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Statistical Aspects of the North Atlantic Basin Tropical Cyclones: Trends, Natural Variability, and Global Warming

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May 2007

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PREFACE

Hurricanes are one of nature's most destructive forces. Because more than half the population lives along the narrow coastal fringe of the U.S., with many living along the coasts from Texas to Maine, there is tremendous potential for loss of life and property should a hurricane's path pass through a heavily populated area. Thus, it is imperative to understand the mechanisms associated with hurricane formation and movement, especially as related to climate change and global warming, with the aim of improving forecasts both for the short term and the long term.

Since 1995, there has been a marked increase in the number of tropical cyclones forming in the North Atlantic basin, with the 2005 season having the highest number of storms on record. Efforts to accurately predict the well above-average 2005 season and the near average 2006 season, proved extremely difficult however, thus lending support to the Biblical adage:

"and I saw every work of God, I concluded that man cannot discover the work which has been done under the sun. Even though man should seek laboriously, he will not discover; and though the wise man should say, "I know," he cannot discover."

Ecclesiastes 8:17 (New American Standard Bible)

While true, it is important to continue predicting the expected activity for the next hurricane season, so that the public can be alerted to the potential for damage and loss of life that always exists should a hurricane form in the North Atlantic basin. It is to this end that this NASA Technical Publication has been written.

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AL	Alabama
AMO	Atlantic multidecadal oscillation
AT	Armagh Observatory surface air temperature
AT_{10}	10-yr moving average of AT
cl	confidence level
CT	Connecticut
D	duration
<D>h	mean duration of all seasonal hurricanes
<D>h$_{10}$	10-yr moving average of <D>h
<D>mh	mean duration of all seasonal major hurricanes
<D>mh$_{10}$	10-yr moving average of <D>mh
<D>s	mean duration of all seasonal tropical cyclones
<D>s$_{10}$	10-yr moving average of <D>s
EN	El Niño
ENSO	El Niño Southern Oscillation
FL	Florida
GA	Georgia
GL	genesis location
ITCZ	intertropical convergence zone
km	kilometer

LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS (Continued)

kt	knots; nautical mile per hour
LA	Louisiana
LF	landfall
LN	La Niña
LP	lowest pressure
LP_{10}	10-yr moving average of LP
<LP>h	mean LP of all seasonal hurricanes
<LP>h$_{10}$	10-yr moving average of <LP>h
<LP>s	mean LP of all seasonal tropical cyclones
<LP>s$_{10}$	10-yr moving average of <LP>s
m	mean
mb	millibar
mph	miles per hour
MA	Massachusetts
MD	Maryland
ME	Maine
MS	Mississippi
n	number of events
N	north latitude
N4/5	number of category 4 and/or 5 hurricanes
N4/5$_{10}$	10-yr moving average of N4/5

LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS (Continued)

NC	North Carolina
NH	New Hampshire; number of hurricanes
NH_{10}	10-yr moving average of NH
NMH	number of major hurricanes (category 3–5 hurricanes)
NMH_{10}	10-yr moving average of NMH
N(S)	number of seasons
NS	number of storms (tropical cyclones)
NS_{10}	10-yr moving average of NS
NUSLFH	number of U.S. landfalling hurricanes
NUSLFH_{10}	10-yr moving average of NUSLFH
NY	New York
Obs.	observed
P(*r*)	probability of obtaining *r*
PDI	power dissipation index
PWS	peak wind speed (during season)
PWS_{10}	10-yr moving average of PWS
<PWS>h	mean PWS of all seasonal hurricanes
$\langle\mathrm{PWS}\rangle\mathrm{h}_{10}$	10-yr moving average of <PWS>h
<PWS>s	mean PWS of all seasonal tropical cyclones
$\langle\mathrm{PWS}\rangle\mathrm{s}_{10}$	10-yr moving average of <PWS>s
QBO	quasi-biennial oscillation

LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS (Continued)

r	correlation coefficient; random variable
r^2	coefficient of determination
RI	Rhode Island
sd	standard deviation
se	standard error of estimate
SC	South Carolina
SNBR	storm number
SOI	southern oscillation index
SST	sea surface temperature
t	t-statistic for independent samples
TX	Texas
VA	Virginia
W	west longitude
WS	wind speed
x	independent variable
y	dependent variable; regression
Δx_{10}	parametric rate of change in 10-yr moving average (where x=NS, NH, …)

TECHNICAL PUBLICATION

STATISTICAL ASPECTS OF THE NORTH ATLANTIC BASIN TROPICAL CYCLONES: TRENDS, NATURAL VARIABILITY, AND GLOBAL WARMING

1. INTRODUCTION

A tropical cyclone is a nonfrontal synoptic-scale low-pressure system that forms over the warm tropical or subtropical waters (at least 26.5 °C or 80 °F) and that has organized convection and cyclonic surface wind circulation.[1,2] When sustained winds are below 34 kt, (61 km/hr or 39 mph), it is referred to as a tropical depression, while when its sustained winds are ≥34 kt it becomes a tropical cyclone or tropical storm. When winds are at least 64 kt (119 km/hr or 74 mph), it is a hurricane (or typhoon in the Northwest Pacific Ocean or severe tropical cyclone in the Southwest Pacific Ocean and Southeast Indian Ocean), and when winds are at least 96 kt (178 km/hr or 111 mph), it becomes classified as an intense or major hurricane. Intense or major hurricanes are those classified as category 3 or higher on the Saffir-Simpson Hurricane Scale, a one through five intensity scale used to estimate potential property damage (<http://www.nhc.noaa.gov/aboutsshs.shtml>).

A tropical cyclone derives its energy primarily from the evaporation of water from the ocean and the associated condensation in the convective clouds near its center of circulation. A characteristic of the tropical cyclone is its warm core structure that produces very strong winds near the surface causing high storm surge, flooding, and coastal erosion through wave action.

Owing to the routine use of aircraft reconnaissance and continuous satellite viewing, from the 1960s, the North Atlantic basin (including the North Atlantic Ocean, the Gulf of Mexico, and the Caribbean Sea) has the most complete and reliable record of tropical cyclonic activity, extending from the mid-1940s to the present.[3–4] It is this record, available at <http://www.nhc.noaa.gov/tracks1851to2005_atl.txt>, that will be examined in this NASA Technical Publication (TP).

