SUMMARY OF 2001 ATLANTIC TROPICAL CYCLONE ACTIVITY AND VERIFICATION OF AUTHORS' SEASONAL ACTIVITY FORECAST

A Successful Forecast of an Active Hurricane Season – But the 2nd Consecutive Year Without US Hurricane Landfall

(as of 20 November 2001)

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

Thomas Milligan or Jennifer Dimas, Colorado State University Media Representatives (970-491-6432) are available to answer questions about this forecast.

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The following appeared as a misprint in the Fort Collins Coloradoan Newspaper on 22 May 2001 – referring to NOAA's mid-May forecast. We wonder how the verification is going?...........

A4, The Coloradoan, Tuesday, May 22, 2001

Nation

500-700 hurricanes forecasted this year

WASHINGTON — Storm experts forecast five to seven hurricanes to threaten the East and Gulf coasts this year and urged Americans to be prepared.

Weather experts characterized the tropical storm outlook as normal, but stressed that even the mildest year can contain monster storms.

SUMMARY OF 2001 SEASONAL FORECASTS AND VERIFICATION

Tropical Cyclone Seasonal Parameters (1950-90 Ave.)	Sequence of Forecast Updates 7 Dec 00 Forecast	6 Apr 01 Forecast	7 Jun 01 Forecast	7 Aug 01 Forecast	Observed* 2001 Totals
Named Storms (NS) (9.3)	9	10	12	12	14
Named Storm Days (NSD) (46.9)	45	50	60	60	59
Hurricanes (H)(5.8)	5	6	7	7	8
Hurricane Days (HD)(23.7)	20	25	30	30	24
Intense Hurricanes (IH) (2.2)	2	2	3	3	4
Intense Hurricane Days (IHD)(4.7)	4	4	5	5	5
Hurricane Destruction Potential (HDP) (70.6)	65	65	75	75	65
Maximum Potential Destruction (MPD) (61.7)	60	60	70	70	83
Net Tropical Cyclone Activity (NTC)(100%)	90	100	120	120	132

*A few of the numbers may change slightly in the National Hurricane Center's final tabulation

VERIFICATION OF 2001 MAJOR HURRICANE LANDFALL FORECAST

	Forecast Probability of one or more cyclones and the Climatology for the last 100 Years (in parentheses)	Observed
1. Entire United States Coastline	72% (50%)	0
2. Florida Peninsula and East Coast	54% (31%)	0
3. Gulf Coast	40% (30%)	0
4. Caribbean and Bahama Land Areas	72% (51%)	2
5. East Coast of Mexico	28% (18%)	0

VERIFICATION OF AUGUST-ONLY ATLANTIC BASIN HURRICANE FORECAST (ISSUED 7 AUGUST 2001)

Average August Tropical Cyclone Activity (1949–1999)	2001 August Forecast	2001 Verification
Named Storms (NS) (2.8)	3	3
Named Storm Days (NSD) (11.6)	7	11.75
Hurricanes (H)(1.6)	1	0
Hurricane Days (HD)(5.7)	2.50	0
Intense Hurricanes (IH) (0.6)	1	0
Intense Hurricane Days (IHD)(1.3)	0.50	0
Net Tropical Cyclone Activity (NTC)(26.1%)	21.8	9.5

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 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.

Major Hurricane - (MH) Same as intense hurricane.

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 10^3 kt.

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. 1 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, 18-60°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 = 0.515 meters per second.

ABSTRACT

This report summarizes tropical cyclone (TC) activity which occurred in the Atlantic basin during 2001 and verifies the authors' seasonal forecasts of this activity which were initially issued on 7 December 2000 with updates on 6 April, 7 June and 7 August of this year. These forecasts also contained estimates of the probability of U.S. hurricane landfall during 2001. The 7 August update also included a forecast of August-only tropical cyclone activity for 2001. Although our December and April forecasts did not anticipate such an active year, the early June and early August updates verified quite well. The 2001 hurricane season was characterized by enhanced levels of tropical cyclone activity but no U.S. hurricane landfalls (three tropical storms did make U.S. landfall however). A total of 14 named storms (average is 9.3) and 8 hurricanes (average is 5.8) occurred and persisted for a total of 24 hurricane days (average is 24). The seasonal total of named storm days was 59 which is 126 percent of the long-term average. There were 4 intense (or major) hurricanes (Saffir/Simpson intensity category 3-4-5) (average of 2.3) with 5 intense hurricane days (average is 4.7). Net Tropical Cyclone (NTC) Activity was 132 percent of the 1950–1990 average and 210 and 176 percent of average of the recent 5 and 25 year periods of 1990–94 and 1970–94, respectively.

1 Introduction

The Atlantic basin (including the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico) experiences more year-to-year hurricane variability than any other global tropical cyclone basin. The number of Atlantic basin hurricanes per season in recent years has ranged as high as 12 (1969), 11 (1995 and 1950), 10 (1998), and as low as 2 (1982) and 3 (1997, 1994, 1987, 1983, 1972, 1962, and 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 atmospheric and ocean precursor climate signals for surprisingly skillful 3-to-11 month (in advance) predictions of Atlantic basin seasonal hurricane activity. This research now allows us to issue extended-range forecasts as early as December for next year's Atlantic basin hurricane activity with updates in early April, early June, and early August of the forecast year. This end-of-season report compares our forecasts for 2001 with the actual hurricane activity observed during the 2001 hurricane season.

2 Factors Known to be Associated With Atlantic Seasonal Hurricane Variability

Our forecasts which are issued at four separate lead times prior to each hurricane season, are based on the current values of indices derived from various global and regional 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 geographic locations for which the various forecast parameters are obtained. The development of each new forecast emphasizes the analysis of the current and likely trends in the previously noted precursor oceanic and atmospheric conditions associated with hurricane activity during the following season. The predictors include the following:

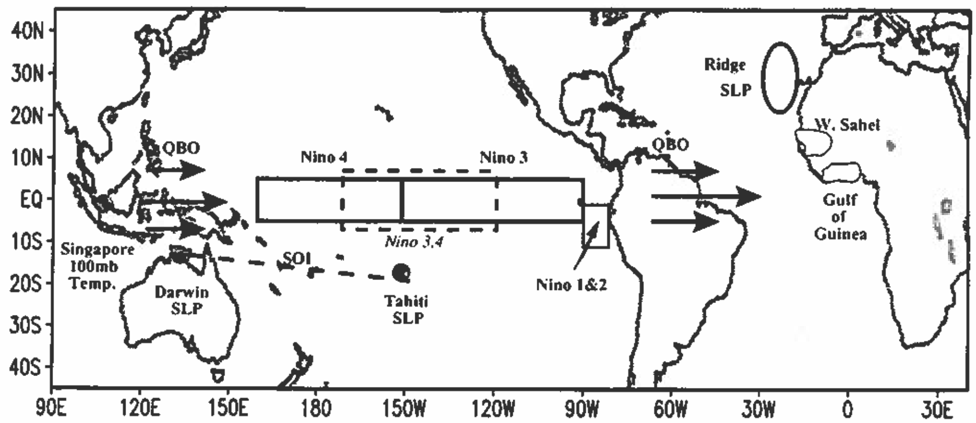


Figure 1: Areas from which specific oceanographic and meteorological parameters used as predictors in our seasonal forecasts are obtained.

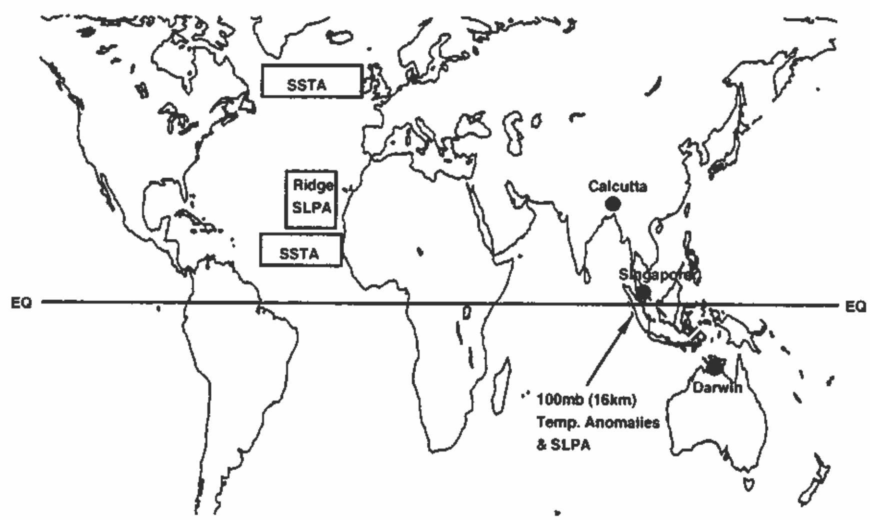


Figure 2: Additional predictor locations which are also considered in formulating our Atlantic seasonal hurricane forecasts.

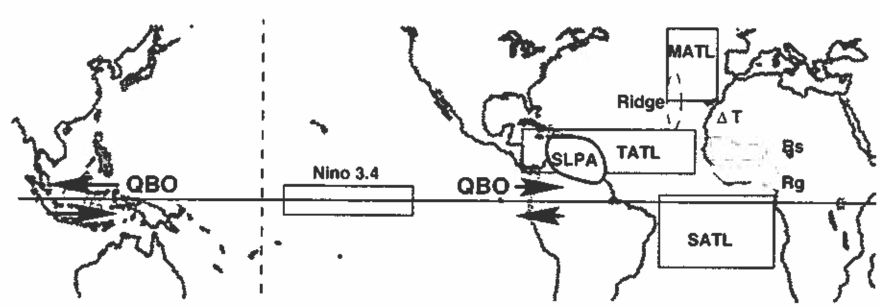


Figure 3: Additional meteorological parameters which are now used in our reformulated early June and early August forecasts.

