hurricanes (H), Hurricane Days (HD), Intense (category 3-4-5) Hurricanes (IH), and Intense

Table 1: Summary of information for named tropical cyclones occurring during the 1999 Atlantic season. Information on Tropical Storms (TS), Hurricanes (H) and Intense Hurricanes (IH) and the highest Saffir/Simpson category of each is shown. This information was supplied by of the National Hurricane Center.

Highest Category	Name	Dates of Named Storms	Peak Sustained Winds (kts)/ lowest SLP in mb	NSD	HD	IHD	HDP
*TS	Arlene	Jun.11-18	50/1006	4.50			
IH-4	Bret	Aug.18-24	125/944	4.25	2.50	1.25	9.8
IH-4	Cindy	Aug.19-31	120/944	11.00	6.00	1.50	17.4
H-2	Dennis	Aug.24-Sep.5	90/963	11.50	5.75		14.0
TS	Emily	Aug.24-28	45/1004	4.00			
IH-4	Floyd	Sep.7-17	135/921	9.25	6.25	3.75	27.6
IH-4	Gert	Sep.11-23	130/930	11.25	9.75	6.25	42.1
TS	Harvey	Sep.19-22	50/995	2.25			
H-2	Irene	Oct.13-19	90/958	5.75	5.00		9.9
H-2	Jose	Oct.17-25	85/977	7.25	2.50		5.4
TS	Katrina	Oct. 28-Nov.1	35/999	0.25			
H-4	Lenny	Nov. 13-21	130/934	6.00	5.00	2.25	18.9

* Indicates that prelim best track data utilized, other track operation estimates

Table 2: Summary of 1999 hurricane activity in comparison with long-term and recent average year conditions.

Forecast Parameter	1950–1990 Mean	Obs. 1999	1999 in percent as 1950-1990 Ave.	1999 in percent of 1970-1994 Ave.	1999 in percent of 1990–94 Ave.
Named Storms (NS)	9.3	12	129	140	143
Named Storm Days (NSD)	46.9	77	165	199	208
Hurricanes (H)	5.8	8	138	161	174
Hurricane Days (HD)	23.7	43	180	267	316
Intense Hurricanes (IH)	2.2	5	217	329	500
Intense Hurricane Days (IHD)	4.7	15	319	595	1200
Hurricane Destruction Potential (HDP)	70.6	145	204	322	338
Maximum Potential Destruction (MPD)	61.7	114	173	288	347
Net Tropical Cyclone Activity (NTC)	100	193	193	257	357

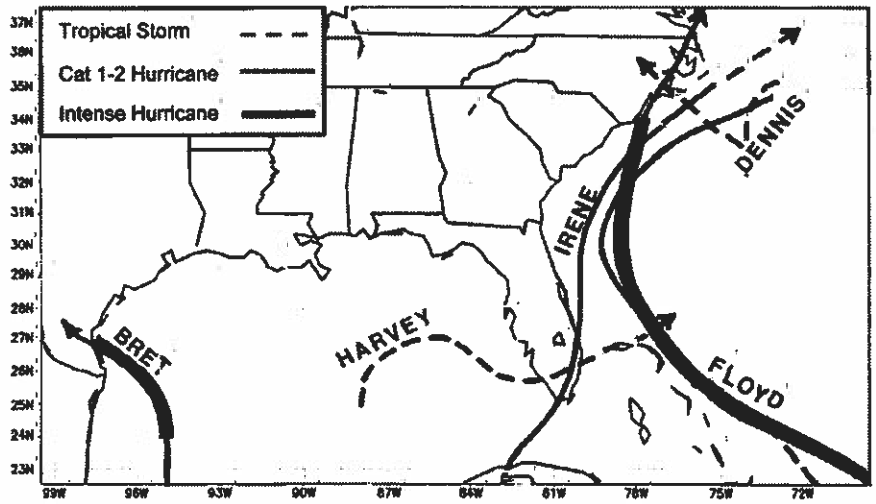

Figure 5: All 1999 U.S. landfalling tropical cyclones by intensity class.

1999. Extending this comparison back to 1880, only the 1887, 1893, 1906, 1916, 1926 and 1933 hurricane seasons were comparable to or greater than 1999.

4 Special Characteristics of the 1999 Season

The 1999 season saw the following:

1. Five major hurricanes, all of which were category-4 on the Saffir/Simpson scale. Records show no prior season with as many as five category-4 hurricanes. (Accurate intensity records are only available back to the mid-1940s). Regardless, 1999 continued the recent strong upturn in major hurricane activity which began in 1995.

2. Major hurricane Lenny (category-4, near category-5)formed in mid November. Records indicate that there have been only two other major hurricanes of this intensity this late in the season. These occurred in 1912 and 1932. There has never been a hurricane or tropical storm with so long an easterly track in the Caribbean.

3. Bret was the strongest hurricane to strike the South Texas coast since hurricane Celia in 1970. Fortunately, it made landfall in a largely unpopulated coastal area of south Texas.

4. An exceptional outbreak of tropical cyclone activity occurred during the latter part of August. Four tropical cyclones (Bret, Cindy, Dennis, and Emily) formed within a six-day period.

5. All of the 1999 Caribbean hurricane activity came during October and November; most Caribbean basin hurricane activity typically occurs in August and September.

Hurricane Days (IHD).

6. A total of three hurricanes and two tropical storms made landfall on the U.S. coast during 1999. Whereas Bret was a major hurricane, Floyd made landfall in North Carolina as a strong category-2 hurricane. The unusually heavy rainfall with Floyd was due, in part, to its interaction with a strong upper-air trough to the west. Most landfalling cyclones do not have such interactions.

5 Individual 1999 Tropical Cyclone Characteristics

Tropical Storm Arlene originated in the subtropical Atlantic about 550 miles southeast of Bermuda from a non-tropical disturbance on 11 June and strengthened into a tropical storm while drifting northward the following day. Arlene then turned westward and peaked with winds of 60 mph. For a brief time Arlene threatened Bermuda but passed about 100 miles to the east and did not significantly impact these islands. Arlene dissipated on the 18th to the northeast of Bermuda.

Hurricane Bret formed in the southern Gulf of Mexico on the 18th of August about 310 miles east-southeast of Tampico, Mexico. It reached tropical storm strength during the afternoon of the 19th. Bret moved on a general northward course and became a hurricane late on the 20th. The hurricane began to strengthen rapidly on the 21st and reached category-4 status over the western Gulf of Mexico. The following day Bret turned toward the west-northwest and is estimated to have reached its peak intensity of 140 mph on the morning of the 22nd about 100 miles east of the south Texas coast. Bret made landfall later that evening in a sparsely-populated area midway between Brownsville and Corpus Christi, Texas as a category-3 hurricane with maximum sustained winds of 125 mph. Bret gradually weakened while producing heavy rains of 5 to 10 inches as it moved slowly west-northwest over extreme southern Texas and the Rio Grande Valley.

Hurricane Cindy formed in the eastern tropical Atlantic near the Cape Verde Islands late on the 18th of August. It intensified to a tropical storm on the afternoon of the 20th and became a hurricane late on the 21st. By the 22nd Cindy began to experience strong easterly vertical shear and was downgraded to a tropical storm that afternoon. The shear decreased on the 25th and Cindy regained hurricane status later that day. While turning north-northwest the hurricane reached its peak intensity of 140 mph as a category-4 storm on the morning of the 28th. Cindy then moved west-northwest through the 24th and then northwest from the 25th the 28th. On the 29th the system turned northeast and began to accelerate on the 30th. Cindy became extratropical on the morning of the 31st as it merged with a mid-latitude low over the North Atlantic about 1000 miles west of the Azores.