Previous examination of the number of North Atlantic basin tropical cyclones has revealed considerable yr-to-yr variability, with little evidence for the presence of a significant trend.[1,4] In contrast, intense cyclones (major hurricanes) have exhibited a pronounced downward trend from the mid-1940s through the early 1990s, although close inspection suggests that the change over time may have been somewhat more abrupt than a simple linear decrease.[4–6] Additionally, a decrease in the mean intensity of the North Atlantic basin tropical cyclones has been seen, although the maximum intensity reached in any single yr has shown no appreciable change.[5] The very active mid-to-late 1990s suggests a return to a more active state than was seen during the 1970s and 1980s.[7,8] Hence, these behavioral changes over time may reflect a natural variability of multidecadal timescale and/or, perhaps, an increased sensitivity to recent global warming.[9–36]

This study examines the 1945–2005 North Atlantic basin tropical cyclone record, particularly the statistics of the storm trends including number, peak wind speed (PWS), lowest pressure (LP), duration (D), and parametric interrelationships including those against global temperature.

2. RESULTS AND DISCUSSION

2.1 The Frequency of Occurrence and Statistics of the North Atlantic Basin Tropical Cyclones (1945–2005)

Figure 1 (panel a) displays the yearly number of storms (NS) with sustained wind speed (WS) ≥34 kt that formed in the North Atlantic basin between 1945 and 2005, some 646 events. The thin jagged line is the yearly count and the thick smooth line is the 10-yr moving average. Between 1945 and 2005 the average NS per yr (thin horizontal line) measures 10.6 with a standard deviation (*sd*) of 3.9 and a range of 4 (in 1983) to 28 (in 2005). Prior to 1995, the highest NS per yr occurred in 1969 (18 events). All years from 1995, except 1997, have had yearly counts higher than the mean (*m*), with 2005 having 28 events—the highest number ever recorded. Compared to the long-term mean, the 2005 count is about 4.5 *sd* higher. The 10-yr moving average reflects the general trend, which has been upward since about 1989, becoming larger than the mean in 1992, and measuring about 14.4 in 2000 (the last entry). While both the NS mean and *sd* for the most recent years (1975–2005) are larger than the mean and *sd* for the earlier years (1945–1974), being 11.3 as compared to 9.9 (*m*) and 4.7 as compared to 2.8 (*sd*), hypothesis testing of the difference in means for the two independent samples of NS reveals that the difference is not statistically important (t=1.407, or at <90-percent confidence level (*cl*) for the given sample sizes). However, if one presumes the existence of more active (1945–1969 and 1995–2005; see in the discussion of panels c–e) and less active intervals (1970–1994), then hypothesis testing suggests that the difference in means (11.5 versus 9.3) is statistically important (t=2.223, or at *cl* ≥95 percent for the given sample sizes). Compared to the mean number of events for the more active interval, the 28 events for 2005 is about 3.6 *sd* higher. Hence, 2005 stands out as a most unusual yr, especially for NS.

Figure 1 (panel b) displays the number of hurricanes (NH) with sustained WS ≥64 kt that formed in the North Atlantic basin between 1945 and 2005, some 376 events. The format follows that for NS. The long-term mean equals 6.2, the *sd* equals 2.6, and the range equals 2 (1982) to 15 (2005). The trend has been upward since about 1989, becoming larger than the mean in 1994 and measuring 8.0 in 2000. As seen for NS, the mean and *sd* of NH for the most recent years are larger than for the earlier years, being 6.4 as compared to 6.0 (*m*) and 2.9 as compared to 2.3 (*sd*), yet the difference in means is not statistically important (t=0.596). However, as before, by presuming the existence of more active and less active intervals the difference in means (6.9 versus 5.0) is statistically important (t=3.023, or at *cl* ≥99.5 percent for the given sample sizes). Compared to the long-term mean, the 15 events for 2005 is about 3.4 *sd* higher, while being about 2.9 *sd* higher when compared against the mean for the more active interval.

Figure 1 (panel c) displays the number of major hurricanes (NMH) with sustained WS ≥96 kt that formed in the North Atlantic basin between 1945 and 2005, some 162 events. Again, the format follows that for NS and NH. The long-term mean equals 2.7, the *sd* equals 1.9, and the range equals 0 (in 1968, 1972, 1986, and 1994) to 8 (1950). The behavior of the 10-yr moving average suggests that the NMH has decreased from a predominantly more active interval in the 1950s and 1960s to a predominantly less active interval in the 1970s and 1980s. Since the mid-1990s, however, it has increased again to another