(a) El Niño-Southern Oscillation (ENSO): El Niño events are characterized by anomalously warm sea surface temperature anomalies in the eastern equatorial Pacific areas termed Niño 1-2, 3, 3.4 and 4 (Fig. 1), a negative value of the Tahiti minus Darwin surface pressure gradient, and enhanced equatorial deep convection near the Dateline. These conditions alter the global atmospheric circulation fields contributing to anomalously westerly upper-level winds over the Atlantic basin which typically reduce Atlantic basin hurricane activity. Conversely, during La Niña seasons, anomalously cold sea surface temperatures are present, along with high values of Tahiti minus Darwin surface pressure difference and reduced deep equatorial convection near the Dateline. La Niña seasons are usually 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, more intense (category 3-4-5) Atlantic basin hurricane activity occurs during seasons when equatorial stratospheric winds at 30 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 the prior year rainfall during August-September in the western Sahel region is above average and when August-November Gulf of Guinea rainfall during the prior year is also above average. The June-July rainfall (in the western Sahel) is also a predictor for 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) Strength of the October-November (prior year) and March northeast Atlantic Subtropical Ridge(ONR). When this surface pressure feature is anomalously weak during these 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 decreased evaporative surface cooling rates in this area of the Atlantic. In this way, a weak ridge leads to warmer tropical Atlantic SSTs 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, 18-60°W) during April through June] and [NATL; 50-60°N, 10-50°W and TATL during the previous year.]: [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 provide unfavorable conditions for TC activity.

(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 potential 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 (Gray *et al.* 1994a).

Our four different 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 look for those years with specific precursor climate signals strongly similar to the current forecast year whereby the recurrence of similar TC activity is likely.

3 Statistical Summary of 2001 Atlantic Tropical Cyclone Activity

The 2001 Atlantic hurricane season officially ends on 30 November. As of late November, there have been eight hurricanes and 24 hurricane days during the 2001 season. The total named storms (i.e., the number of hurricanes plus tropical storms) was 14, yielding 59 named storm days. There were four intense or major (Cat. 3-4-5) hurricanes this season. All designated tropical cyclone activity parameters exceeded their long-term average values except for Hurricane Destruction Potential (HDP) which was slightly below average. Figure 4 and Table 1 show the tracks and give statistical summaries, respectively, for the 2001 season. Table 2 characterizes 2001 seasonal tropical cyclone activity in terms of annual average percentage of activity for the 1950-1990, 1970–94 and 1990–94 periods. Note that 2001 hurricane activity was much above the seasonal averages for 1970–1994 and for the more recent 1990–1994 period. The biggest changes in recent years have occurred for the most intense cyclones. Figure 5 shows the U.S. landfalling tropical storms of 2001. No hurricanes have made landfall in the U.S. for the second consecutive year.

Table 1: Summary of information for named tropical cyclones occurring during the 2001 Atlantic season. Information on Tropical Storms (TS), Hurricanes (H) and Intense Hurricanes (IH) and the highest Saffir/Simpson category of each is shown. (Based on information supplied by the National Hurricane Center).

Highest Category	Name	Dates	Peak Sustained Winds (kts)/ lowest SLP in mb	NSD	HD	IHD	HDP	NTC
TS	Allison	Jun.5-6	50kt/1002mb	0.75				0.6
TS	Barry	Aug.2-6	60/990	4.00				2.6
TS	Chantal	Aug.15-22	60/994	4.50				4.8
TS	Dean	Aug.22-Aug.28	60/992	2.50				2.8
IH-3	Erin	Sep.1-15	105/968	10.75	6.25	1.25	16.7	20.4
IH-3	Felix	Sep.7-19	100/965	7.25	4.50	0.75	13.1	15.4
H-1	Gabrielle	Sep.11-19	70/983	5.75	1.00		1.8	6.6
H-2	Humberto	Sep.21-27	90/970	5.75	3.50		7.4	9.5
IH-4	Iris	Oct.4-9	120/950	3.75	2.50	0.75	8.5	9.6
TS	Jerry	Oct.6-8	45/1003	1.75				1.3
H-1	Karen	Oct.12-15	70/982	2.50	1.00		1.8	3.3
TS	Lorenzo	Oct.27-31	35/1007	1.50				0.7
IH-4	Michelle	Oct.29-Nov.6	115/933	6.00	4.50	1.75	15.6	18.2
H-1	Noel	Nov.5-6	65/984	1.25	0.50		0.8	1.7
Total	14			59	24	5	65	132

By most measures, 2001 was an active hurricane year particularly in comparison with the average season between the period of 1970-1994 which had unusually suppressed activity.

4 Characteristics of Individual Storms During the 2001 Season

Tropical Storm Allison: Allison developed over the northwest Gulf of Mexico on June 5. The system was not fully tropical as it interacted with an upper-level low but produced a small low-level circulation with maximum winds of 60 mph. It quickly moved inland over southeast Texas that

Table 2: Summary of 2001 hurricane activity in comparison with long-term (1950–1990) and recent (1970–1994; 1990–1994) annual average conditions.

Forecast Parameter	1950–1990 Mean	Obs. 2001	2001 in percent as 1950-1990 ave. season Climatology	2001 in percent of ave. season between 1970-1994	2001 in percent of ave. season between 1990–94
Named Storms (NS)	9.3	14	151	163	167
Named Storm Days (NSD)	46.9	59	126	154	159
Hurricanes (H)	5.8	8	138	161	174
Hurricane Days (HD)	23.7	24	101	149	176
Intense Hurricanes (IH)	2.2	4	182	263	400
Intense Hurricane Days (IHD)	4.7	5	106	198	320
Hurricane Destruction Potential (HDP)	70.6	65	92	144	193
Maximum Potential Destruction (MPD)	61.7	83	135	166	201
Net Tropical Cyclone Activity (NTC)	100	132	132	176	210

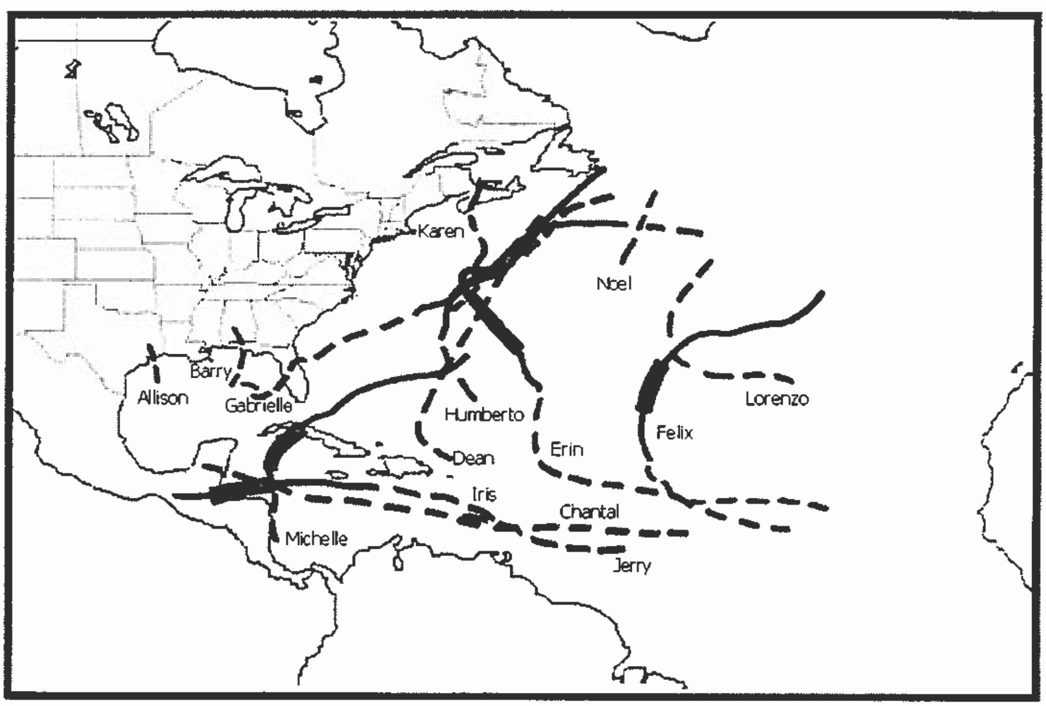


Figure 4: Tracks of the 14 named tropical cyclones of 2001. Dashed lines indicate the tropical storm intensity stage, thin solid lines indicate the Saffir/Simpson hurricane category 1-2 stage, and thick lines show the intense (or major) hurricane category 3-4-5 stage.