Hurricane Dennis formed in the western Atlantic a couple hundred miles east of the S.E. Bahamas late on the 23rd of August. The system moved slowly west-northwest to northwest for the next several days. It became a tropical storm on the afternoon of the 24th of August and a hurricane early on the 26th. Dennis reached a peak intensity of 105 mph (category-2) on the afternoon of the 28th and maintained this intensity until early on the 30th while paralleling the lower southeast U.S. coast. The hurricane buffeted the North Carolina coast on the 30th and part of the 31st with sustained tropical storm force winds with gusts to hurricane force. Large waves and high surf were observed. Dennis turned northeastward away from the coast on the morning of the 30th. It stalled about 150 miles east of Cape Hatteras on the morning of the 31st and then began to drift westward and weaken as a tropical storm. Dennis meandered about 100 miles east and southeast of Cape Hatteras through 2 September. By 4 September Dennis re-intensified as it turned back toward the coast and made landfall as a strong tropical storm on the North Carolina outer banks, about 35 miles east-northeast of Morehead City. Dennis weakened to a depression early on the 5th while moving northwestward into north central North Carolina. It dissipated in south central Virginia on 6 September. Dennis produced heavy rains over North Carolina and the mid-Atlantic states and contributed (through raising the water table) to the catastrophic North Carolina flooding that took place 10 days later with Hurricane Floyd.

Tropical Storm Emily formed about 400 miles east of the Windward Islands during the afternoon of the 24th of August. The system was upgraded to a tropical storm later that day. By the 26th hurricane Cindy began to adversely affect the small circulation of Emily. Emily was downgraded to a depression that afternoon while moving northwestward. Emily turned northward on the 27th and briefly regained tropical storm status. Cindy continued to influence Emily and Emily became absorbed within Cindy's circulation on the 28th while moving northward.

Hurricane Floyd was the most powerful hurricane of the 1999 season. It formed from a tropical wave which moved off the coast of Africa on 2 September. The system became a tropical depression on 7 September about 1000 miles east of the Lesser Antilles. It strengthened into a tropical storm early the next day while located about 850 miles east of the Lesser Antilles. Floyd developed into a hurricane about 240 miles northeast of the northern Leeward Islands. Turning west and then northwest Floyd avoided the Caribbean Islands and leveled off in strength as it interacted with a mid/upper-level weather system to the northwest. However, as Floyd turned back to the west it strengthened into a major hurricane, a strong category-4 system packing winds of 155 mph winds. Weakening only slightly the hurricane lashed portions of the central and northwest Bahamas on 13-14 September. It posed a serious threat to Florida and the southeast U.S. coast but turned northward just before reaching the South Florida Coast.

Hurricane Floyd turned northwestward and then north while slowly weakening. It eventually made landfall near Cape Fear, NC as a strong category-2 hurricane during the early morning hours of 16 September. After hitting North Carolina Floyd raced north-northeastward up the coast and weakened to a tropical storm before entering New England and losing its tropical characteristics early on the 17th. Floyd is responsible for massive inland flooding over portions of the eastern United States, particularly in North Carolina. The current death toll as reported by the media was about 70. This would make this the deadliest United States tropical cyclone since Agnes of 1972. The damage (mostly from flooding) total is estimated to be between 5 and 6 billion dollars. Floyd will be retired as one of the deadliest and costliest hurricanes to affect the U.S. coast this century. A sizable portion of the unusual U.S. flooding damage from Floyd can be attributed to its interaction with a strong upper-air trough on its west side.

Hurricane Gert formed over the eastern Atlantic about 200 miles south of the Cape Verde Islands on 11 September. It became a tropical storm on the 12th while centered about 560 miles west of the Cape Verde Islands. Gert moved toward the west and strengthened into a hurricane about 1400 miles east of the Lesser Antilles on 13 September. Gert continued to strengthen and became the fourth major hurricane of the season reaching a peak intensity on the 15th about 750 miles east of the Leeward Islands with winds near 150 mph. Gert maintained major hurricane status for nearly 6 days. During this time it turned northwest and then north and passed 130 miles to the east of Bermuda on the 21st as a strong category-2 hurricane. Gusts to hurricane force were experienced on that island. Gert then turned north-northeastward and accelerated into the far North Atlantic. It passed very close to Newfoundland on the 23rd where large waves caused some damage.

Tropical Storm Harvey formed from a tropical wave which moved through the Caribbean Sea and into the Gulf of Mexico. The system became a tropical depression on 19 September over the Central Gulf and began to move toward the east-northeast. Despite unfavorable upper-level westerly winds the cyclone became a tropical storm while centered about 315 miles south-southeast of New Orleans. Winds peaked at 60 mph while Harvey was located about 250 miles west-southwest of Tampa, Florida. The storm then took an abrupt turn toward the southeast and weakened before moving inland south of Naples, Florida. Harvey produced tropical storm force winds over portions of the Keys and extreme South Florida as it moved across the Peninsula. The cyclone was then absorbed by a frontal system just off the southeast Florida coast on 22 September.

Hurricane Irene originated from a broad area of low pressure in the southwest Caribbean in the second week of October. The low gradually became better organized over a period of several days and a tropical depression formed on the 13th. Tropical storm strength was reached later that day with the center about 230 miles south of the Isle of Youth, Cuba. Irene moved northward turned north-northeastward making landfall on the Isle of Youth on the 14th. The center of Irene continued north-northeastward over western Cuba and into the Florida Straits and became a hurricane around this time. The center passed over Key West early on the 15th. However, most of the hurricane force winds were east of the center over the Florida Keys. Later that day the center made landfall on the Florida Peninsula near Flamingo moving across southeast Florida. Torrential rains with accumulations of 10-20 inches were experienced over mainland Florida with hurricane force winds over the east Florida coastal waters. The center of Irene emerged in the Atlantic near Jupiter, Florida later on the 15th. It retained hurricane strength as it moved northward parallel to the Florida coast. Irene then turned and accelerated to the northeast just east of the North Carolina outer banks early on the 18th. After passing the outer banks Irene rapidly strengthened nearing category-3 status with an intensity of 105 mph on the 18th. Irene continued northeastward and was absorbed by an extratropical low on the 19th. Although damage estimates are not yet available, Irene caused considerable damage due to flooding in South Florida. Seven deaths are indirectly attributed to Irene in Florida.

Hurricane Jose originated from a tropical wave that moved off the west coast of Africa on the 8 October. The wave moved slowly westward across the tropical Atlantic for several days. When the system was located about midway between Africa and the Lesser Antilles it became better organized. It developed into a tropical depression about 700 miles east of the southern Windward Islands on the 17th. Moving west-northwestward, the depression strengthened into tropical storm Jose on the 18th while centered about 400 miles east of the Windward Islands. After turning to the northwest Jose became a hurricane late on the 19th about 150 miles east of the Leeward Islands. Hurricane Jose struck the northern Leeward Islands. It passed over Antigua and St. Maarten on the 20th and 21st. There was severe flooding due to very heavy rains over portions of these islands. Jose then weakened to a tropical storm just before moving over the British Virgin Islands on the 21st. The storm passed just northeast of Puerto Rico before turning northward and then north-northeastward on the 22nd. It regained hurricane strength and passed 300 miles east of Bermuda on the 24th. Jose accelerated into the North Atlantic and lost tropical characteristics on the 25th.

Tropical Storm Katrina developed from a broad area of low pressure in the southwest Caribbean. It reached tropical depression status on the 28th while located about 200 miles east of the central Nicaraguan Coast. The depression initially moved west then northwest as it approached the Nicaraguan Coast. It reached tropical storm strength just prior to making landfall south of Puerto Cabezas, Nicaragua on the 29th. It maintained tropical storm status for only one day. Katrina rapidly weakened to a tropical depression as it moved northwestward across northeastern Nicaragua and Honduras. The depression then moved into the Gulf of Honduras on the 30th and across Belize and the Yucatan Peninsula on the 31st. Katrina was absorbed by a non-tropical low pressure area over the southern Gulf of Mexico on 1 November.