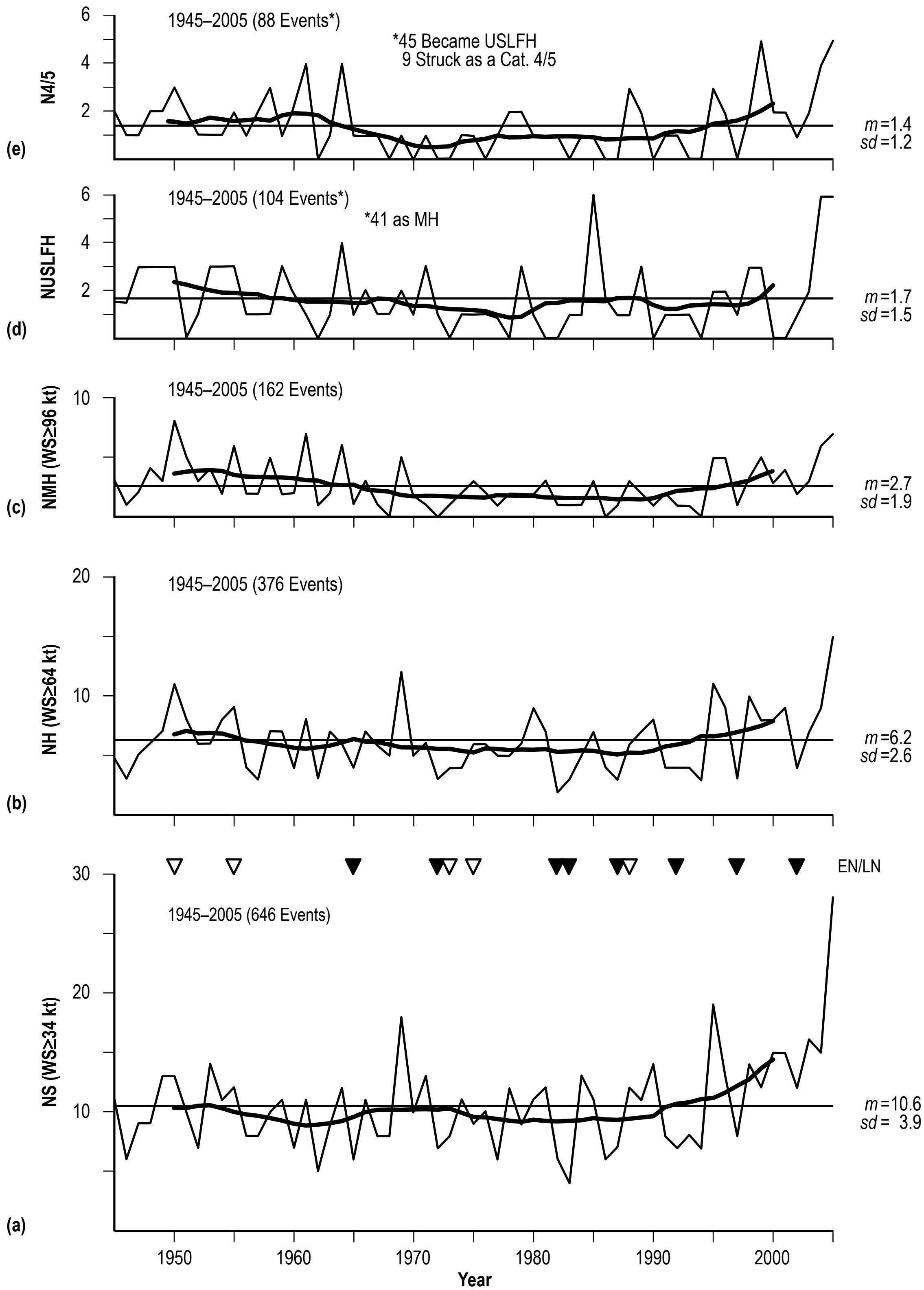


Figure 1. The yearly variation of NS (panel a), NH (panel b), NMH (panel c), NUSFLH (panel d), and N4/5 (panel e) for the interval 1945–2005. The thin jagged lines are the yearly numbers, the thick smooth lines are the 10-yr moving averages, and the thin horizontal lines are the long-term means.

predominantly more active interval, although the yearly values have not, as yet, exceeded that which was seen in the former more active interval. Using the same dates as previously used for NS and NH to define the more active and less active intervals, hypothesis testing reveals the difference in means (3.4 versus 1.5) to be statistically very important (t=4.440, or at cl≥99.9 percent for the given sample sizes). Compared to the long-term mean, the seven events for 2005 is about 2.3 *sd* higher, while being only about 1.8 *sd* higher when compared against the mean for the more active interval.

Figure 1 (panel d) displays the number of U.S. landfalling hurricanes (NUSLFH) that occurred between 1945 and 2005, some 104 events, of which 41 struck as major hurricanes. As before, the format follows that for NS, NH, and NMH. The long-term mean equals 1.6, the *sd* equals 1.4, and the range equals 0 (in 1951, 1962, 1973, 1978, 1981, 1982, 1990, 1994, 2000, and 2001) to 6 (2005). Interestingly, the behavior of the 10-yr moving average seems to mimic the behavior of the NMH, with more landfalls during the 1950s and 1960s, reaching a low in the 1970s and 1980s, and then increasing again afterwards to values above the long-term mean in the late 1990s. Compared to the long-term mean, the six events for 2005 is about 2.9 *sd* higher, while being about 2.7 *sd* higher when compared against the mean for the more active interval. (Predicting the NUSLFH in advance of a season, especially the states where landfall occurs, is somewhat foolhardy because one cannot reliably predict the path for any specific storm without first knowing exactly the specific climatology that is being encountered at that time).

Figure 1 (panel e) displays the number of category 4 and/or 5 hurricanes (N4/5) that formed in the North Atlantic basin between 1945 and 2005, some 88 events, of which 45 became U.S. landfalling hurricanes and 9 struck as a category 4 or 5 storm. The long-term mean equals 1.4, the *sd* equals 1.2, and the range is 0 (in 1962, 1968, 1970, 1972, 1973, 1976, 1983, 1986, 1987, 1990, 1993, 1994, and 1997) to 5 (in 1999 and 2005). The trend has been upward since 1990, rising above the long-term mean in 1995. Compared to the long-term mean, the five events for 2005 are about 3.0 *sd* higher, while being about 2.4 *sd* higher when compared against the mean for the more active interval.

Also shown in figure 1 (panel a above the NS plot) is a series of filled and unfilled triangles representing, respectively, the occurrences of El Niño (EN) and La Niña (LN) years as determined using the best ENSO Index developed by Catherine Smith and Prashant Sardeshmukh (available at http://www.cdc.noaa.gov/people/cathy.smith/best/).[37] This particular series combines the effects of both an atmospheric process, the southern oscillation index (SOI) with an oceanic process, the sea surface temperature (SST), for Niño 3.4 (5N–5S and 120–170W). In particular, Smith and Sardeshmukh have generated a table of monthly values from 1871 to 2005 of 5-mo running means expressed by a series of 0s (neutral), 1s (El Niño), and –1s (La Niña). In this TP, a yr is called an El Niño yr when it has at least three consecutive 1s occurring in the interval of March–November and a La Niña yr when it has at least three consecutive –1s occurring in the interval of March–November. Thus, on the basis of this particular series, there are eight El Niño years (1965, 1972, 1982, 1983, 1987, 1992, 1997, and 2002) and five La Niña years (1950, 1955, 1973, 1975 and 1988) between 1945 and 2005. It should be noted that the list presented here, based on the Smith-Sardeshmukh series, has fewer events as compared to other less restrictive listings; see, for example, http://ggweather.com/enso/years.htm.

Interestingly, three El Niño events are found to occur during the presumed more active interval and five during the less active interval, while two La Niña events are found to occur during the first more active interval (none, as yet, during the current more active interval) and three during the less active interval.

Hence, the occurrences of El Niño and La Niña events occur independently of the ongoing activity level (more versus less) presumed to be modulating the North Atlantic basin tropical cyclones. Based on the list of El Niño and La Niña events, El Niño events have occurred, on average, about every 5 yr, having an *sd* of about 3 yr, and a range of 1–10 yr, with the last El Niño having occurred in 2002, and La Niña events have occurred, on average, about every 10 yr, having an *sd* of about 7 yr, and a range of 2–18 yr, with the last La Niña having occurred in 1988.