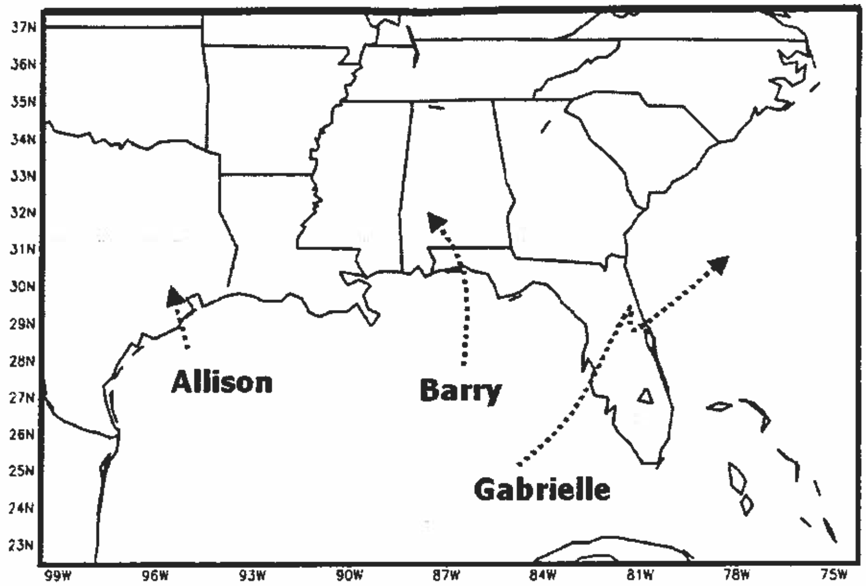


Figure 5: All 2001 U.S. landfalling tropical storms.

afternoon while weakening slightly with a landfall intensity of 50 mph. However, Allison was a slow-moving storm and stalled over Texas producing torrential rainfall. Several stations in the Houston metro area reported storm totals over 30 inches with amounts exceeding 20 inches in southeast Louisiana. The circulation moved offshore on the 9th and gained subtropical characteristics while dumping heavy rain along its track through the Southeast U.S. Allison tracked east-northeast toward North Carolina where heavy rainfall was again a problem as the system stalled. The storm finally moved off the coast on June 17. At least 32 people lost their lives with damage estimates of up to 5 billion dollars occurring mostly in the Houston area.

Tropical Storm Barry: Barry formed from a tropical wave over the eastern Gulf of Mexico on August 2. The storm moved slowly westward due to a weak steering current with unfavorable vertical wind shear. This caused Barry to weaken back to a depression. The system turned to the north and reintensified into a tropical storm which made landfall just east of Destin, FL (on the panhandle) with near hurricane (70 mph) strength winds. Although Barry caused 30 million dollars in damage, no deaths occurred.

Tropical Storm Chantal: Chantal was the first system in the deep tropics and was generated from a tropical wave well east of the Windward Islands. The system was fast-moving with a forward speed above 20 knots at times. It approached the Lesser Antilles on August 16 as a minimal tropical storm producing heavy rain and gusty winds. The circulation dissipated as it was moving through the islands, but redeveloped the next day. Though attaining estimated maximum winds of 70 mph south of Jamaica and despite a generally favorable environment, the storm never reached hurricane status. Vertical wind shear again disrupted the storm's circulation and it weakened on the 19th. Subsequently, Chantal slowed down and the environment became more favorable allowing Chantal to make landfall near the Mexico-Belize border late on the 20th as an intensifying 70 mph tropical storm. The system dissipated a few days later over southeastern Mexico.

Tropical Storm Dean: Dean rapidly formed from a tropical wave near the Virgin Islands on August 22. Strong winds and heavy rains pelted the northern islands of the Caribbean, with hurricane force wind gusts reported over St. Croix. However, Dean quickly weakened as it encountered strong wind shear the next day. Its remnants moved north-northwestward over the open Atlantic and showed signs of regeneration on the 26th as it interacted with a weak frontal trough. It reached a maximum intensity of 70 mph as it was moving northeastward over the north Atlantic before weakening as it encountered cool water.

Hurricane Erin: Erin was the first intense hurricane of the season, becoming a tropical storm on the 2nd of September while still in the far eastern Atlantic. However, like several storms this year, westerly shear destroyed the westward-moving circulation in the deep tropics. and it weakened to a depression on the 5th a few hundred miles east-northeast of the Leeward Islands. A new center formed on the northern side of the disturbed weather associated with Erin, and it strengthened steadily into a hurricane on the 8th. It reached a maximum intensity of 120 mph at a rather high latitude while northeast of Bermuda on the 9th. Erin passed near Cape Race, Newfoundland on the 14th and became extratropical.

Hurricane Felix: Felix developed from a tropical wave on the 6th of September and moved westward. Similar to Erin, it weakened into a tropical wave a few days later as it encountered strong shear. A new center developed on the 10th about a thousand miles east of the Lesser Antilles, and the storm turned to the north over the next few days. It briefly reached major hurricane status on the 13th with winds of 115 mph. Felix turned northeastward and passed a few hundred miles southwest of the Azores before stalling and dissipating on the 18th.

Hurricane Gabrielle: Gabrielle's origins were a weak frontal zone extending from the southeastern US on September 11th. The system slowly looped over the eastern Gulf of Mexico before intensifying into a 70 mph tropical storm just west of Naples, Florida and moving inland on the 14th, causing a large storm surge of up to 5 feet above normal near Ft. Myers. The system weakened over land as it continued slowly moving northeast before reintensifing into a hurricane over the open Atlantic. Gabrielle reached a peak intensity of 80 mph on the 18th and became an extratropical storm on the 19th, dumping heavy rainfall on Newfoundland. Gabrielle caused an estimated total of about 230 million dollars in damage in the U.S. with two fatalities.

Hurricane Humberto: Humberto was yet another non-tropical origin hurricane which formed on September 21st from a frontal trough left by the extratropical remnants of Gabrielle. Humberto became a tropical storm several hundred miles north-northeast of Puerto Rico while slowly drifting to the north. It reached an intensity of 100 mph west of Bermuda but weakened during the next few days. However, as the upper environment over the system became very favorable, Humberto reintensified at a unusually high latitude north of 40N, to reach a maximum intensity of 105 mph on the 26th. It then weakened quickly and became extratropical over the north Atlantic.

Hurricane Iris: Iris was the most intense storm of the season, forming from a tropical wave on the 6th of October. It quickly intensified as it was moving through the central Caribbean, becoming a hurricane the next day. Iris continued moving westward and passed very near Jamaica, but its effects were mostly felt offshore. Iris intensified further and reached a maximum intensity of 145 mph just before landfall in southern Belize. Iris was an extremely small cyclone with an eye diameter of less than 10 miles. The estimated death total was at least 31.

Tropical Storm Jerry: Jerry became a tropical storm on the 6th of October about 500 miles east of the Lesser Antilles. The center passed near St. Vincent with a maximum intensity of 50 mph. However, vertical wind shear took its toll, and the storm dissipated on the 8th before leaving the Caribbean Sea.

Hurricane Karen: Karen was the third baroclinically-initiated hurricane of the season, originating from a cold low southeast of Bermuda. The intensifying system passed near Bermuda, lashing the island with sustained hurricane force winds as it was transitioning into a hurricane. Thereafter it moved generally northward, reaching a peak intensity of 80 mph several hundred miles south of Nova Scotia. Karen made landfall as a 45 mph tropical storm on October 15th and dumped heavy rains on St. Johns, Newfoundland with 100 year floods reported.

Tropical Storm Lorenzo: Lorenzo formed from a non-tropical low in the eastern Atlantic, gradually acquiring tropical characteristics and becoming a tropical storm on the 29th as it was moving slowly westward. However, the storm turned northwest over cooler waters and became extratropical, never intensifying more than a minimal tropical storm with winds of 40 mph.

Hurricane Michelle: Michelle was the fourth and final intense hurricane of the 2001 season. It could be tracked from a tropical wave that exited the western Caribbean on October 24th and developed near the coast of Nicaragua while interacting with a cold front and slowly moved inland. The depression then moved slowly northward and emerged back over water to become TS Michelle on the last day of October. It quickly intensified and became a major hurricane late on the 2nd of November about 300 miles south of Cuba. The storm reached a peak intensity of 135 mph and minimum pressure of 933 mb on the 3rd while slowly moving northward. Michelle made landfall in Cuba with 135 mph winds near the Zapata Peninsula on the southern coast of central Cuba. It weakened steadily and made a second landfall near Nassau in the Bahamas with winds sustained near 85 mph. The hurricane slowly weakened and lost tropical characteristics becoming extratropical on the 6th.

Hurricane Noel: Noel was the fourth non-tropical origin hurricane of the season, forming from a low pressure system in the north Atlantic. A ship reported sustained winds of 75 mph on the morning of November 6th which was the time of maximum intensity. Noel was short-lived as it moved to the north while rapidly losing tropical characteristics over cooler water the next day.

5 Specifics Regarding Primary Forecast Parameters During 2001

Specific trends in the factors which we know to be associated with seasonal variation of hurricane activity during 2001 included the following:

a) ENSO Conditions. Equatorial Pacific SSTAs (expressed as °C) in Niño-1-2, 3, 3.4 and 4 (see Fig. 1 for locations) are shown in Table 3. Mixed neutral, weakly cool and weakly warm water conditions were variously present in much of the area throughout most of the season. The Tahiti minus Darwin surface pressure difference (the Southern Oscillation Index, SOI) was weakly negative (as occurs in neutral ENSO conditions) while equatorial Outgoing Longwave Radiation (OLR) values near the Dateline indicated no strong trend in deep convection. Overall we judge ENSO conditions to be neutral throughout the 2001 hurricane season.

Table 3: April through October 2001 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	1.1	–0.5	–1.1	–0.8	–0.8	–1.2	–1.4
Niño-3	0.1	–0.2	0.0	–0.2	–0.3	–0.6	–0.5
Niño-3.4	–0.2	–0.2	0.2	0.2	0.2	–0.1	0.0
Niño-4	–0.2	0.0	0.2	0.5	0.5	0.6	0.6
Normalized SOI in S.D.	–0.1	–0.8	–0.1	–0.4	–1.0	0.2	–0.4

b) Stratospheric QBO Winds

Table 4 shows 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 2001. We had projected both 30 and 50 mb QBO winds to be from a relative easterly direction and, therefore, would be an inhibiting feature for this year's major hurricane activity in the deep tropics. Both 30 and 50 mb QBO wind anomalies remained easterly throughout the 2001 season.

Table 4: Observed March through October 2001 values of stratospheric QBO zonal winds (U) in 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}.