Hurricane Lenny originated from an enhanced equatorial trough that had moved over the southwest Caribbean Sea in the second week of November. A disturbance gradually formed. For several days the tropical disturbance drifted slowly northward and became better organized on 11 November close to the Cayman Islands. The system became a tropical depression on 12 November while located midway between Jamaica and the Yucatan Peninsula. On the 13th, the depression turned southeast and then east and acquired tropical storm strength a few hundred miles southwest of Jamaica. By the 14th Lenny was rapidly intensifying and became a hurricane about 150 miles south-southwest of Jamaica. Lenny continued on its unusual eastward path south of Jamaica and Hispaniola between 14 and 16 November. It strengthened to category-2 intensity for a brief time early on the 14th with 100 mph winds. It then weakened to a category-1 system. By the 15th Lenny had begun to reintensify and reclaimed category-2 strength about 240 miles south-southwest of Santo Domingo. On the 16th Lenny became a major hurricane over the east central Caribbean Sea and continued to intensify threatening Puerto Rico and the U.S./British Virgin islands. Between 16 and 17 November Lenny intensified into a rare category-4 hurricane during for the month of November. The hurricane turned more east-northeast and then northeast by the morning of the 17th as winds increased to 150 mph. Lenny lashed St. Croix during the early afternoon of 17 November. Its forward motion then staled and it brought massive amounts of rainfall to the northern Leeward Island. Its forecast motion to the northeast never materialized. It gradually filled from the 18th to the 21st and then slowly moved eastward as a weak tropical storm and depression and dissipated late on the 21st.

Lenny was one of the most unusual tropical cyclones ever to exist in the Atlantic. Only two other hurricanes (1912, 1932) of this approximate intensity have been recorded as late in the season as Lenny. And, there has never been a hurricane or tropical storm, that we know of, to track eastward across nearly the whole Caribbean Sea.

6 Variation of 1999 Forecast Parameters – Factors Known to be Associated with Seasonal Variation of Hurricane Activity

Factors known to be associated with seasonal variation of hurricane activity that were present during 1999 include the following:

a) La Niña Conditions. Equatorial Pacific SSTAs (in °C) in Niño-1-2, 3, 3.4 and 4 (see Fig. 1 for locations) are shown in Table 3. Cold water (or La Niña) conditions were present throughout this season. In addition, the Tahiti minus Darwin surface pressure difference or Southern Oscillation Index (SOI) was generally positive (as occurs during La Niña) while Outgoing Longwave Radiation (OLR) values near the Dateline were high, indicating diminished deep convection. These conditions greatly enhanced this year's hurricane activity.

b) Stratospheric QBO Winds

Table 3: June through October 1999 Niño sea surface temperature anomaly indices (in °C) and for Tahiti minus Darwin (SOI) surface pressure differences (in SD).

	April	May	June	July	August	September	October
Niño-1-2	−1.0	−0.5	−0.8	−1.0	−0.9	−1.0	−0.5
Niño-3	−0.6	−0.3	−0.6	−0.5	−0.8	−0.9	−0.9
Niño-3.4	−0.7	−0.6	−0.8	−0.6	−1.1	−0.7	−0.8
Niño-4	−1.0	−0.7	−0.5	−0.6	−0.6	−0.5	−0.5
Normalized SOI in S.D.	1.4	0.1	−0.1	0.5	0.1	−0.1	0.9

Tables 4 and 5 show both the absolute and relative (i.e., anomaly) values of 30 mb (23 km) and 50 mb (20 km) stratospheric QBO zonal winds near 12°N during March through October 1999. At the height of the 1999 hurricane season QBO winds were anomalously westerly and were ideal for the enhancing of this year's hurricane activity.

Table 4: Observed March through October 1999 values of stratospheric QBO zonal winds (U) in the (critical) latitude belts between 11-13°N, as obtained from Caribbean stations at Curacao (12°N), Barbados (13°N), and Trinidad (11°N). Values are in ms^{-1} (as supplied by James Angell and Colin McAdie).

Observed

Level	March	April	May	Jun	Jul	Aug	Sept	Oct
30 mb (23 km)	+7	+4	0	−3	−5	−7	−5	−2
50 mb (20 km)	+7	+5	+2	−1	−6	−8	−3	+1

Table 5: As in Table 4, but for the 1999 zonal wind anomalies (i.e., the annual wind cycle has been removed). Values are in ms^{-1}. All winds were anomalously westerly.

Observed

Level	March	April	May	Jun	Jul	Aug	Sept	Oct
30 mb (23 km)	+12	+12	+13	+13	+14	+10	+12	+10
50 mb (20 km)	+7	+8	+8	+9	+8	+6	+7	+7

c) Sea-Level Pressure Anomaly (SLPA)

Table 6 gives information on regional Caribbean basin and Gulf of Mexico SLPA during the 1999 season. Caribbean SLPA was only slightly below average during August through October but was much below average in September. This condition contributed to increased hurricane activity. Knaff's (1997) Atlantic SLPA forecast scheme for 1999 was correct in predicting slightly below average pressure conditions during the major months of the hurricane season.

d) Zonal Wind Anomalies (ZWA)

Table 6: Lower Caribbean basin SLPA for 1999 in mb (for San Juan, Barbados, Trinidad, Curacao and Cayenne) - top row and for the Caribbean-Gulf of Mexico. Brownsville, Miami, Merida (Mexico), San Juan, Curacao and Barbados - bottom row (as kindly supplied by Colin McAdie of NHC in combination with our CSU analysis). Values in millibars (mb).

	Apr	May	Jun	Jul	Aug	Sep	Oct
5-station Lower Caribbean Ave. SLPA	+0.9	+1.1	-0.2	+0.1	+0.1	-0.8	+0.4
6-station Caribbean plus Gulf of Mexico Ave. SLPA	-0.2	-0.2	-0.3	+0.4	-0.5	-0.9	+0.7

Table 7 shows that the upper tropospheric (12 km or 200 mb) Zonal Wind Anomalies (ZWA) were negative (easterly) in all months between June and October. These negative ZWA values reduce regional tropospheric vertical wind shear and are a primary factor in explaining the active 1999 season. Negative ZWA conditions allowed the westward moving easterly waves from Africa to experience less vertical wind shear and become better organized. Whereas negative ZWA values are typical of La Niña years, negative ZWA values in 1999 were stronger than most La Niña periods and likely were a major (but not the only) factor for the enhancement of this season's hurricane activity.

Table 7: 1999 Caribbean basin 200 mb (12 km) Zonal Wind Anomaly (ZWA) in ms^{-1} (as supplied by Colin McAdie of NHC, in combination with CSU data) for the four stations including Kingston (18°N), Curacao (12°N), Barbados (13.5°N), and Trinidad (11°N).

	April	May	June	July	August	September	October
Average ZWA	-1.8	-0.9	-1.0	-1.4	-3.8	-6.8	-5.1

e) <u>African Western Sahel Rainfall in 1999</u>

Summer rainfall in the Western Sahel region of Africa turned out to be near normal during June through September (-0.08 SD) despite early June and July dryness. The early dryness was largely made up by above average August and September rainfall. In watching the daily satellite loops, one might conclude that western Sahel rainfall was above average. But as recently pointed out by S. Nicholson (1999), satellite estimates of rainfall tend to overestimate rainfall (wet bias) as compared with rain gage data.

7 Verification of Individual 1999 Lead Time Forecasts

Table 8 compares our forecasts for 1999 at four different lead times with observed values and Table 9 provides a comparison of our statistical forecasts versus the final forecasts we actually made. Note in Table 9 that all of our statistical forecasts underestimated 1999 hurricane activity. Note also that we consistently forecast a very active 1999 hurricane season beginning

4 December 1998 and held this forecast essentially in tact in our subsequent 7 April, 4 June and 6 August updates. We consider this one of our best forecasts where in we also forecast a higher probability of U.S. landfall (which also occurred).