It is apparent from figure 1 that El Niño years generally associate with depressed tropical cyclone activity in the North Atlantic basin, especially as compared to La Niña years. For the eight El Niño years, the mean, *sd*, and range for NS are, respectively, 7.1, 2.3, and 6–12; for NH 3.3, 0.7, and 2–4; for NMH 1.0, 0.5, and 0–2; for NUSLFH 0.9, 0.4, and 0–1; and for N4/5 0.5, 0.5, and 0–1. For the five La Niña years, the mean, *sd*, and range for NS are, respectively, 10.8, 2.2, and 8–13; for NH 7.2, 2.8, and 4–11; for NMH 4.2, 2.8, and 1–8; for NUSLFH 1.6, 1.3, and 0–3; and for N4/5 1.8, 1.3, and 0–3. The difference in means is statistically important for all subgroups except for NUSLFH. Thus, knowing in advance that a season will be characterized as an El Niño yr, one probably would forecast seasonal counts for the various subgroups less than or equal to their long-term averages. On the other hand, knowing in advance that a season will be characterized as a non-El Niño yr (either a neutral yr or a La Niña yr), one probably would forecast seasonal counts for the various subgroups of either average or above average size, dependent upon the specific level of activity (more versus less) currently in vogue. Unfortunately, a season like the 2005 season would be nearly impossible to accurately predict on the basis of such a simple statistical climatology.

Table 1 gives 5-yr counts for NS, NH, NMH, NUSLFH/NMH, N4/5, and N(LP <925 mb) for 1945–2004, where the term N(LP <925 mb) is the number of such events that occurred during the specific 5-yr interval, along with the names of the storms. The counts for 2005 are also given for comparison. At the bottom of the table are the median, mean, and *sd* for each subgroup and for the two separate time intervals, 1945–1994 and 1945–2004. On the basis of the twelve 5-yr intervals during the span of 1945–2004, one finds that, on average, there were 51.5 NS, 30.1 NH, 12.9 NMH, 8.2 NUSLFH (with 3.0 striking as major hurricanes), 6.9 N4/5, and 1.3 N(LP <925 mb). Because the 2005 counts are quite large, being respectively 28, 15, 7, 6/4, 5, and 3, it might be that this is an indication that the next interval of 2005–2009 will possibly see counts that will exceed the record and near-record intervals that were seen in 1995–1999 and 2000–2004.

Table 2 gives the monthly frequency of occurrence for the aforementioned subgroups. For NS, every month except March has seen the formation of at least one tropical cyclone in the North Atlantic basin during the interval of 1945–2005, with September representing the peak (about 34 percent of the total) and August–October accounting for about 78 percent of the total. November (the last official month of a hurricane season) accounts for about 5 percent of the total, and June–July (the opening months of the official hurricane season) account for about 14 percent of the total. For NH and NMH, September accounts for about 39 and 52 percent of the totals, respectively, and December–April have either no occurrences (NMH) or only a few occurrences (NH=3). For NUSLFH, none have occurred during the span of December–May, as is the case for N4/5. The most powerful North Atlantic basin tropical cyclones, N(LP <925mb) occurred exclusively in the span of August–October. Interestingly, only one of these, Andrew, occurred during an El Niño yr and two, Janet and Gilbert, occurred during La Niña years. Hence, the bulk of the most powerful storms (15 of 18 events) occurred during ENSO-neutral years. For the El Niño and La Niña years in table 2, the subgroup NUSLFH displays two sets of numbers for the

Table 1. Five-yr statistics of North Atlantic basin tropical cyclones.

5-Yr Interval	NS	NH	NMH	NUSLFH/ NMH	N4/5	N (LP<925 mb)
1945–1949	48	26	13	13/4	8	0
1950–1954	55	39	22	10/5	8	0
1955–1959	49	30	17	9/5	9	1 (Janet)
1960–1964	44	28	18	8/3	11	1 (Hattie)
1965–1969	51	34	10	7/3	4	2 (Beulah, Camille)
1970–1974	49	22	6	6/2	2	0
1975–1979	46	28	10	6/2	6	1 (David)
1980–1984	46	26	8	3/2	4	1 (Allen)
1985–1989	47	27	9	13/3	6	3 (Gloria, Gilbert, Hugo)
1990–1994	44	23	5	3/2	2	1 (Andrew)
1995–1999	66	41	19	11/3	12	3 (Opal, Mitch, Floyd)
2000–2004	73	37	18	9/3	11	2 (Isabel, Ivan)
2005–2009	(28)	(15)	(7)	(6/4)	(5)	(3) (Katrina, Rita, Wilma)
Median (1945–1994)	47.5	27.5	10.0	7.5/3.0	6.0	1.0
m (1945–1994)	47.9	28.3	11.8	7.8/3.1	6.0	1.0
sd (1945–1994)	3.3	5.1	5.6	3.6/1.2	3.0	0.9
Median (1945–2004)	48.5	28.0	11.5	8.5/3.0	7.0	1.0
m (1945–2004)	51.5	30.1	12.9	8.2/3.0	6.9	1.3
sd (1945–2004)	9.1	6.2	5.7	3.4/1.1	3.5	1.1

months, the first being the actual number of such events and the second being the number of such events that struck as major hurricanes.

Figure 2 displays the yearly variation of the average genesis location (GL) of the North Atlantic basin tropical cyclones (N latitude, left panels; W longitude right panels), when the storms first attained tropical WS (bottom panels), and when they first attained hurricane WS (top panels). The thin jagged lines are the yearly values and the thick smooth lines 10-yr moving average. The mean and *sd* are also given for each. Thus, prior to about 1965, on average, tropical cyclones and hurricanes usually formed at latitudes below the long-term mean, while in the late 1960s to about 1990, they usually formed at latitudes above the long-term mean. Since about 1990, there appears to have been a return to lower latitudes for the usual sites of storm formation. Concerning the average longitude for usual storm formation, it has been below (eastward) the long-term mean since the mid-1980s.

Figure 3 shows the progression of the yearly centroid based on the 10-yr moving averages of latitude and longitude, given in figure 2, for storm formation, with tropical cyclones in the lower panel and hurricanes in the upper panel. Time ticks are given to show the reader the direction of actual yearly movements (along the dotted line). Thus, for both tropical cyclones and hurricanes, the 1950s saw the average centroid of storm formation occurring in the lower left quadrant, indicating formations deeper in the tropics and closer to the U.S. The progression, however, moved upward (more northward) and to the right (more eastward) in the 1960s (the lower right and upper right quadrants), then into the upper left

Table 2. Monthly statistics of North Atlantic basin tropical cyclones 1945–2005.