OBSERVED WIND

Level	March	April	May	Jun	Jul	Aug	Sept	Oct
30 mb (23 km)	−13	−14	−17	−22	−26	−25	−20	−14
50 mb (20 km)	−5	−4	−7	−13	−20	−23	−18	−11

OBSERVED WIND ANOMALIES

Level	March	April	May	Jun	Jul	Aug	Sept	Oct
30 mb (23 km)	−12	−8	−5	−4	−5	−5	−1	+3
50 mb (20 km)	−6	−4	−2	−2	−6	−9	−7	−4

As with ENSO, the QBO element of our 2001 forecast presented some special challenges. It was our assessment that the QBO would be in the (TC inhibiting) easterly phase during the 2001 hurricane season. In particular, the QBO winds at 30 mb (the level below which the QBO mode becomes increasingly important for Atlantic hurricanes) had turned easterly during May 2000. The mean duration of the east phase at 30 mb is approximately 14 months. Hence, there was the prospect that this easterly event would be gone (at 30 mb) by September 2001 (17 months later). However, there is also a tendency for the downward propagation of the east phase to stop or even reverse itself and ascend during the Boreal winter. The descending east phase was not yet past 40 mb in November 2000 and thus there was a good prospect that the latter delay or "hanging" of the east phase in mid stratosphere would occur during the 2000/2001 winter.

The TC enhancing QBO west phase cannot begin its downward propagation until the east phase is well established near the tropical tropopause ($\sim$ 100 mb). Consequently, it was thus likely that the west phase would be delayed and that the easterly QBO would persist throughout the 2001 hurricane season (as did occur). The QBO east phase is well correlated with strong upper tropospheric warming, upper westerly wind anomalies and above average surface pressure conditions in much of the tropical Atlantic. Thus, the easterly QBO may also have coupled with the peculiar SST anomaly patterns in the east Pacific to enhance deep convection in that area, leading to enhanced upper-level outflow which moved into the Atlantic and created the anomalous conditions that suppressed deep tropical Atlantic hurricane genesis until very late in the season.

c) Sea-Level Pressure Anomaly (SLPA)

Table 5 gives information on regional Caribbean basin and Gulf of Mexico SLPA during this season. The anomalies that occurred were likely due to the ENSO/QBO effects noted previously. Caribbean SLPA was quite high during August and moderately high during September and October. The very high August SLPA values with the typical greater mass subsidence is judged to have been the primary inhibiting influence on this season's conditions. Knaff's (1997) Atlantic SLPA forecast scheme had predicted below average SLPA for 2001 which did not develop. It is surprising that 2001 hurricane activity was as active as it was given the generally high western Atlantic tropical SLPAs. The observed large amounts of hurricane activity were largely due to the exceptionally large number of sub-tropical latitude cyclones which formed. In general, when climate factors inhibit low latitude development, we usually see more higher latitude cyclone activity. However, this year's high latitude activity was well above our expectations.

Table 5: Lower Caribbean basin SLPA for 2001 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). Note: we use a SLP mean from 1950–1990 which is lower than the mean SLP during the last three decades by about 0.5 mb.

	Jun	Jul	Aug	Sep	Oct
5-station Lower Caribbean Average SLPA	0.5	–0.1	0.6	0.1	0.1
6-station Caribbean plus Gulf of Mexico Average SLPA	1.2	–0.2	0.9	–0.1	0.8

d) Zonal Wind Anomalies (ZWA)

Table 6 shows the average upper tropospheric (12 km or 200 mb) ZWA during the June through October period. Consistent with the prior ENSO/QBO discussion, all months except October had positive wind anomalies. These positive ZWA values enhanced regional tropospheric vertical wind shear and were a primary factor (along with positive SLPA) in suppressing July through September low latitude hurricane activity. It was only very late (early October to mid November) when lower latitude tropospheric wind conditions became favorable for TC formation. Positive ZWA conditions caused westward-moving easterly waves from Africa to experience increased tropospheric vertical wind shear and remain disorganized.

Table 6: 2001 Caribbean basin 200 mb (12 km) Zonal Wind Anomaly (ZWA) in ms^{-1} for the four stations including Kingston (18°N), Curacao (12°N), Barbados (13.5°N), and Trinidad (11°N).

	June	July	August	September	October
Average ZWA (1950-90 Climatology)	+2.2	+2.8	+1.8	+3.1	–0.5
Average ZWA (1958-96 Climatology)	+1.6	+1.6	+0.3	+1.8	–1.3

e) African Western Sahel Rainfall in 2001

Summer rainfall in the West Sahel region of Africa turned out to be significantly below average during June through September (–0.50 SD) despite the generally active hurricane season. Daily satellite loops of infrared (deep convective storms) imagery suggested that the western Sahel ITCZ cloudiness and rainfall might be near or above average. But as recently pointed out by S. Nicholson (1999), satellite estimates of rainfall appear to overestimate rainfall (wet bias) as compared with the available rain gauge data.

So far we have been unable to explain this lack of a positive Sahel rainfall/major hurricane association since 1995. Our previous research has shown (Gray 1990, Landsea 1991, Landsea and

Gray 1992, Landsea *et al.* 1992) a strong relationship between western Sahel rainfall and Atlantic basin major hurricane activity. This relationship has not held up since 1995 and is clearly a topic needing further study.

6 Characteristics of TC Activity During the 2001 Season

The 2001 season included the following special features:

1. The unusual late start of the 2001 season; the first 2001 hurricane not forming until September 8th. This trend was partly mitigated by the fact that there were three August tropical storms that were only five knots short of being classified as hurricanes. Nevertheless, this is the latest date for the first hurricane to form since 1984. Despite the very late start there were 10 named storms, 8 hurricanes and 4 major hurricanes which formed after 1 September. These 8 hurricanes tied 1969 and two previous years for the most ever hurricanes occurring after 1 September. We attribute the late start of the season to the very high surface pressure in the west Atlantic basin and a stronger than normal tradewind inversion during August. Figure 6 presents the 2001 Atlantic basin activity by month and by cyclone intensity class as well as the background monthly climatology. Note the increased cyclone activity in September, October and November compared with climatology and how inactive the first half of the season was from June through August in comparison with climatology.

2. Four major hurricanes developed during the second half of the season. This year saw the persistence of the recent strong upturn in major hurricane activity which began in 1995. Before 1995, the last season with as many as four major hurricanes was 1964. The years 1995-2001 are the most active seven-year period on record with 27 major hurricanes, 57 hurricanes and 93 named storms. It must be pointed out, however, that pre-World War II records are less reliable for weaker cyclone systems and for those in the central Atlantic.

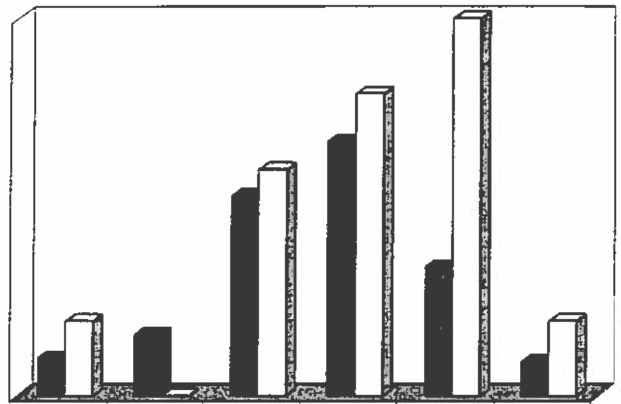
3. No U.S. hurricane landfall events occurred for the second consecutive year. This has not happened since 1981–1982 seasons. However, three 2001 tropical storms (Allison, Barry, and Gabrielle) did make landfall on the U.S. coast (Fig. 5). Both Barry and Gabrielle were just 5 knots short of hurricane intensity. Barry caused 30 million in damage and Gabrielle caused 230 million in damage with two fatalities. Allison was one of the most costly tropical storms on record ($\sim$ 5-6 billion in flood damage.

4. Only two hurricanes formed equatorward of 23.5° latitude and these developed only in the western Caribbean late in the season (after 5 October). This deficit of low-latitude cyclones is unusual for such a busy year. Of special note is the lack of any hurricane at tropical latitudes east of the Antilles (most unusual for an active hurricane season). The last time this occurred in an active year was 1954.

5. There were four Baroclinically-Initiated (BI) cyclones (Gabrielle, Humberto, Karen and Noel) which formed in association with prior middle-latitude baroclinic features which later transformed into warm-core systems (Elsner *et al.* 1996). There have been only four other years (1991, 1984, 1969, 1966) since 1950 when as many BI cyclones developed.

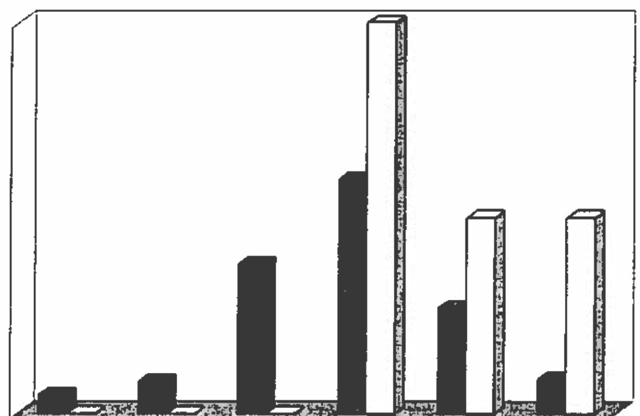
6. Four systems (Chantal, Dean, Erin and Felix) formed in the tropics, degenerated into a tropical wave, and then reformed in the subtropics. Having four such events in one year is very rare.