Table 8: Verification of our 1999 total seasonal hurricane predictions.

Forecast Parameter	1950-1990 Mean	4 Dec 1998 Fcst.	Apr 7 1999 Fcst.	Jun 4 1999 Fcst.	Aug 6 1999 Fcst.	1999 Observed Activity
Named Storms (NS)	9.3	14	14	14	14	12
Named Storm Days (NSD)	46.9	65	65	75	75	77
Hurricanes (H)	5.8	9	9	9	9	8
Hurricane Days (HD)	23.7	40	40	40	40	43
Intense Hurricanes (IH)	2.2	4	4	4	4	5
Intense Hurricane Days (IHD)	4.7	10	10	10	10	15
Hurricane Destruction Potential (HDP)	70.6	130	130	130	130	145
Maximum Potential Destruction (MPD)	61.7	130	130	130	130	114
Net Tropical Cyclone Activity (NTC) in percent	100	160	160	160	160	193

The following are quotes from the abstracts of our initial and updated 1999 seasonal forecasts.
From our initial 4 December 1998 forecast:

> "The 1999 season should have hurricane activity comparable to the very busy hurricane seasons of 1995, 1996 and 1998. Evidence strongly suggests that we have entered a new era of enhanced major hurricane activity."

> "The major hurricane landfall probabilities for Florida and the East Coast for 1999 are predicted to be 13.7 times larger than the average for 1991-1994. This major hurricane landfall forecast along this coastline for 1999 is 5.5 times higher than the average for the quarter century period 1970-1994 when the thermohaline circulation was weak."

From our 7 april 1999 updated forecast:

> "The 1999 season should have hurricane activity comparable to the recent busy hurricane seasons of 1996 and 1998. Evidence suggests that we have entered a new era of enhanced major hurricane activity."

From our 4 June 1999 updated forecast:

> "Collectively, net tropical cyclone activity is expected to be about 160 percent of the long term average, comparable to the recent busy 1996 and 1998 hurricane seasons. Landfall probabilities this year are appreciably above the last 100-year average."

From our 6 August 1999 updated forecast:

> "Landfall probabilities this year are substantially above the last 100-year average."

Table 9: Comparison of 1999 statistical and final forecasts for the four lead time periods. Note that in each forecast we chose to increase our actual forecasts over that specified by our statistical model. These alterations were based primarily on our analog methodology which consistently suggested that greater amounts of activity were likely.

Forecast Parameter	1 Dec 98 Statistical Scheme	Actual 4 Dec 98 Fcst	1 Apr 99 Statistical Scheme	Actual 7 Apr 99 Fcst
Named Storms (NS)	10.6	14	11.6	104
Named Storm Days (NSD)	53.9	65	71.7	65
Hurricanes (H)	6.6	9	7.3	9
Hurricane Days (HD)	27.1	40	28.6	40
Intense Hurricanes (IH)	2.4	4	3.8	4
Intense Hurricane Days (IHD)	5.2	10	4.1	10
Hurricane Destruction Potential (HDP)	71.7	130	85.4	130
Maximum Potential Destruction (MPD)	64.9	130	71.1	130
Net Tropical Cyclone Activity (NTC)	98.7	160	129.8	160

Forecast Parameter	1 Jun 99 Statistical Scheme	Actual 5 Jun 99 Fcst	1 Aug 99 Statistical Scheme	6 Aug 99 Fcst
Named Storms (NS)	11.9	14	10.2	14
Named Storm Days (NSD)	49.9	75	48.8	75
Hurricanes (H)	5.9	9	6.8	9
Hurricane Days (HD)	26.6	40	20.5	40
Intense Hurricanes (IH)	2.5	4	2.9	4
Intense Hurricane Days (IHD)	3.5	10	4.5	10
Hurricane Destruction Potential (HDP)	58.7	130	55	130
Maximum Potential Destruction (MPD)	64.5	130	65	130
Net Tropical Cyclone Activity (NTC)	89.4	160	129.5	160

Most of the explanations of the active 1999 hurricane season appearing in the media have been based solely in terms of the 1999 cold La Niña conditions. This is over simplistic; other climate influences were also at work. Several prior hurricane seasons with La Niña conditions have had below average Atlantic hurricane activity. These include the hurricane seasons of 1917, 1922, 1942, 1956, 1970 and 1973. In addition to cold La Niña conditions, the 1999 season also "benefitted" from ideal stratospheric QBO wind conditions, above average tropical Atlantic sea surface temperatures, and below average Atlantic sea level pressure. Also, North Atlantic (50-60°N, 10-50°W) SSTs were above average in association with the continued presence of enhanced Atlantic Ocean conveyor circulation since 1995. Thus, 1999, as with other recent active hurricane seasons (1995, 1996, and 1998) had additional positive environmental influences beside La Niña .

8 Seasonal Forecast Methodology

Table 9 showed that purely statistical predictions for 1999 were much less skillful than were our actual final forecasts. This tendency has been true for most of our purely statistical forecasts since 1995, the time when we likely entered a new multi-decadal era of seasonal hurricane activity. Consequently, our previous methodology which was based on trends from the mid-1960s through the mid-1990s were less applicable. We based our 1999 seasonal forecast more on an analog methodology which chooses years whose atmosphere and ocean precursor climate conditions were most similar to the precursor climate signals of 1999.

We determined that there were five years since 1950 wherein 3 to 12 month precursor ocean and atmosphere conditions were similar to 1999: 1950, 1955, 1961, 1964 and 1995. Table 10 lists the properties of these five analog years in comparison with 1999. Similarities included the following:

1. Ideal QBO wind conditions for intense hurricane activity with (extrapolated) zonal wind in September at 50 mb and 30 mb being positive and the vertical wind shear between these two levels very small. Activity is highest with the smallest negative values for September U_{50mb} plus U_{30mb} minus $|U_{50} - U_{30}|$. Any value higher than −30 is favorable for enhanced hurricane activity. The value for this year was -12.

2. Active multi-decadal hurricane periods which are characterized by a strong Atlantic thermohaline conveyor as gaged by a proxy measurement of SSTA in the North Atlantic (50-60°N, 10-50°W) during the prior 19-month period. Warm SSTA's in this location indicate a stronger than average conveyor; cold anomalies a below average Atlantic Ocean conveyor. Hurricane activity tends to be enhanced with a strong Atlantic conveyor circulation as was judged to be the case for this year.

3. Projected cool SSTA for August-October in the Nino 3.4 area. This also verified.

4. Projected negative Caribbean basin 200 mb ZWA conditions for August through October which also verified.

5. Projected negative Caribbean basin SLPA conditions for August through October. These values were generally below average during these months.

6. Projected slightly above average Western Sahel (of Africa) rainfall. Rainfall in the Sahel was neutral (i.e., near normal) for this year.

Table 10: The five analog years (since 1950) which had 3-11 month precursor conditions similar to 1999.

Year	Extrapolated Sept QBO	Inferred Strong Atlantic Ocean Conveyor Circulation	Cold Aug-Oct Nino 3.4 SSTA	Negative Aug-Oct ZWA	Negative Aug-Sept SLPA (mb)	Western Sahel June-Sept Rainfall Anomaly
1950	West	yes	Yes	Yes	Yes	Wet
1955	West	yes	Yes	Yes	Yes	Wet
1961	West	yes	Yes	Yes	Yes	Wet
1964	West	yes	Yes	Yes	Yes	Wet
1995	West	yes	Yes	Yes	Yes	Wet
Projected Aug-Oct 1999 Conditions	West	yes	Yes	Yes	Yes	Neutral

Table 11 lists the seasonal hurricane activity during these five analog years in comparison with 1999 activity. Note that the observed seasonal tropical cyclone parameters for 1999 were all very close to the average for the five prior analog years. Clearly, the methodology of consulting prior analog years compliments our statistical methodology and we hope to spend the next few years improving this element of our methodology.