Group	Frequency of Occurrence												
	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Total
NS	1	1	0	2	8	35	55	171	220	113	33	7	646
NH	0	0	0	0	2	11	21	96	147	73	23	3	376
NMH	0	0	0	0	1	3	4	38	84	27	4	0	161
NUSLFH	0	0	0	0	0	4	10	27	46	16	1	0	104
N4/5	0	0	0	0	0	1	2	29	44	9	3	0	88
N (LP<925 mb)	0	0	0	0	0	0	0	5	9	4	0	0	18
	El Niño Yr (1965, 1972, 1982, 1983, 1987, 1992, 1997, 2002)												
NS	0	0	0	1	1	5	5	14	24	6	1	0	57
NH	0	0	0	0	0	2	2	7	12	3	0	0	26
NMH	0	0	0	0	0	0	0	2	5	1	0	0	8
NUSLFH	0	0	0	0	0	1/0	1/0	2/2	1/1	2/0	0	0	7/3
N4/5	0	0	0	0	0	0	0	2	2	0	0	0	4
N (LP<925 mb)	0	0	0	0	0	0	0	1	0	0	0	0	1 (Andrew)
	La Niña Yr (1950, 1955, 1973, 1975, 1988)												
NS	0	0	0	0	0	1	4	15	20	12	1	1	54
NH	0	0	0	0	0	0	2	10	15	8	1	0	36
NMH	0	0	0	0	0	0	0	6	10	6	0	0	22
NUSLFH	0	0	0	0	0	0	0	2/1	5/3	1/1	0	0	8/5
N4/5	0	0	0	0	0	0	0	3	5	1	0	0	9
N (LP<925 mb)	0	0	0	0	0	0	0	0	2	0	0	0	2 (Janet, Gilbert)

quadrant in the 1970s. In the 1980s, the movement was to the right (the upper right quadrant), and in the 1990s it was downward (the lower right quadrant). Presently for the year 2000, the last available entry, the average centroid of storm formation is in the lower right quadrant, indicating a return to lower tropical latitudes for usual storm formation, but eastward of the long-term mean longitude.

Table 3 provides a convenient list of the 104 North Atlantic basin tropical cyclones that made U.S. landfall (LF) as a hurricane during the interval of 1945–2005. The storm number (SNBR), name of the storm (when named), LF date, state or states where LF occurred, category of the hurricane at LF, and GL of the storms (when they first attained tropical storm WS, when they first attained hurricane WS, and when they first attained major hurricane WS) are given in the table. All these data are available at <http://www.nhc.noaa.gov/tracks1851to2005_atl.txt>. The GLs are given as degrees N degrees W.

Inspection of table 3 shows that the earliest LF occurred June 9, 1966 (Alma, SNBR=910) and the latest occurred on November 21, 1985 (Kate, SNBR=1106). Most LF hurricanes are found

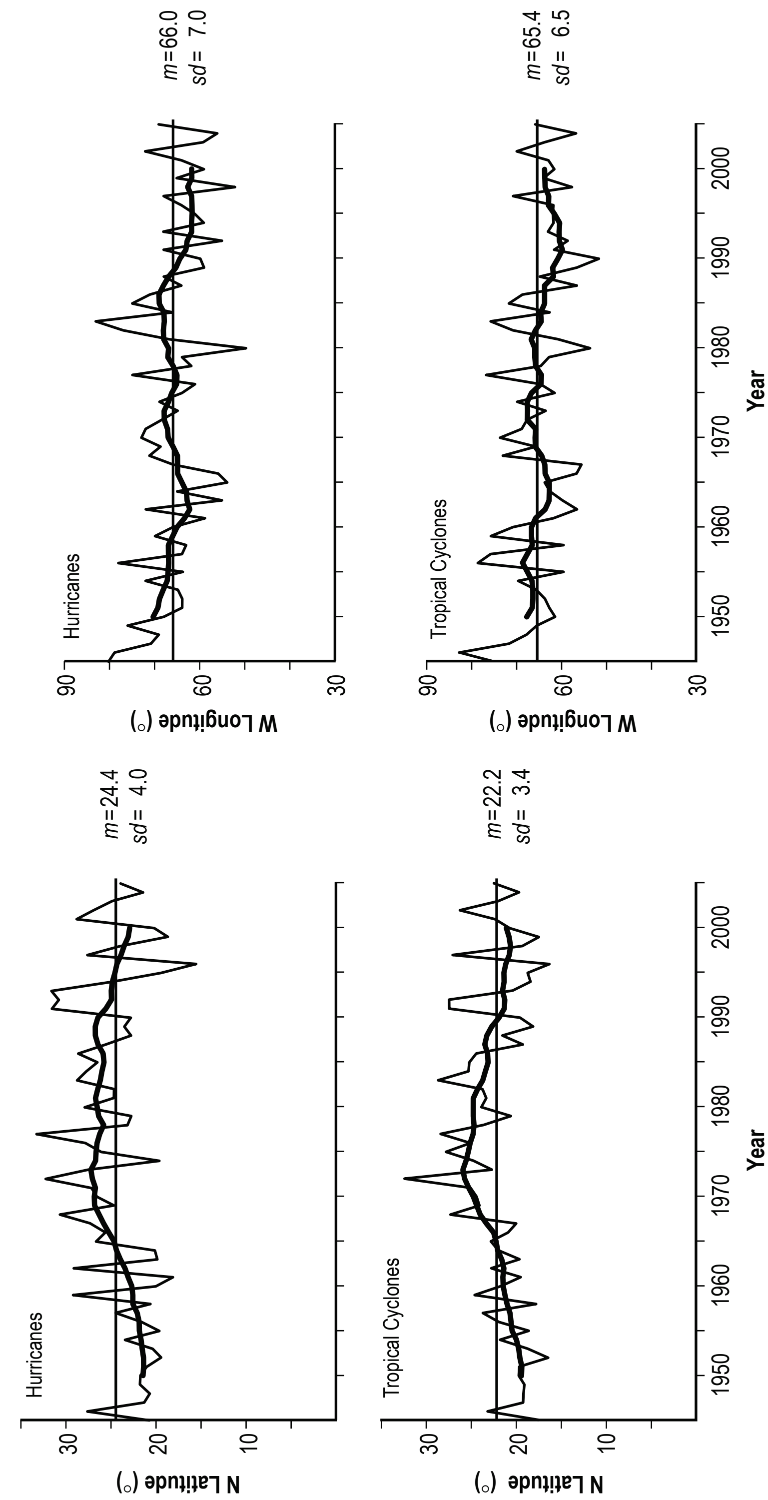
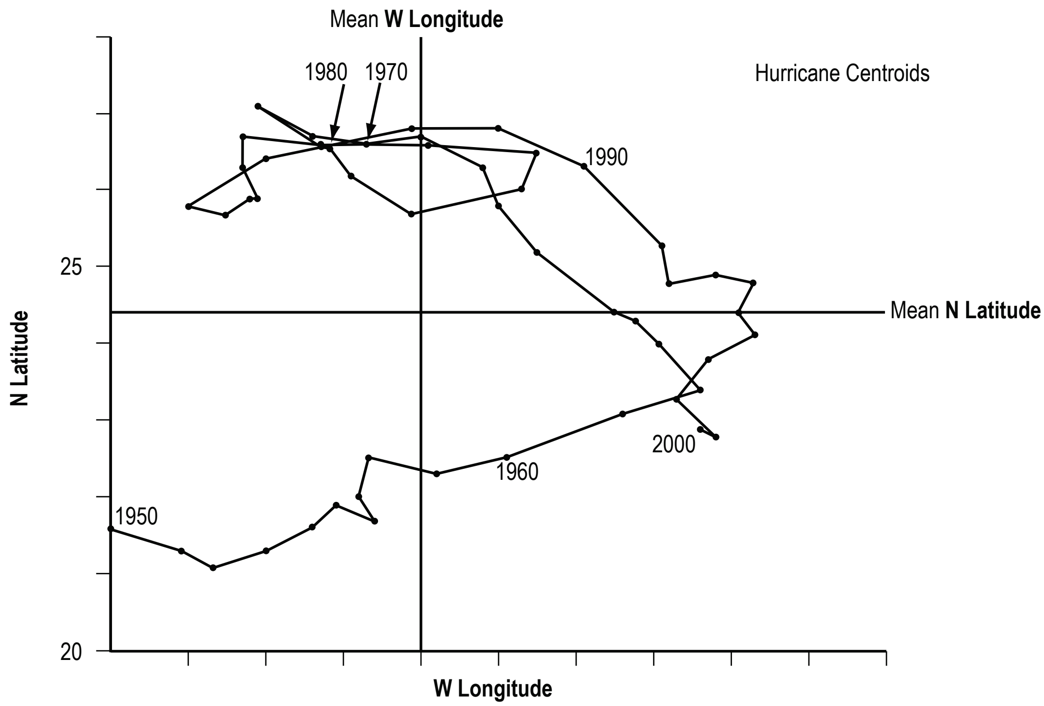