Number of Named Storms per Month for 2001



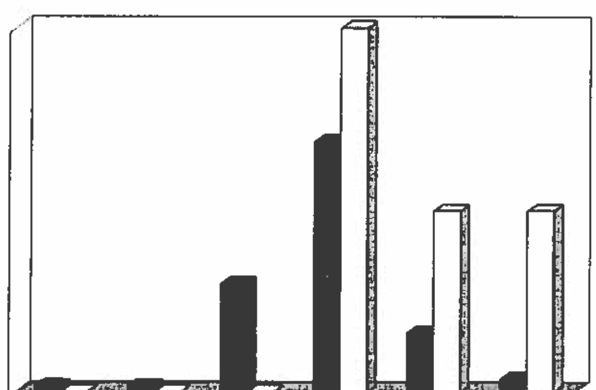
	June	July	August	September	October	November
■ Climatology	0.52	0.82	2.65	3.38	1.71	0.46
□ Named Storms	1	0	3	4	5	1

Number of Hurricanes per Month for 2001



	June	July	August	September	October	November
■ Climatology	0.19	0.33	1.52	2.4	1.08	0.35
□ Hurricanes	0	0	0	4	2	2

Number of Intense Hurricanes per Month for 2001



	June	July	August	September	October	November
■ Climatology	0.04	0.04	0.6	1.38	0.33	0.08
□ Intense Hurricane	0	0	0	2	1	1

Figure 6: Comparison of 2001 NS, H and IH numbers in each month (white shading) with monthly climatology (in black).

7. This season registered the lowest ever total of NSD and HD for any season with 14 named storms and 8 hurricanes the 1990 season had 8 hurricanes with 28 hurricane days and 1953 had 14 named storms with 64 named storm days. This season recorded only 59 named storm days and 24 hurricane days. For example, this season had 140 percent of the seasonal average number of hurricanes but only 100 percent of the average number of hurricane days.

8. Very active October-November period - four hurricanes, two intense hurricanes. The last season with both 4 hurricanes and 2 intense hurricanes after 1 October was 1950.

9. First time since 1932 there were two simultaneous hurricanes in existence in November.

10. Very warm North Atlantic (10-70oN latitude) Sea Surface Temperatures - one of the top three warmest of the last century.

11. Three tropical storms (Barry, Chantal and Dean) were just five knots short of hurricane intensity. Had all three of these been just five knots stronger, there would have been 11 hurricanes this season. Only the years of 1995, 1969, 1950 and 1916 had 11 or more hurricanes.

12. There have now been 18 consecutive hurricanes in the Atlantic without a US landfall. This eclipses the old record of 17 between Allen (1980) and Alicia (1983).

13. Five storms moved to the same latitude-longitude area (35-40N, 60-65W): Dean, Erin, Gabrielle, Humberto and Karen (see Fig. 4).

7 Verification of Individual 2001 Lead Time Forecasts

Table 7 shows a comparison of our 2001 forecasts for four different lead times with this year's observed numbers. Whereas our early June and early August forecasts worked out very well, our early December 2000 and early April 2001 forecasts were not very successful. Overall, we consider this year to have been among our better June and August Atlantic basin forecasts.

Table 7: Verification of our 2001 total seasonal hurricane predictions.

	Sequence of Forecast Updates				
Tropical Cyclone Seasonal Parameters (1950-90 Ave.)	7 Dec 00 Forecast	6 Apr 01 Forecast	7 Jun 01 Forecast	7 Aug 01 Forecast	Observed* 2001 Totals
Named Storms (NS) (9.3)	9	10	12	12	14
Named Storm Days (NSD) (46.9)	45	50	60	60	59
Hurricanes (H)(5.8)	5	6	7	7	8
Hurricane Days (HD)(23.7)	20	25	30	30	24
Intense Hurricanes (IH) (2.2)	2	2	3	3	4
Intense Hurricane Days (IHD)(4.7)	4	4	5	5	5
Hurricane Destruction Potential (HDP) (70.6)	65	65	75	75	65
Maximum Potential Destruction (MPD) (61.7)	60	60	70	70	83
Net Tropical Cyclone Activity (NTC)(100%)	90	100	120	120	132

*A few of the numbers may change slightly in the National Hurricane Center's final tabulation

Our forecast of an above-average probability of U.S. hurricane landfall did not verify however. Landfall probability is a different type of forecast which is better judged in aggregate over periods of 4-5 years rather than for individual years. Higher numbers of landfalling hurricanes virtually always occur during 4-5 active seasons in comparison with 4-5 inactive seasons.

Table 8 compares our objective forecast aids for our early-August seasonal prediction. Column (1) gives the 1950-1990 climatology. Column (2) lists our statistical predictions. Column (3) is our analog predictions based on the best judged analog years to 2001 of 1951, 1952, 1960, 1996 and 2000. Column (4) is our adjusted forecast, and column (5) is the verification of what actually did occur. Again, as in most years since 1995, our analog method was superior to our statistical method.

Table 8: Verification of our early August forecast techniques compared to the actual tropical cyclone activity which occurred.

Full Forecast Parameters	(1) 1950-1990 Climatology	(2) Statistical Prediction	(3) Analog Prediction	(4) Adjusted Actual Fcst	(5) Verification
Named Storms (NS)	9.3	8.7	10.2	12	14
Named Storm Days (NSD)	46.9	40.9	54	60	59
Hurricanes (H)	5.8	4.4	7	7	8
Hurricane Days (HD)	23.7	21.7	31	30	24
Intense Hurricanes (IH)	2.2	2.4	3.2	3	4
Intense Hurricane Days (IHD)	4.7	5.5	6.2	5	5
Hurricane Destruction Potential (HDP)	70.6	69	95	75	65
Maximum Potential Destruction (MPD)	61.7	61.9	72	70	83
Net Tropical Cyclone Activity (NTC)	100%	107%	130	120	132

8 Aggregate Verification of our Last Three Seasonal Forecasts

Each of our last three seasonal forecasts have worked out very well. Figure 7 lists each of these three yearly forecasts while Fig. 8 compares the average of the aggregate of the three forecasts expressed as percentage of climatology versus. the observed three year percentage of climatology for each of nine separate forecast parameters. Although this three year aggregate forecast shows considerable skill, favorable elements of random variability likely also contributed to this success.

9 Prediction of Hurricane Activity for Individual Months

Background. Periods of a few weeks to a month or more within various active or inactive Atlantic basin hurricane seasons often do not conform to the overall trend of the season. For example, although 1961 was a very active hurricane season, there was no tropical cyclone activity during the month of August. In 1995, 19 named storms formed in the Atlantic, but only one new named storm developed during the 30-day period spanning the statistical peak of the hurricane season between 27 August and 26 September. Conversely, the inactive season of 1941 had only six named storms (average 9.3), but four of these storms developed during September (average September activity is 3.4 storms). During the inactive hurricane season of 1968, three of eight total named storms formed during June (June average is 0.5).

1999 ATLANTIC BASIN SEASONAL HURRICANE FORECAST

Tropical Cyclone Seasonal	4 Dec 1998 Forecast for 1999	Updated 7 April 1999 Forecast	Updated 4 June 1999 Forecast	Updated 6 Aug 1999 Forecast	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
Max. Potential Destruction (MPD) *(61.7)*	130	130	130	130	114
Net Tropical Cyclone Activity (NTC) *100%*	160	160	160	160	193

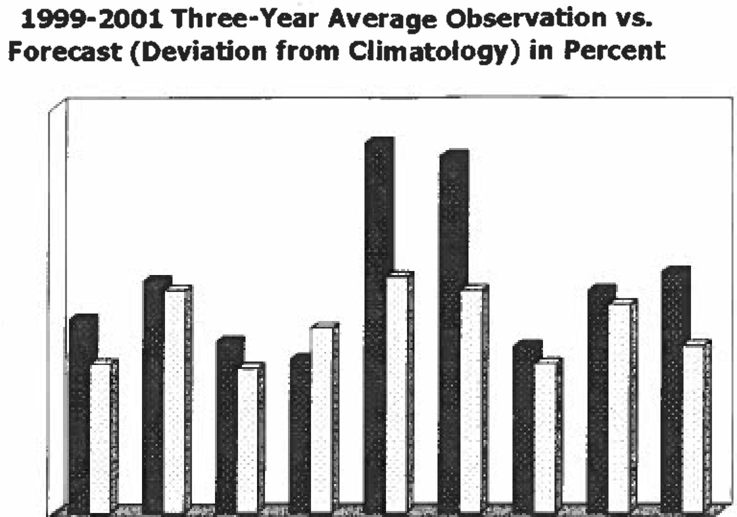
2000 ATLANTIC BASIN SEASONAL HURRICANE FORECAST

Tropical Cyclone Seasonal	8 Dec 1999 Forecast for 2000	Updated 7 April 2000 Forecast	Updated 7 June 2000 Forecast	Updated 4 Aug 2000 Forecast	2000 Observed Activity
Named Storms (NS) *(9.3)*	11	11	12	11	14
Named Storm Days (NSD) *(46.9)*	65	65	75	75	77
Hurricanes (H) *(5.8)*	7	7	8	7	8
Hurricane Days (HD) *(23.7)*	25	25	35	30	32
Intense Hurricanes (IH) *(2.2)*	3	3	4	3	3
Intense Hurricane Days (IHD) *(4.7)*	6	6	8	6	5.25
Hurricane Destruction Potential (HDP) *(70.6)*	85	85	100	90	85
Max. Potential Destruction (MPD) *(61.7)*	70	70	75	70	78
Net Tropical Cyclone Activity (NTC) *100%*	125	125	160	130	134

2001 ATLANTIC BASIN SEASONAL HURRICANE FORECAST

Tropical Cyclone Seasonal	7 Dec 2000 Forecast for 2001	Updated 7 April 2001 Forecast	Updated 7 June 2001 Forecast	Updated 7 Aug 2001 Forecast	Results as of 12 Nov.
Named Storms (NS) *(9.3)*	9	10	12	12	14
Named Storm Days (NSD) *(46.9)*	45	50	60	60	59
Hurricanes (H) *(5.8)*	5	6	7	7	8
Hurricane Days (HD) *(23.7)*	20	25	30	30	24
Intense Hurricanes (IH) *(2.2)*	2	2	3	3	4
Intense Hurricane Days (IHD) *(4.7)*	4	4	5	5	5
Hurricane Destruction Potential (HDP) *(70.6)*	65	65	75	75	73
Max. Potential Destruction (MPD) *(61.7)*	60	60	70	70	83
Net Tropical Cyclone Activity (NTC) *100%*	90	100	120	120	132

Figure 7: Atlantic basin seasonal hurricane forecasts for 1999, 2000, and 2001.