Table 11: Hurricane activity in analog years versus 1999 activity.

Year	NS	NSD	H	HD	IH	IHD	HDP	NTC
1950	13	98	11	60	7	15.5	200	240
1955	12	83	9	47	5	13.75	158	196
1961	11	71	8	48	6	20.75	170	220
1964	12	71	6	43	5	9.75	139	167
1995	19	121	11	62	5	11.5	172	231
Average	13.4	88.6	9	52	5.6	14.25	168	211
1999 Hurricane Activity	12	77	8	43	5	15	145	193
1999 activity as a percent of the average for the five analog years	90%	87%	89%	82%	89%	105%	86%	91%

Our seasonal forecasts could not have been much different than the one we issued, given the similarity of 1999 precursor analog conditions to those of the very active analog years of 1950–1955–1961–1964–1995. The atmosphere-ocean system does indeed contain long lead-time precursor information as to how it is likely to behave 3 to 12 months in advance.

9 The Greatly Enhanced Atlantic Basin Hurricane Activity and U.S. Landfall During the Last Five Years

A major rearrangement of Atlantic Ocean SST features began in mid-1995 and has continued through October 1999 (Fig. 7). This change is well associated with increased Atlantic basin hurricane activity during the last five years. We hypothesize that these strong, broadscale SST changes are due to a major change in the strength of various components of the Atlantic Ocean thermohaline ("conveyor belt") circulation. This interpretation is consistent with changes in a long list of global atmospheric circulation features during the last five years which conform to a major shift towards a stronger Atlantic Ocean thermohaline circulation between 1994 and 1995. Such changes in Atlantic multi-decadal thermohaline circulation shifts appear to occur on periods of 25–50 years. If this interpretation is correct, then increased Atlantic basin intense (category 3-4-5) hurricane activity may be expected to persist through the early decades of the 21st century, in contrast with the greatly diminished activity during the 1970s through the early 1990s.

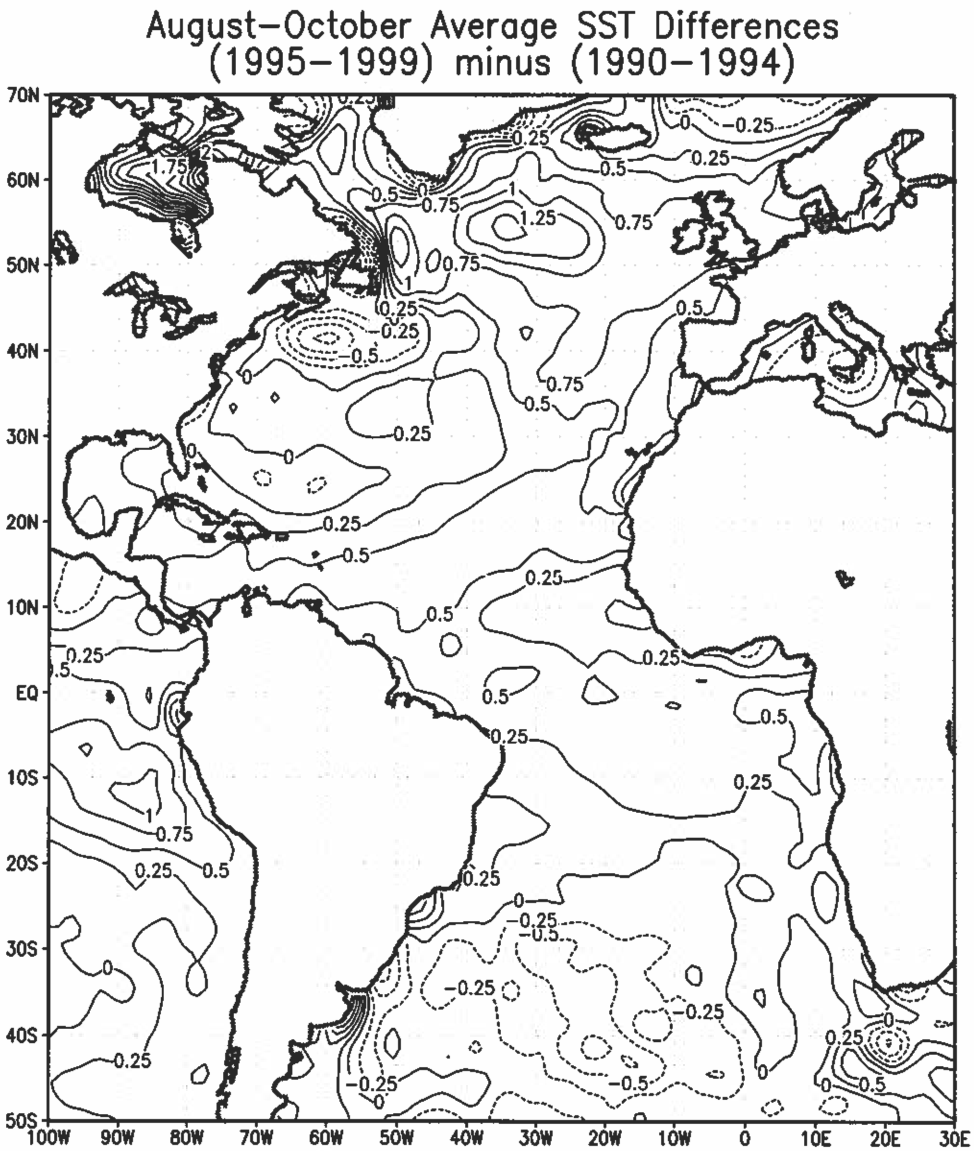

Figure 6: August through October SST differences (in °C) for the two five-year periods of 1995 to 1999 minus 1990 to 1994.

For some years we have suggested that the era of greatly reduced intense Atlantic category

3-4-5 hurricane activity between the late 1960s to early 1990s would end and that the U.S. and Caribbean coastal regions should expect to see an eventual increase in landfalling major hurricanes (Gray 1990). This outlook is ominous because, when normalized by increasing coastal population, inflation, and per capita wealth [see Pielke and Landsea (1998) and Gray (1998)] major hurricanes (on a statistical basis) cause more than 80 percent of all U.S. tropical cyclone linked destruction.

Evidence indicates that we have entered into a new era of increased intense hurricane activity. Despite El Niño-linked reduced hurricane activity of 1997, the last five years (1995–1999) are together the most active five consecutive years on record. Table 12 lists the total number of named storms (65), hurricanes (41), major hurricanes (category 3-4-5) (20), major hurricane days (51) and Net Tropical Cyclone (842) which occurred during 1995–1999. Note that despite the weak 1997 season, the annual average NS, H, IH, IHD and NTC during these five years was 155, 178, 304, 400, 816 and 267 percent of the NS, H, HD, IH, IHD, and NTC hurricane activity of the prior (1990–94) five-year period. Figure 7 portrays differences in H and IH tracks during these periods. Note also that NS, H, HD, IH, IHD and NTC during the last five years are 151, 165, 257, 263, 405 and 224 percent of the average for the prior 25-year (1970-1994) period; the greatest increase having occurred for IH and IHD activity. Hence, these trends of increased hurricane activity give strong support to the suggestion that we have indeed entered a new era of greatly increased major hurricane activity.