Figure 2. The yearly GL variation of the mean N-latitudinal position for tropical cyclones (lower left panel) and hurricanes (upper left panel) and the yearly GL variation of the mean W-longitudinal position for tropical cyclones (lower right panel) and hurricanes (upper right panel).The thin jagged lines are the yearly values, the thick smooth lines are the 10-yr moving averages, and the thin horizontal lines are the long-term means.



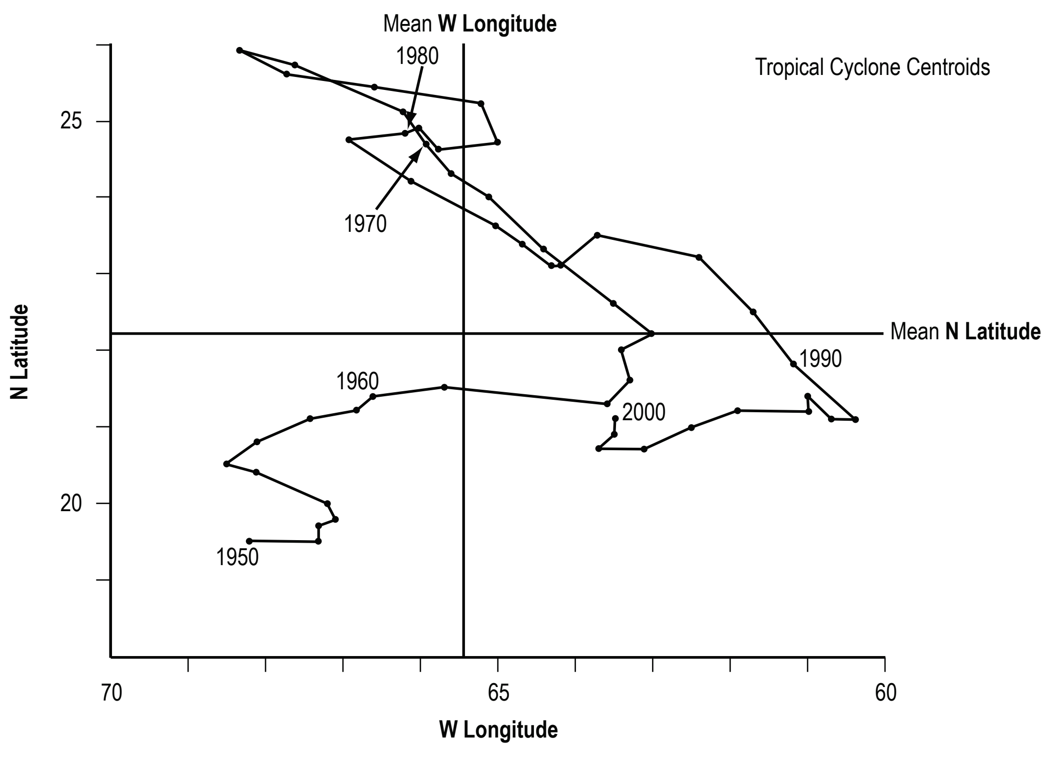


Figure 3. The time-ticked variation of the GL centroids, latitude, and longitude for tropical cyclones (lower panel) and hurricanes (upper panel). The thin vertical and horizontal lines are the long-term means.

Table 3. List of U.S. landfalling hurricanes 1945–2005.