	NS	NSD	H	HD	IH	IHD	HDP	MPD	NTC
■ Observed	43%	51%	38%	34%	82%	79%	37%	49%	53%
□ Forecasted	33%	49%	32%	41%	52%	49%	33%	46%	37%

Figure 8: Three year (1999–2001) average observation versus forecast deviation from climatology (in percent). For instance, Named Storms (NS) was observed to be 43 percent higher than climatology for these three years while our three year forecasts were 33 percent above climatology.

In efforts being spearheaded by Eric Blake of our project, we are studying how well various sub-season and/or individual monthly trends can be forecast. It is, in general, more difficult to predict shorter periods of hurricane activity than to predict the entire seasonal activity. [Most predictive signals will vary more from climatology in relation to monthly than to seasonal trends.] Despite these inherent difficulties, we have devised a skillful "August-only" forecast scheme (as determined by 51 years of hindcast testing using a seasonal independent jackknife approach). This technique involves searching global (mostly) June and July data for potential predictors associated with active versus inactive August periods while predicting the same activity parameters (NS, NSD, H, HD, etc.) as in our seasonal scheme. This August-only forecast methodology will be more fully documented in forthcoming reports. Project member Philip Klotzbach is developing a September-only forecast scheme and we also plan to develop an October-November scheme.

Verification. Table 9 summarizes our forecast of TC activity for August 2001, along with a jackknife estimate of hindcast skill for the 51-year period of 1949–1999, long term August mean values and final adjusted August 2001 forecast and verification. The 2001 effort marks the second year in which we have made an August-only forecast.

The 2001 forecast indicate that a below normal August despite the seasonal forecast which called for an above average year. Generally, when the seasonal activity is above normal, the August activity is also enhanced. August ended up being much below normal and generally similar to the forecast. The forecast was not as successful as last years August-only forecast but was still more skillful than climatology.

Conditions over the Atlantic basin were not favorable for genesis in August. SLPA was very high and ZWA was slightly above normal. Tropical waves had trouble organizing in the deep tropics, though all three cyclones that did form, formed from waves. Even though no August hurricanes occurred, there were three named storms. The main disagreement in the August forecast concerned

Table 9: Prediction of August 2001 Atlantic basin seasonal hurricane activity, 51-year hindcast variance (r^2) explained (skill) and the August climatology.

Forecast Parameter	Statistical Forecast	Jackknife Hindcast Skill	August Climatology	Analog	2001 Final Adjusted Forecast Values	August 2001 Observed Number
NS	1.60	.49	2.76	2.8	3	3
NSD	-1.66	.61	11.80	7.4	7	11.75
H	0.62	.53	1.55	1.4	1	0
HD	-1.09	.62	5.67	2.8	2.5	0
IH	0.77	.58	0.57	0.2	1	0
IHD	0.59	.70	1.18	0.1	0.5	0
NTC	12.60	.73	26.1	15.4	21.8	9.5

whether an IH would occur during the month. The statistical model suggested there would be one while our analog year analysis hinted at only a small chance. Another problem was that the early statistical forecasts for HD gave a negative result. In the hindcast database, this had only occurred a few times but generally is indicative of a below normal August with no more than one H and fewer than three HD. The final NSD and HD forecast was taken from the analysis of analog years, as shown in Table 8. It is notable that an analog year composite forecast would have been a slightly better forecast than the one issued. There were no hurricanes observed and therefore the hurricane day forecast was too high. The NSD forecast was close to observed. The large error in the NTC parameter was due to the forecast that an IH would form in August.

The following statements are taken from our 7 August 2001 forecast and annotated with brief comments on what was actually observed.

a. "Blake expects August 2001 to have below-average activity." (There were no hurricanes in August, and total August activity was about 36 percent of normal).

b. "We expect the longevity of TC's in August 2001 to be much less than August 2000." (August 2000 saw 24.75 NSD while August 2001 observed only 11.75 NSD).

c. "An analysis of the July 2001 predictors indicated that September and October 2001 were likely to have above-average hurricane activity." (Although we well anticipated a below average August and above average conditions in September and October, we could not have foreseen that the early (June-August) versus later (September-November) seasonal activity differences would be as large as they were.)

10 Landfall Probabilities for 2001

A new aspect of our research involves efforts to develop forecasts of the seasonal probability of hurricane landfall along the U.S. coastline. Whereas individual hurricane landfall events cannot be accurately forecast for an individual year, the net yearly probability of landfall (relative to climatology) can be forecast with statistical skill. With the premise that landfall is a function of varying climate conditions, a probability specification has been accomplished through a statistical analysis of all U.S. hurricane and named storm landfalls during the last 100 years (1900–1999). Specific landfall probabilities can be given for all cyclone intensity classes for a set of distinct U.S. coastal regions. Net landfall probability is statistically related to the overall Atlantic basin

Net Tropical Cyclone Activity (NTC) and to climate trends linked to multi-decadal variations of the Atlantic Ocean thermohaline circulation (as measured by recent past years of North Atlantic SSTA*). Table 10 gives verifications of our landfall probability estimates for 2001. Fortunately for the U.S. the favorable odds of having hurricane landfall this year did not materialize.

Table 10: Estimated probability (percent) of one or more U.S. landfalling tropical storms (TS), category 1-2 hurricanes, and category 3-4-5 hurricanes, total hurricanes and named storms along the entire U.S. coastline, along the Gulf Coast (region 1-4), and along the Florida and the East Coast (Regions 5-11) for 2001. The mean annual percentage of one or more landfalling systems during the last 100 years is given in parentheses. The actual landfall numbers for 2001 follow the dash "–" symbol.

Coastal Region	TS	Category 1-2 HUR	Category 3-4-5 HUR	All HUR	Named Storms
Entire U.S. (Regions 1-11)	82% (80)–3	73% (68)–0	60% (52)–0	89% (84)–0	98% (97)–3
Gulf Coast (Regions 1-4)	67% (59)–2	46% (42)–0	34% (30)–0	62% (61)–0	87% (83)–2
Florida plus East Coast (5-11)	47% (51)–1	52% (45)–0	39% (31)–0	72% (62)–0	86% (81)–1

Active research continues on this technique and full documentation of the methodology for estimating hurricane landfall probability study is being prepared. Landfall probabilities include specific forecasts of the probability for landfalling tropical storms (TS) and hurricanes of category 1, 2, 3, and 4-5 for each of 11 units of the U.S. coastline (Fig. 9). These 11 units are further subdivided into 96 regions based on coastal population. Statistics are also being developed for each 100 km (65 mile) segment of the entire U.S. coastline.

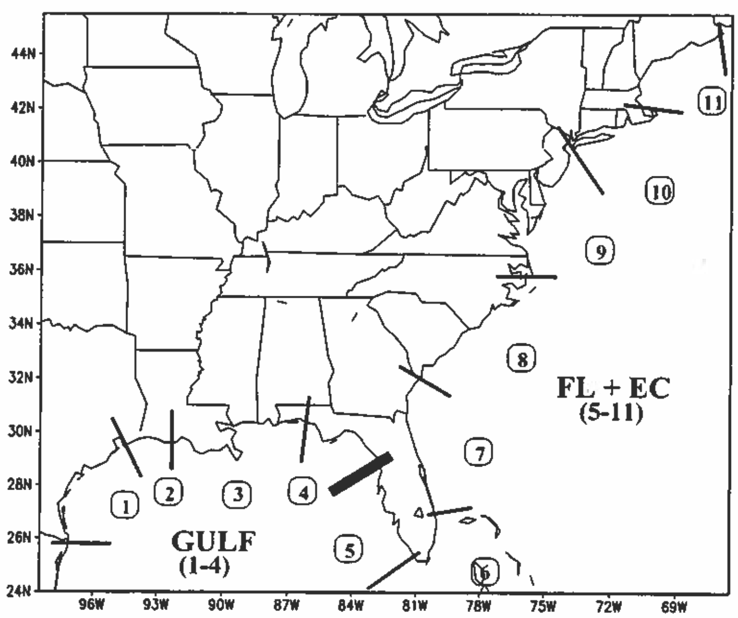


Figure 9: Location of the 11 coastal regions for which separate hurricane landfall probability estimates are made.

Figure 10 offers a summary and a general outline of the landfall probability estimate methodology. These landfall forecast probabilities will be supplemented with additional probability values for each 100 km coastal segments receiving tropical storm force winds ($\geq$ 40 mph), sustained hurricane force winds ($\geq$ 75 mph), and major hurricane (category 3-4-5) winds ($\geq$ 115 mph). Discussions of potential tropical cyclone spawned hurricane destruction within each of the 96 different U.S. coastal locations are also in preparation.