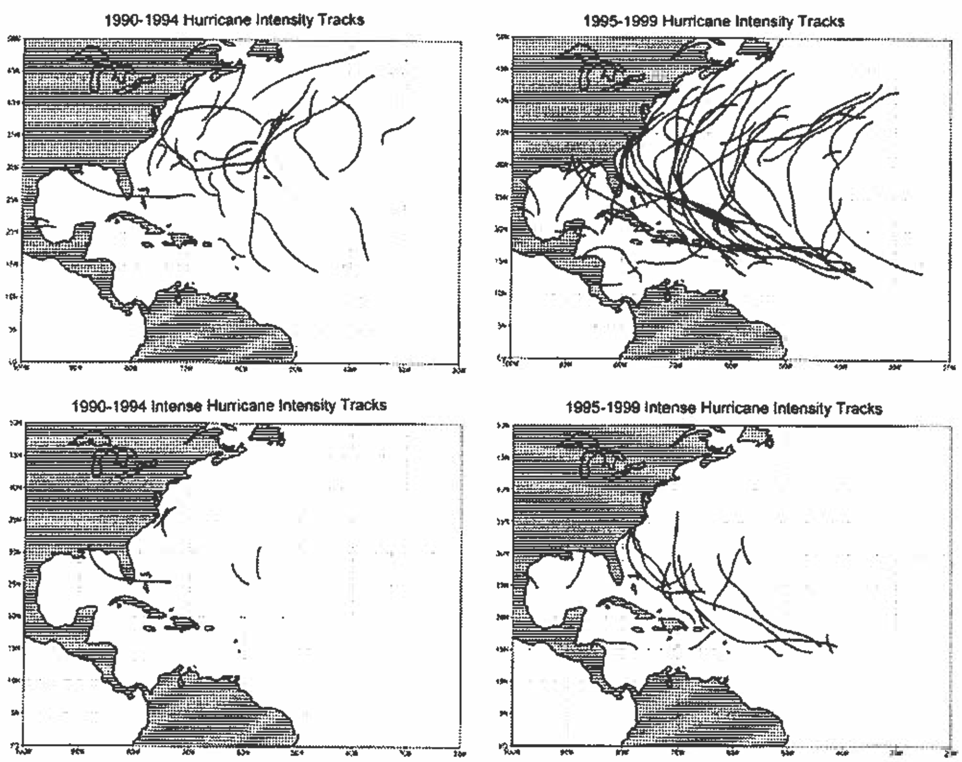

Figure 7: Comparison of cyclone tracks of hurricane intensity (top diagrams) and of category 3-4-5 intensity (bottom) during two five-year periods, 1990–94 (left) and 1995–99 (right).

<u>Recent Upswing of U.S. Landfalling Tropical Cyclones.</u> Table 13 lists the number of U.S. landfall named storms during the most recent two five-year periods, 1990–1994 and 1995–1999.

Table 12: Comparison of recent five-year period (1995–1999) hurricane activity with prior five-year period (1990–1994) and the recent quarter century period of 1970–1994.

Year	Named Storms (NS)	Hurricanes (H)	Hurricane Days (HD)	Cat 3-4-5 Hurricanes (IH)	Cat 3-4-5 Hurricane Days (IHD)	Net Tropical Cyclone Activity (NTC)
1995	19	11	60	5	11.50	229
1996	13	9	45	6	13.00	198
1997	7	3	10	1	2.25	54
1998	14	10	49	3	9.25	168
1999	12	8	43	5	15.00	193
TOTAL	65	41	207	20	51.00	842
five-year Ave 1995-1999	13.0	8.2	41.4	4.00	10.2	168
1990	14	8	27	1	1.00	104
1991	8	4	8	2	1.25	59
1992	6	4	16	1	3.25	62
1993	8	4	10	1	0.75	55
1994	7	3	7	0	0	37
TOTAL	43	23	68	5	6.25	317
five-year ave.	8.4	4.6	13.6	1.0	1.25	63
Ratio 1995-99/1990-94 in percent	155	178	304	400	816	267
Annual Ave. Ratio 1995–99/1970–94 in percent	151	165	257	263	405	224

Note the large increase in U.S. landfall during (21) the last five years. This is consistent with the overall increase in net Atlantic basin hurricane activity as shown in Table 12. Table 14 gives ratios of 1995–99 versus 1990–94 incidence of landfalling tropical cyclones and hurricanes. Overall, hurricane landfall activity increased 367 percent between the earlier and later period. The 1995–99 annual average of U.S. landfall hurricanes versus the previous 25-year (1970–94) period for tropical storms and hurricanes was only nine percent and eleven percent as much. This gives more meaning to the importance of the changes of the last five years.

Table 13: Comparison of U.S. landfalling tropical cyclones of various intensity class TS, Cat 1-2, and Cat 3-4-5 hurricanes during 1990–1994 versus 1995–1999.

1990–1994	NAMED STORMS
1990	1 (Marco – TS)
1991	1 (Bob – Cat 2)
1992	2 (Andrew – Cat 4; Cat 3), (Danielle – TS)
1993	1 (Arlene – TS), (Emily – Cat 3)
1994	3 (Alberto –TS), (Beryl –TS), (Gordon –TS)
1990–1994	8 TOTAL
1995–1999	NAMED STORMS
1995	5(Allison –TS), (Dean – TS), (Erin – Cat 1; Cat 2), (Jerry –TS), (Opal – Cat 3)
1996	3 (Bertha – Cat 2), (Fran – Cat 3), (Josephine –TS)
1997	1 (Danny – Cat 1)
1998	7(Bonnie - Cat 2), (Charlie –TS), (Earl – Cat 1), (Frances –TS) (Georges – FL Cat 2; MS Cat 2), (Hermine – TS), (Mitch –TS)
1999	5(Bret – Cat 3), (Dennis –TS), (Floyd – Cat 2), (Harvey –TS), (Irene – Cat 1)
1995–1999	21 TOTAL

Table 14: Comparison of U.S. landfalling of named storms and hurricanes of various intensity during the recent five-year periods 1990–1994 and 1995–1999.

	1990–1994	1995–1999	Ratio 1995-99/1990–94
TS Only	6	10	1.67
Hurricanes Only	3	11	3.67
TOTALS	9	21	

10 The 1995–1999 Hurricane Seasons and Global Warming

Some may interpret the recent large upswing in Atlantic hurricane activity (since 1995) as being in some way related to increased man-made greenhouse gases such as carbon dioxide (CO_2). There is no scientifically reasonable way that such an interpretation of this recent upward shift can be made. Anthropogenic greenhouse gas warming, even if a physically valid hypothesis, is a very slow and gradual process that, at best, might only be expected to bring about small changes in global circulation over periods of 50 to 100 years and could not cause the abrupt and dramatic upturn in hurricane activity as occurred between 1994 and 1995. Also, the large downturn in Atlantic basin major hurricane activity between 1970–1994 would need to be reconciled with proposed global warming scenarios during this period. Atlantic intense (or category 3-4-5) hurricane activity showed a substantial decrease during 1970–1994 to levels about 40 percent of the amount which occurred during the 1950–1969 or the 1995–99 periods. And, even if man induced greenhouse increases were shown to be causing global temperature increases over the last 25 years, there is no way to relate such a small global temperature increase to more hurricane activity.

In contrast with the large increase in Atlantic basin major hurricane activity during the last five years, total hurricane and typhoon activity in the (East and West) North Pacific region has decreased versus the 1990–94 period. And, when we combine Atlantic and North Pacific tropical cyclone activity, we see a net downward trend for the recent 1995–99 period (Table 15). Hence, we should not interpret the recent enhancement of major hurricanes in the Atlantic as indicative of the changes of hurricane activity around the globe. It is only in the Atlantic where hurricane activity has shown a sharp rise and this rise is in conformity with the changes in Atlantic sea surface temperature patterns. Such up and down multi-decadal changes in Atlantic intense sea surface temperature and tropical cyclone activity have been observed to take place in the past and are considered to be naturally occurring modes of multi-decadal variability.

Table 15: Comparison of North Pacific and Atlantic tropical cyclone activity during 1990–1994 versus 1995–1999.