SNBR	Name	LF Date	LF State/Category	GL (TS)	GL (H)	GL (MH)
0708		1945–07–23	FL1	17.5, 85.7	27.6, 85.6	27.6, 85.6
0712		1945–08–27	TX2	19.4, 94.0	21.6, 95.2	26.6, 96.8
0716		1945–09–15	FL3	19.0, 56.6	19.0, 56.6	20.4, 68.3
0723		1946–10–07	FL1	18.0, 87.2	19.6, 85.6	22.3, 84.1
0727		1947–08–24	TX1	24.0, 80.0	26.5, 90.6	
0728		1947–09–17,18	FL4, LA3, MS3, FL2	14.5, 20.1	14.1, 24.0	16.1, 54.7
0732		1947–10–15	GA2, SC2, FL1	15.4, 82.0	24.1, 82.3	
0738		1948–09–03	LA1	23.8, 94.7	25.8, 92.6	
0740		1948–09–21	FL3, FL2	18.2, 78.8	18.5, 80.8	22.8, 82.0
0741		1948–10–05	FL2	15.3, 81.8	19.4, 85.1	22.2, 83.3
0743		1949–08–24	NC1	21.3, 62.6	22.3, 64.7	
0744		1949–08–25	FL3	18.2, 60.0	23.4, 73.0	24.6, 76.4
0752		1949–10–03	TX2	12.5, 89.5	22.0, 94.3	26.0, 95.5
0757	Baker	1950–08–30	AL1	16.3, 55.0	16.5, 57.4	16.7, 60.0
0760	Easy	1950–09–04	FL3	19.1, 84.1	21.0, 82.8	26.9, 83.2
0766	King	1950–10–17	FL3	16.0, 84.2	18.2, 79.6	20.9, 78.5
0780	Able	1952–08–30	SC1	16.4, 51.2	21.9, 64.7	
0787	Barbara	1953–08–13	NC1	22.8, 73.9	29.2, 75.9	
0789	Carol	1953–09–07	ME1	10.6, 37.7	14.2, 49.5	17.3, 56.3
0793	Florence	1953–09–26	FL1	16.9, 75.8	20.9, 85.0	23.4, 87.0
0802	Carol	1954–08–31	NY3, CT3, RI3, NC2	25.1, 75.5	28.9, 76.2	
0804	Edna	1954–09–11	MA3, ME1	19.3, 62.8	22.2, 70.8	25.9, 75.2
0808	Hazel	1954–10–15	SC4, NC4, MD2	12.4, 59.2	12.8, 61.1	13.3, 67.2
0812	Connie	1955–08–12	NC3, VA1	15.7, 39.2	18.0, 54.9	18.3, 56.6
0813	Diane	1955–09–17	NC1	18.9, 54.3	24.0, 61.1	25.3, 60.8
0819	Ione	1955–09–19	NC3	15.4, 44.2	19.3, 62.3	26.5, 72.7
0829	Flossy	1956–09–23,24	LA2, FL1	22.2, 89.8	26.9, 91.0	
0832	Audrey	1957–06–27	TX4, LA4	21.6, 93.3	22.0, 93.4	27.9, 93.8
0846	Helene	1958–09–27	NC3	22.5, 64.8	26.7, 72.0	31.0, 77.1
0852	Cindy	1959–07–08	SC1	31.5, 77.1	32.3, 78.2	
0853	Debra	1959–07–24	TX1	27.5, 93.1	28.3, 95.4	
0856	Gracie	1959–09–29	SC3	21.8, 74.1	23.3, 73.0	29.4, 77.1
0864	Donna	1960–09–09,11,12	FL4, NC3, NY3, FL2, CT2, RI2, MA1, NH1, ME1	10.3, 26.9	12.2, 39.4	13.3, 44.3
0865	Ethel	1960–09–15	MS1	23.9, 90.6	25.6, 89.7	27.0, 89.1
0869	Carla	1961–09–11	TX4	16.3, 82.7	18.8, 85.1	22.3, 87.3
0886	Cindy	1963–09–17	TX1	26.7, 93.7	28.0, 93.9	
0896	Cleo	1964–08–27	FL2	13.4, 46.8	14.1, 51.3	15.3, 57.8
0897	Dora	1964–09–09	FL2	11.7, 47.0	17.8, 56.5	24.0, 62.1
0901	Hilda	1964–09–29	LA3	22.0, 84.2	23.4, 88.1	24.2, 90.1
0902	Isbell	1964–10–14	FL2, FL2	20.0, 85.0	21.7, 84.5	23.2, 83.6
0906	Betsy	1965–09–08,09	FL3, LA2	19.2, 63.4	21.2, 64.7	22.8, 70.2

Table 3. List of U.S. landfalling hurricanes 1945–2005 (Continued).