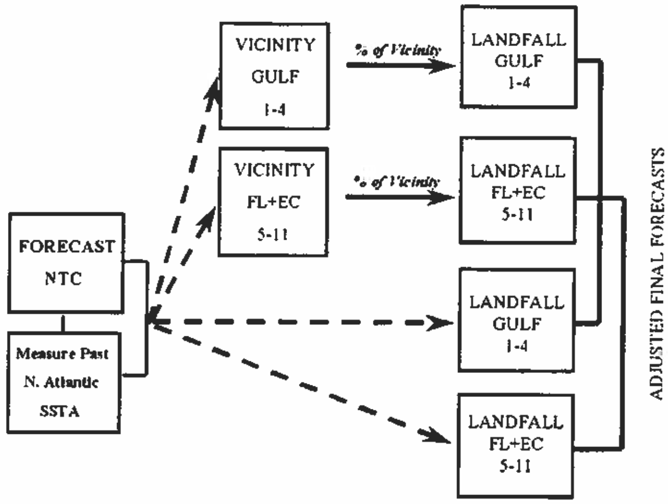


Figure 10: General flow diagram illustrating how forecasts of U.S. hurricane landfall probability are made. We forecast NTC and use an observed measure of the last few years of North Atlantic (50-60°N, 10-50°W) SSTA*. Regression equations are then developed from the combinations of forecast NTC and measured SSTA* values. A regression is then developed from U.S. hurricane landfall measurements of the last 100 years and separate equations are derived for the Gulf and for Florida and the East Coast (FL+EC).

11 Increased Level of Atlantic Basin Hurricane Activity During the Last Seven Years - But Decrease in Landfall

A major reconfiguration of the distribution of Atlantic SST anomalies began in mid-1995 and has persisted through the present. In clarification, North Atlantic SSTs have become about 0.4 to 0.6°C warmer than normal. This trend is well associated with increased major hurricane activity in the Atlantic basin during the last seven years. We hypothesize that these strong broadscale SST changes are associated with basic changes in the strength 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 seven years which conform to a prominent shift into hurricane-enhancing Atlantic circulation patterns. Historical and geographic evidence going back thousands of years indicated that shifts in the Atlantic multi-decadal thermohaline circulation tend to occur on periods of 25–50 years. If the recent 7-year shift follows prior occurrences then it is likely that enhanced intense Atlantic basin hurricane activity will persist through the early decades of the 21st century. This will be in contrast with the diminished activity which persisted from 1970-1994.

Despite El Niño-linked reduction of hurricane activity during 1997, the last seven years (1995–2001) constitute the most active seven consecutive years on record. Table 11 provides a summary of the total number of named storms (93), named storm days (520), hurricanes (57), hurricane days (263), major hurricanes (27), major hurricane days (61.25) and Net Tropical Cyclone activity

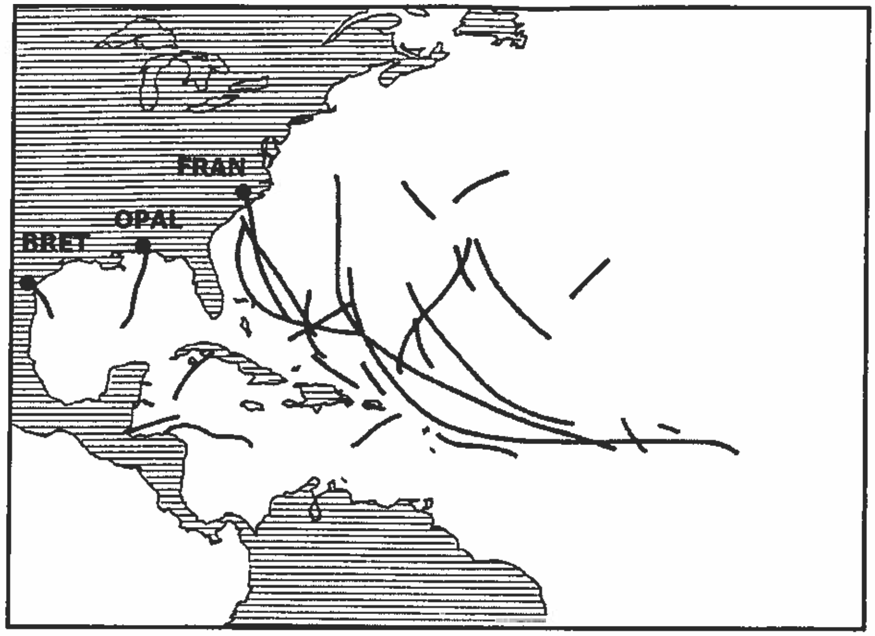


Figure 11: Intense (Cat 3-4-5) hurricane tracks during the period from 1995-2001. Note that despite there being twenty-seven intense hurricanes during this period that only three (Bret, Opal and Fran) made US landfall. Bret made landfall at the least vulnerable location in the US, and Opal and Fran made landfall in areas not densely populated areas.

(1108) which occurred during 1995–2001. Despite the inactive 1997 season the annual average NS, NSD, H, HD, IH, IHD and NTC during these seven years was 137, 196, 140, 233, 254, 347 and 211 percent respectively above the averages of the prior 25-year period of 1970–1994. Note also that NS, NSD, H, HD, IH, IHD and NTC during these seven years are 143, 158, 142, 159, 175, 186 and 158 percent of the climatological average for the period 1950–1990 with the greatest increase occurring for IH and IHD activity. These trends toward increased hurricane activity give strong support to the suggestion that we have indeed entered a new era of greatly increased major hurricane activity. NTC activity during the seven-year period averaged 211 percent of the level observed during 1970-1994 period. Excluding 1997, average NTC for the other six years from (1995-2001) was 176. There have been as many Atlantic basin intense hurricanes during the seven years between 1995-2001 as there were during the eighteen years between 1977-1994.

Beginning about 1990, we have been suggesting that the era of greatly reduced intense Atlantic category 3-4-5 hurricane activity that began during the late 1960s was likely coming to an end and that the U.S. and Caribbean coastal regions should expect a long term increase in landfalling major hurricanes (Gray 1990). Such an increase is an ominous prospect considering the strong increases in U.S. and Caribbean coastal population in recent years and that, when hurricane destruction is normalized for coastal population, inflation, and wealth per capita [see Pielke and Landsea (1998)], it is found that major hurricanes cause about 85 percent of all U.S. tropical cyclone-linked destruction.

Good fortune has been manifest during the last seven years as a persistent upper-air trough located along the U.S. East Coast much of the time during hurricane season. The presence of this upper-level trough caused a large portion of otherwise northwest moving major hurricanes to recurve to the north before they reached the U.S. coastline. Figure 11 provides a summary illustration of these effects showing the tracks of major hurricanes during their intense stages for

Table 11: Comparison of recent seven-year (1995–2001) hurricane activity with climatology and prior quarter century period of 1970–1994.

Year	Named Storms (NS)	Named Storm Days (NSD)	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	121	11	60	5	11.50	229
1996	13	78	9	45	6	13.00	198
1997	7	28	3	10	1	2.25	54
1998	14	80	10	49	3	9.25	168
1999	12	77	8	43	5	15.00	193
2000	14	77	8	32	3	5.25	134
2001	14	59	8	24	4	5.00	132
TOTAL	93	520	57	263	27	61.25	1108
Seven-year Ave. 1995-2001	13.3	74.3	8.1	37.6	3.86	8.75	158
Ratio 1995-01/climatology in percent	143	158	142	159	175	186	158
Ratio 1995-01/1970-94 in percent	137	196	140	233	254	347	211

the last seven years. Note that though many major hurricanes passed not too far from the U.S. coastline, only three made landfall. This run of good luck cannot be expected to continue.

Table 12 further demonstrates the good luck of the last seven years (1995-2001) expressed in terms of the number of U.S. major hurricane landfalls per year during the 95-year period of 1900–1994. Along the Florida Peninsula and the East Coast, major hurricane landfall per year has been only 38 percent as great as in the average year between 1900-1994 and 58 percent as large for the whole U.S. coastline.

In terms of the ratio of the number of U.S. major hurricane landfalls per number of Atlantic basin major hurricanes the last seven years have witnessed a very strong downturn. Table 13 shows that the U.S. Gulf in the last seven years has experienced only 46 percent as many major hurricane landfall events per Atlantic basin major hurricanes as during the average of the previous 95 years. The Florida and the East Coast rate of landfall in major hurricane the last seven years has been only 22 percent as great; for the whole U.S. coastline 35 percent. This fortuitous landfall downturn cannot continue.

Table 12: The incidence of U.S. average major hurricane landfall per year. Number in parentheses indicate the percentage ratio for 1995-2001 versus 1900-1994).

	Gulf Coast Regions 1-4	Florida Peninsula and East Coast Regions 5-11	Whole U.S. Coast Regions 1-11
1900-1994	.358	.379	.737
1995-2001	.258(80%)	.143(38%)	.429(58%)

Table 13: The incidence of U.S. average major hurricane landfall per year expressed as percent of Atlantic basin total major hurricanes. Number in parenthesis indicate the annual percentage ratio for 1995-2001 versus 1900-1994).

	Gulf Coast Regions 1-4	Florida Peninsula and East Coast Regions 5-11	Whole U.S. Coast Regions 1-11
1900-1994	.162	.172	.321
1995-2001	.074(46%)	.037(22%)	.111(35%)

12 Downturn in the Incidence of U.S. Hurricane Landfall in Recent Decades

During the 102 years between 1900 and 2001, 112 category 1-2 hurricanes and 73 category 3-4-5 hurricanes made landfall on the U.S. coast. However, the annual incidence of landfall in Florida and the East Coast was nearly twice as great during the first 67 years (1900–1966) as it was during the recent 36 year period (1966–2001) (see Tables 14 and 15). Given the much greater incidence of major U.S. hurricanes in terms of landfall numbers during the earlier portions of the last century, our luck at having fewer intense hurricane landfalls that specified by climatology has now extended for over three decades. For example, in the 36 years since 1966 the U.S. has experienced 18 major landfall events, hence an incidence of 0.50 per year. This rate is only 69 percent of the annual incidence (0.80/year) of major hurricane landfall events which occurred during the prior 66 year period spanning 1900–1965.