(1990–1994)	No. of Systems $\geq$ TS Intensity	No. of Systems $\geq$ HUR. Intensity	No. of Major Hurricane
North Pacific (East and West)	252	199	87
Atlantic	43	23	5
Total	295	222	92
(1995–1999)			
North Pacific (East and West)	213	164	64
Atlantic	65	41	20
Total	278	205	84
Ratio of Total North Pacific + Atlantic 1995–99/1990–94	0.94	0.92	0.91

11 Forthcoming Early December Forecasts for 2000 Hurricane Activity

We will be issuing a seasonal forecast for 2000 Atlantic basin hurricane activity on 8 December 1999. This forecast will be based on data available to us through November 1999. A new aspect of the forecast for 2000 will be inclusion of a U.S. hurricane landfall forecast for all U.S. coastal locations and an assessment of hurricane-spawned destruction potential in comparison with the long-term averages. These forecasts will be disseminated on the World

Wide Web.

12 Acknowledgements

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13 Additional Reading

Goldenberg, S. B. and L. J. Shapiro, 1996: Physical mechanisms for the association of El Niño and West African rainfall with Atlantic major hurricane activity. *J. Climate*, 1169-1187.

Gray, W. M., 1984a: Atlantic seasonal hurricane frequency: Part I: El Niño and 30 mb quasi-biennial oscillation influences. *Mon. Wea. Rev.*, 112, 1649-1668.

Gray, W. M., 1984b: Atlantic seasonal hurricane frequency: Part II: Forecasting its variability. *Mon. Wea. Rev.*, 112, 1669-1683.

Gray, W. M., 1990: Strong association between West African rainfall and US landfall of intense hurricanes. *Science*, 249, 1251–1256.

Gray, W. M., C. W. Landsea, P. W. Mielke, Jr., and K. J. Berry, 1992: Predicting Atlantic seasonal hurricane activity 6–11 months in advance. *Wea. Forecasting*, 7, 440-455.

Gray, W. M., C. W. Landsea, P. W. Mielke, Jr., and K. J. Berry, 1993: Predicting Atlantic basin seasonal tropical cyclone activity by 1 August. *Wea. Forecasting*, 8, 73-86.

Gray, W. M., C. W. Landsea, P. W. Mielke, Jr., and K. J. Berry, 1994a: Predicting Atlantic basin seasonal tropical cyclone activity by 1 June. *Wea. Forecasting*, 9, 103-115.

Gray, W. M., J. D. Sheaffer and C. W. Landsea, 1996: Climate trends associated with multi-decadal variability of intense Atlantic hurricane activity. Chapter 2 in "Hurricanes, Climatic Change and Socioeconomic Impacts: A Current Perspective", H. F. Diaz and R. S. Pulwarty, Eds., Westview Press, 49 pp.

Kimberlain, T. B., J. B. Elsner and N. E. LaSeur, 1998: Baroclinically-inhibited hurricanes of North Atlantic basin, 1950–1996. To be submitted.

Knaff, J. A., 1997: Implications of summertime sea level pressure anomalies. *J. Climate*, 10, 789-804.

Knaff, J. A., 1998: Predicting summertime Caribbean sea level pressure. *Weather and Forecasting*, 13, 740–752.

Landsea, C. W., 1991: West African monsoonal rainfall and intense hurricane associations. Dept. of Atmos. Sci. Paper, Colo. State Univ., Ft. Collins, CO, 272 pp.

Landsea, C. W., 1993: A climatology of intense (or major) Atlantic hurricanes. *Mon. Wea. Rev.*, 121, 1703-1713.

Landsea, C. W. and W. M. Gray, 1992: The strong association between Western Sahel monsoon rainfall and intense Atlantic hurricanes. *J. Climate*, 5, 435–453.

Landsea, C. W., W. M. Gray, P. W. Mielke, Jr., and K. J. Berry, 1992: Long-term variations of Western Sahelian monsoon rainfall and intense U.S. landfalling hurricanes. *J. Climate*, 5, 1528–1534.

Landsea, C. W., W. M. Gray, K. J. Berry and P. W. Mielke, Jr., 1997: Revised Atlantic basin seasonal tropical cyclone prediction methods for 1 June and 1 August forecast dates. To be submitted to *Wea. Forecasting.*

Landsea, C. W., W. M. Gray, K. J. Berry and P. W. Mielke, Jr., 1996: June to September rainfall in the African Sahel: A seasonal forecast for 1996. 4 pp.

Landsea, C.W., N. Nicholls, W.M. Gray, and L.A. Avila, 1996: Downward trends in the frequency of intense Atlantic hurricanes during the past five decades. *Geo. Res. Letters*, **23**, 1697-1700.

Mielke, P. W., K. J. Berry, C. W. Landsea and W. M. Gray, 1996: Artificial skill and validation in meteorological forecasting. *Wea. Forecasting*, 11, 153-169.

Mielke, P. W., K. J. Berry, C. W. Landsea and W. M. Gray, 1997: A single-sample estimate of shrinkage in meteorological forecasting. Submitted to *Wea. Forecasting.*

Nicholson, S., 1999: Talk at NOAA, 24th Climate Diagnostics Conference, 3 November, Tuscon, AZ.

Pielke, Jr. R. A., and C. W. Landsea, 1998: Normalized Atlantic hurricane damage, 1925–1995. *Wea. Forecasting*, **13**, 621–631.

Reading, A. J., 1990: Caribbean tropical storm activity over the past four centuries. *International J. of Climatology*, 10, 365-376.

Sheaffer, J. D., 1995: Associations between anomalous lower stratospheric thickness and upper ocean heat content in the West Pacific warm pool. Presentation at the 21st AMS Conference on Hurricanes and Tropical Meteorology, Miami, FL, April 22-28.

Sheaffer, J. D. and W. M. Gray, 1994: Associations between Singapore 100 mb temperatures and the intensity of subsequent El Niño events. Proceedings, 18th Climate Diagnostics Workshop, 1-5 November, 1993, Boulder, CO.

Smith, T. M., et al., 1996: Reconstruction of historical sea surface temperatures using empirical orthogonal functions. *J. Climate*, 9, 1403-1420.

UK Meteorological Office, 1996: Preliminary experimental forecast of 1996 seasonal rainfall in the Sahel and other regions of tropical North Africa (issued 14 May and mid-July, 1996).

Wright, P. B., 1984: Relationship between indices of the southern oscillation. *Mon. Wea. Rev.*, 112, 1913-1919.

Wright, P.B., 1989: Homogenized long-period southern oscillation indices. *Int. J. Climatology*, 9, 33-54.

APPENDIX A: Verification of Past Seasonal Forecasts

The first author has now issued seasonal hurricane forecasts for 16 consecutive years (1984–1999). In the majority of these forecasts, the predictions were superior to climatology (i.e., long-term averages), particularly for named storms. Figures 8 and 9 offer comparisons of our 1 August forecasts of named storms and hurricanes versus climatology and actual year-to-year variability. Overall, there is predictive skill greater than climatology.

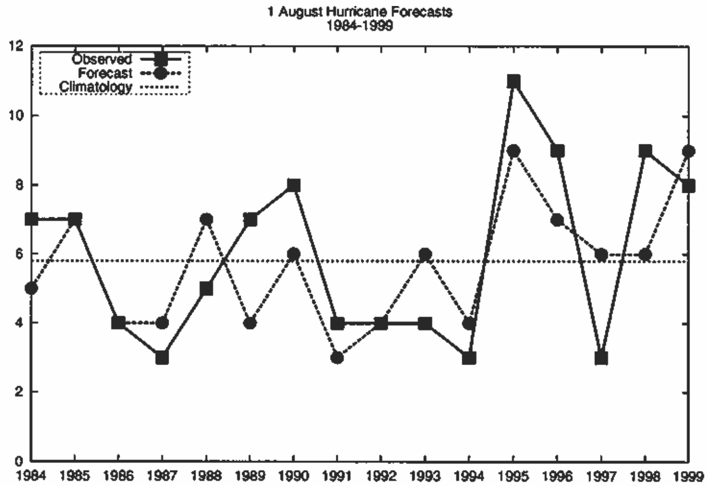

Figure 8: 1 August prediction of total named storms versus the number of actually observed versus long-term climatological mean (r = 0.80) for period 1984–1999.