Table 14: The incidence of U.S. average major hurricane landfall per year. Number in parentheses indicate the percentage ratio for 1966-2001 versus 1900-1965).

	Gulf Coast Regions 1-4	Florida Peninsula and East Coast Regions 5-11	Whole U.S. Coast Regions 1-11
1900-1965	.364	.429	.803
1966-2001	.333(91%)	.222(52%)	.556(69%)

For the Florida Peninsula and the U.S. East Coast, these same considerations are even more skewed. During the 36 years since 1966 only 8 landfalling major hurricanes (an average of 0.22 per year) struck the Florida Peninsula and U.S. East Coast. However, between 1900–1965 there were 29 major landfall events along this same coastline with a mean incidence of 0.43 per year. Hence, the first six decades of the 20th century along the Florida Peninsula and East Coast had twice the number of major hurricanes landfall per year than occurred during the last three and a half decades. It cannot be presumed that this recent downturn in U.S. major hurricane landfall events along the Florida Peninsula and East Coast will continue indefinitely. Climatology will eventually right itself and we must expect a great increase in landfalling major hurricanes in the coming decades. It has been shown by Pielke and Landsea (1998) that when normalized by population, inflation, and

Table 15: The incidence of U.S. average major hurricane landfall per year in percent of Atlantic basin total major hurricanes. Number in parentheses gives per year percentage ratio of 1966-2001 to 1900-1965).

	Gulf Coast Regions 1-4	Florida Peninsula and East Coast Regions 5-11	Whole U.S. Coast Regions 1-11
1900-1965	.167	.200	.366
1966-2001	.167(100%)	.111(55%)	.278(76%)

wealth per capita that major hurricanes, in a long period statistical average cause about 85 percent of all tropical cyclone damage.

Curiously, the large upturn of Atlantic basin hurricane activity during the last seven years (1995–2001) has been attended by a reduction in landfall events during this period which is even more pronounced than what occurred in the 1970-94 period. The portion of developing hurricanes making U.S. landfall during the last seven years has been only one-third as great as the percentage expected to make landfall based on long-term Atlantic basin hurricane climatology. Specifically, of the 27 major hurricanes that developed in the Atlantic basin during the last seven years, only three (Opal, 1995; Fran, 1996; and Bret, 1999) made landfall on the U.S. coastline. Average data for the Atlantic basin over the last century indicates that one in three (73 of 218) intense Atlantic basin storms come inland. Based on these data we should have expected about 9 major hurricane landfalls where only 3 occurred. Similarly there have been a total of 57 Atlantic basin hurricanes (all intensities) since 1995 with 8 coming ashore, where climatology suggests that about 19 U.S. hurricane landfall events.

The last 36 years have also seen a great increase in U.S. southeast coastal population and wealth per capita. When the inevitable return to conditions more typical of the climatologically averages occurs during coming decades, it is inevitable that we will see U.S. hurricane-spawned damage rise to unprecedented levels.

Table 16 demonstrates the special qualities of the last 36 years in terms of the number of U.S. major hurricane landfalls per year. This is particularly the case for the the Florida Peninsula and East Coast where major hurricane landfall per year has been 52 percent as great as during the prior 66 year period of 1900-1965. The same can be said the incidence of major hurricane landfall event per Atlantic basin major hurricane. Table 15 shows that during the last 36 years, the annual incidence for Florida and East Coast major hurricane landfalls per Atlantic major hurricane has only 55 percent as great as during the prior 66 year period. This 36 year long fortuitous multi-decadal downturn in major landfall activity should not be expected to continue.

13 The 1995–2001 Upswing in Atlantic Hurricanes and Global Warming

Various groups and individuals have suggested that the recent large upswing in Atlantic hurricane activity (since 1995) may be in some way related to the effects of increased man-made greenhouse gases such as carbon dioxide (CO_2). There is no reasonable scientific way that such an interpretation of this recent upward shift in Atlantic hurricane activity can be made. The effects of anthropogenic greenhouse gas warming, even if a physically valid hypothesis, are a very slow and gradual process that, at best, might be expected to bring about small changes in global circulation over periods of 50 to 100 years. Hence, greenhouse gas-linked warming could not be responsible for the abrupt and dramatic upturn in hurricane activity which has occurred since 1994. Also, the large downturn in Atlantic basin major hurricane activity between 1970–1994 would need to be reconciled with proposed long-term global warming scenarios during this period. Atlantic intense (or category 3-4-5) hurricane activity decreased 40 percent during 1970–1994 from the levels which occurred during the 1950–1969 or the 1995–2001 periods. There were 82 Atlantic basin major hurricanes during the 26 years of 1950–1969, 1995–2001 versus 38 in the 25 years of 1970–1994, an annual difference of two to one. Even if this man-induced greenhouse gas increases were shown to be causing global temperature increases during the last 25 years, there is no way to relate such a small global temperature increase to this level of increased hurricane activity.

In contrast with the large increase in Atlantic basin major hurricane activity during the last seven years, total global hurricane and typhoon activity during the period 1995–2001 has undergone a small decrease. It is only in the Atlantic basin where hurricane activity has shown a sharp rise.

14 Forthcoming Early December Forecasts of 2002 Hurricane Activity

We will be issuing a seasonal forecast of 2002 Atlantic basin hurricane activity on Friday 7 December 2001. This forecast will be based on data available to us through November 2001. As in the past, updates to the 2002 seasonal forecast will be issued in early April, early June, and early August 2002. The latter will include separate forecasts for August-only and September-only activity during 2002. All of these forecasts will be available at our Web address given on the front cover (http://tropical.atmos.colostate.edu/forecasts/index.html).

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APPENDIX A: Verification of Past Seasonal Forecasts

The first author has now issued seasonal hurricane forecasts for 18 consecutive years (1984–2001). In the majority of these forecasts, the predictions were superior to climatology (i.e., long-term averages), and particularly for named storms (Table 15). Figures 12 and 13 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.

We have issued forecasts for intense or major (category 3-4-5) hurricanes since 1990. The 1 August forecast correlation for these 12 years is r = 0.73.

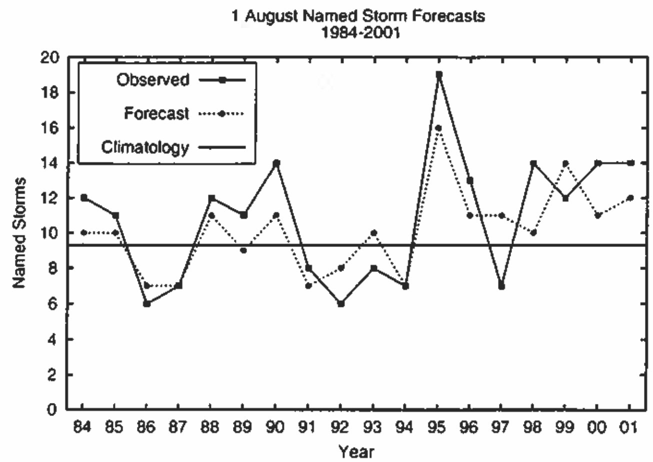

Figure 12: 1 August prediction of total named storms versus the number of actually observed versus long-term climatological mean (r = 0.81) for period 1984–2001.

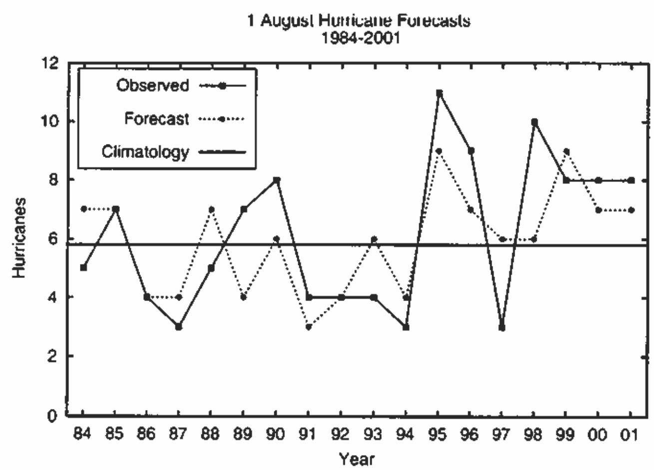

Figure 13: 1 August prediction of total hurricanes versus the number of actually observed versus climatological long-term mean (r = 0.68) for period 1984–2001.

Table 16: Summary verifications of the author's prior seasonal forecasts of Atlantic TC activity between 1984-2001.

	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

2000	8 Dec 1999	Update 7 April	Update 7 June	Update 4 August	Obs.
No. of Hurricanes	7	7	8	7	8
No. of Named Storms	11	11	12	11	14
No. of Hurricane Days	25	25	35	30	32
No. of Named Storm Days	55	55	65	55	66
Hurr. Destruction Potential(HDP)	85	85	100	90	85
Major Hurricanes (Cat. 3-4-5)	3	3	4	3	3
Major Hurr. Days	6	6	8	6	5.25
Net Trop. Cyclone Activity	125	125	160	130	134

2001	7 Dec 2000	Update 6 April	Update 7 June	Update 7 August	Obs.
No. of Hurricanes	5	6	7	7	8
No. of Named Storms	9	10	12	12	14
No. of Hurricane Days	20	25	30	30	24
No. of Named Storm Days	45	50	60	60	59
Hurr. Destruction Potential(HDP)	65	65	75	75	65
Major Hurricanes (Cat. 3-4-5)	2	2	3	3	4
Major Hurr. Days	4	4	5	5	5
Net Trop. Cyclone Activity	90	100	120	120	132