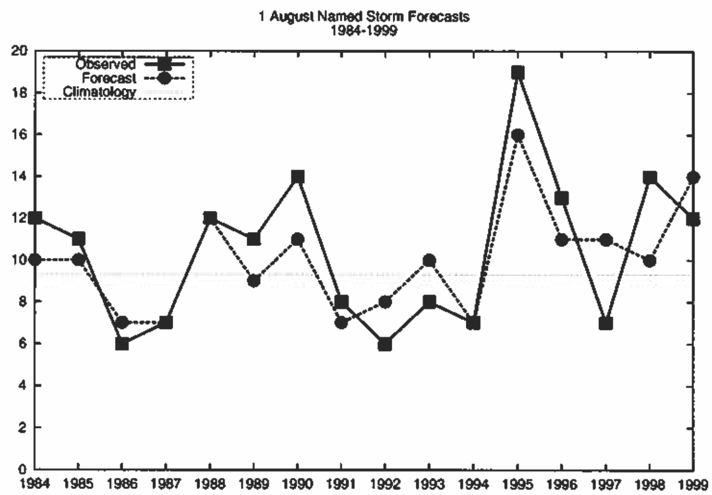

Figure 9: 1 August prediction of total hurricanes versus the number of actually observed versus climatological long-term mean (r = 0.64) for period 1984–1999.

Table 16: Summary verifications of the author's prior seasonal forecasts of Atlantic TC activity between 1984-1999.

	Prediction Dates		
1984	24 May and 30 July Update		Observed
No. of Hurricanes	7		5
No. of Named Storms	10		12
No. of Hurricane Days	30		18
No. of Named Storm Days	45		51
1985	of 28 May	Update 27 July	Observed
No. of Hurricanes	8	7	7
No. of Named Storms	11	10	11
No. of Hurricane Days	35	30	21
No. of Named Storm Days	55	50	51
1986	29 May	Update 28 July	Observed
No. of Hurricanes	4	4	4
No. of Named Storms	8	7	6
No. of Hurricane Days	15	10	11
No. of Named Storm Days	35	25	23
1987	26 May	Update 28 July	Observed
No. of Hurricanes	5	4	3
No. of Named Storms	8	7	7
No. of Hurricane Days	20	15	5
No. of Named Storm Days	40	35	37
1988	26 May and 28 July Update		Observed
No. of Hurricanes	7		5
No. of Named Storms	11		12
No. of Hurricane Days	30		21
No. of Named Storm Days	50		47
Hurr. Destruction Potential(HDP)	75		81
1989	26 May	Update 27 July	Observed
No. of Hurricanes	4	4	7
No. of Named Storms	7	9	11
No. of Hurricane Days	15	15	32
No. of Named Storm Days	30	35	66
Hurr. Destruction Potential(HDP)	40	40	108
1990	5 June	Update 3 August	Observed
No. of Hurricanes	7	6	8
No. of Named Storms	11	11	14
No. of Hurricane Days	30	25	27
No. of Named Storm Days	55	50	66
Hurr. Destruction Potential(HDP)	90	75	57
Major Hurricanes (Cat. 3-4-5)	3	2	1
Major Hurr. Days	Not Fcst.	5	1.00
1991	5 June	Update 2 August	Observed
No. of Hurricanes	4	3	4
No. of Named Storms	8	7	8
No. of Hurricane Days	15	10	8
No. of Named Storm Days	35	30	22
Hurr. Destruction Potential(HDP)	40	25	22
Major Hurricanes (Cat. 3-4-5)	1	0	2
Major Hurr. Days	2	0	1.25

1992	26 Nov 1991	Update 5 June	Update 5 August	Observed
No. of Hurricanes	4	4	4	4
No. of Named Storms	8	8	8	6
No. of Hurricane Days	15	15	15	16
No. of Named Storm Days	35	35	35	39
Hurr. Destruction Potential(HDP)	35	35	35	51
Major Hurricanes (Cat. 3-4-5)	1	1	1	1
Major Hurr. Days	2	2	2	3.25

1993	24 Nov 1992	Update 4 June	Update 5 August	Observed
No. of Hurricanes	6	7	6	4
No. of Named Storms	11	11	10	8
No. of Hurricane Days	25	25	25	10
No. of Named Storm Days	55	55	50	30
Hurr. Destruction Potential(HDP)	75	65	55	23
Major Hurricanes (Cat. 3-4-5)	3	2	2	1
Major Hurr. Days	7	3	2	0.75

1994	19 Nov 1993	Update 5 June	Update 4 August	Observed
No. of Hurricanes	6	5	4	3
No. of Named Storms	10	9	7	7
No. of Hurricane Days	25	15	12	7
No. of Named Storm Days	60	35	30	28
Hurr. Destruction Potential(HDP)	85	40	35	15
Major Hurricanes (Cat. 3-4-5)	2	1	1	0
Major Hurr. Days	7	1	1	0
Net Trop. Cyclone Activity	110	70	55	36

1995	30 Nov 1994	Update 14 April	Update 7 June	Update 4 August	Obs.
No. of Hurricanes	8	6	8	9	11
No. of Named Storms	12	10	12	16	19
No. of Hurricane Days	35	25	35	30	62
No. of Named Storm Days	65	50	65	65	121
Hurr. Destruction Potential(HDP)	100	75	110	90	173
Major Hurricanes (Cat. 3-4-5)	3	2	3	3	5
Major Hurr. Days	8	5	6	5	11.5
Net Trop. Cyclone Activity	140	100	140	130	229

1996	30 Nov 1995	Update 4 April	Update 7 June	Update 4 August	Obs.
No. of Hurricanes	5	7	6	7	9
No. of Named Storms	8	11	10	11	13
No. of Hurricane Days	20	25	20	25	45
No. of Named Storm Days	40	55	45	50	78
Hurr. Destruction Potential(HDP)	50	75	60	70	135
Major Hurricanes (Cat. 3-4-5)	2	2	2	3	6
Major Hurr. Days	5	5	5	4	13
Net Trop. Cyclone Activity	85	105	95	105	198

1997	30 Nov 1996	Update 4 April	Update 6 June	Update 5 August	Obs.
No. of Hurricanes	7	7	7	6	3
No. of Named Storms	11	11	11	11	7
No. of Hurricane Days	25	25	25	20	10
No. of Named Storm Days	55	55	55	45	28
Hurr. Destruction Potential(HDP)	75	75	75	60	26
Major Hurricanes (Cat. 3-4-5)	3	3	3	2	1
Major Hurr. Days	5	5	5	4	2.2
Net Trop. Cyclone Activity	110	110	110	100	54

1998	6 Dec 1997	Update 7 April	Update 5 June	Update 6 August	Obs.
No. of Hurricanes	5	6	6	6	10
No. of Named Storms	9	10	10	10	14
No. of Hurricane Days	20	20	25	25	49
No. of Named Storm Days	40	50	50	50	80
Hurr. Destruction Potential(HDP)	50	65	70	75	145
Major Hurricanes (Cat. 3-4-5)	2	2	2	2	3
Major Hurr. Days	4	4	5	5	9.2
Net Trop. Cyclone Activity	90	95	100	110	173

1999	5 Dec 1998	Update 7 April	Update 4 June	Update 6 August	Obs.
No. of Hurricanes	9	9	9	9	8
No. of Named Storms	14	14	14	14	12
No. of Hurricane Days	40	40	40	40	43
No. of Named Storm Days	65	65	75	75	77
Hurr. Destruction Potential(HDP)	130	130	130	130	145
Major Hurricanes (Cat. 3-4-5)	4	4	4	4	5
Major Hurr. Days	10	10	10	10	15
Net Trop. Cyclone Activity	160	160	160	160	193