SNBR	Name	LF Date	LF State/Category	GL (TS)	GL (H)	GL (MH)
0910	Alma	1966–06–09	FL2	18.1, 84.2	18.5, 84.1	24.2, 82.4
0918	Inez	1966–10–04	FL1	14.8, 48.7	15.8, 56.0	16.1, 60.4
0922	Beulah	1967–09–20	TX3	13.9, 60.8	14.7, 62.9	15.8, 65.1
0936	Gladys	1968–10–18	FL2, FL1	19.4, 83.3	21.7, 83.5	
0939	Camille	1969–08–17	LA5, MS5	19.4, 82.0	20.7, 83.8	21.2, 84.1
0943	Gerda	1969–09–09	ME1	29.7, 79.7	32.0, 78.0	37.8, 72.2
0957	Celia	1970–08–03	TX3	23.3, 85.8	24.3, 87.2	24.3, 87.2
0970	Edith	1971–09–16	LA2	12.7, 69.1	13.2, 73.8	14.2, 80.5
0971	Fern	1971–09–10	TX1	26.9, 92.6	26.4, 93.7	
0972	Ginger	1971–09–30	NC1	27.7, 66.1	27.9, 63.3	
0979	Agnes	1972–06–19	FL1, NY1, CT1	20.0, 86.2	23.8, 85.6	
0998	Carmen	1974–09–07	LA3	17.0, 67.4	17.0, 76.0	17.7, 83.2
1008	Eloise	1975–09–23	FL3	19.0, 65.6	19.5, 68.4	28.4, 87.3
1015	Belle	1976–08–09	NY1	25.6, 73.2	26.6, 74.2	29.5, 75.3
1024	Babe	1977–09–05	LA1	27.6, 88.5	28.7, 91.4	
1042	Bob	1979–07–11	LA1	23.5, 93.8	26.2, 91.6	
1044	David	1979–09–03,04	FL2, FL2, GA2, SC2	11.6, 42.2	11.8, 48.5	12.2, 52.9
1046	Frederic	1979–09–12	AL3, MS3	11.5, 36.0	12.9, 48.7	25.7, 85.8
1050	Allen	1980–08–09	TX3	11.0, 42.8	12.4, 51.4	13.3, 59.1
1079	Alicia	1983–08–17	TX3	27.2, 91.0	27.4, 93.3	28.9, 95.0
1087	Diana	1984–09–13	NC2	28.5, 77.4	30.5, 80.0	32.6, 78.4
1097	Bob	1985–07–24	SC1	26.2, 83.8	30.5, 80.5	
1099	Danny	1985–08–15	LA1	23.7, 87.8	26.8, 91.5	
1100	Elena	1985–09–02	AL3, MS3, FL3	22.6, 80.0	25.0, 85.0	28.6, 83.9
1102	Gloria	1985–09–17	NC3, NY3, CT2, NH2, ME1	14.6, 28.3	17.7, 55.3	21.9, 66.8
1105	Juan	1985–10–28,29	LA1	23.8, 92.5	27.8, 91.2	
1106	Kate	1985–11–15	FL2	21.1, 63.8	21.1, 65.3	25.2, 85.3
1108	Bonnie	1986–06–25	TX1	26.6, 89.5	27.7, 92.2	
1109	Charley	1986–08–17	NC1	32.2, 78.5	34.4, 76.6	
1119	Floyd	1987–10–12	FL1	16.0, 82.2	24.0, 82.9	
1126	Florence	1988–09–09	LA1	22.7, 90.2	27.4, 89.2	
1134	Chantal	1989–08–01	TX1	25.4, 91.0	27.9, 92.8	
1139	Hugo	1989–09–21	SC4	12.5, 29.2	12.8, 43.5	13.8, 50.5
1141	Jerry	1989–10–15	TX1	20.4, 93.0	28.1, 94.6	
1158	Bob	1991–18–19	NY2, RI2, MA2	26.4, 75.8	29.0, 77.1	36.5, 74.5
1166	Andrew	1992–08–23,25	FL5, FL4, LA3	12.3, 42.0	25.6, 67.0	25.6, 71.1
1176	Emily	1993–09–01	NC3	28.0, 60.4	26.9, 61.7	34.5, 75.2
1191	Erin	1995–08–01	FL1, FL2	22.3, 73.2	23.6, 74.9	
1201	Opal	1995–10–04	FL3	21.1, 88.5	21.0, 92.3	24.5, 90.1
1207	Bertha	1996–07–12	NC2	11.0, 39.0	16.5, 58.4	20.3, 67.7
1211	Fran	1996–09–05	NC3	14.6, 44.9	16.4, 53.7	26.4, 73.9
1223	Danny	1997–07–17,19	LA1, AL1	28.3, 91.4	29.2, 89.9	

Table 3. List of U.S. landfalling hurricanes 1945–2005 (Continued).

SNBR	Name	LF Date	LF State/Category	GL (TS)	GL (H)	GL (MH)
1228	Bonnie	1998–08–26	NC2	17.3, 57.3	21.1, 67.3	24.1, 71.5
1231	Earl	1998–09–02	FL1	22.4, 93.8	28.2, 89.0	
1233	Georges	1998–09–28	FL2, MS2	10.6, 31.3	12.3, 40.0	14.9, 52.0
1242	Bret	1999–08–22	TX3	19.8, 94.7	21.9, 94.5	24.7, 95.1
1246	Floyd	1999–09–15	NC2	15.3, 48.2	19.3, 58.8	23.0, 66.2
1249	Irene	1999–10–15	FL1	18.5, 83.4	23.8, 82.2	
1294	Lili	2002–10–03	LA1	12.1, 54.6	19.6, 79.6	23.6, 87.2
1297	Claudette	2003–07–15	TX1	13.2, 59.8	17.5, 82.8	
1303	Isabel	2003–09–18	NC2, VA1	13.9, 32.7	14.4, 37.3	17.1, 42.0
1311	Alex	2004–08–03	NC1	31.6, 79.2	33.0, 77.4	38.5, 66.0
1313	Charley	2004–08–13,14	FL4, FL1, FL1, SC1, NC1	12.9, 65.3	16.7, 76.8	23.0, 82.6
1316	Frances	2004–09–05	FL2, FL1	11.5, 39.8	13.3, 45.8	15.4, 49.3
1317	Gaston	2004–08–29	SC1	31.3, 78.2	32.8, 79.5	
1319	Ivan	2004–09–16	AL3, FL3	09.7, 30.3	09.5, 43.4	10.2, 46.8
1320	Jeanne	2004–09–26	FL3, FL1, FL1	16.4, 62.6	18.6, 68.5	26.6, 76.9
1328	Cindy	2005–07–06	LA1	25.1, 90.2	28.5, 90.3	
1329	Dennis	2005–07–10	FL3	13.0, 65.9	16.2, 73.0	18.5, 76.1
1336	Katrina	2005–08–28,29	FL1, LA3, MS3, AL1	24.5, 76.5	25.9, 80.3	24.4, 84.7
1340	Ophelia	2005–09–15	NC1	27.9, 78.8	28.6, 79.3	
1342	Rita	2005–09–24	LA3, TX2	22.2, 72.3	23.7, 80.3	24.2, 84.0
1347	Wilma	2005–10–24	FL3, FL2	16.9, 79.6	16.2, 80.3	16.6, 81.8

to occur in September, accounting for nearly half the total (table 2). Eighty-six percent of the total NUSLFH occur in the span of August–October. Only Camille, in 1969, and Andrew, in 1992, have struck the U.S. as category 5 storms. Katrina and Rita struck Louisiana as category 3 storms in 2005, and Wilma struck Florida as a category 3 storm, also in 2005.

Table 4 lists the various states that have experienced landfalling hurricanes, number of landfalling category 1–2 hurricanes, number of landfalling category 3–5 hurricanes (major hurricanes), total number of landfalling hurricanes, and the proportion, as compared to the 104 NUSLFH that have been recorded. By far, the state of Florida has experienced the most landfalling hurricanes (both category 1–2 and 3–5) with nearly 37 percent of all landfalling hurricanes striking the state. The state of Alabama ranks seventh, being tied with the state of New York, both having been struck by three category 1–2 storms and three category 3–5 storms, accounting for nearly 6 percent of the total NUSLFH. The three major hurricanes to hit Alabama were Frederic in 1979, Elena in 1985, and Ivan in 2004. Katrina hit Alabama as a category 1 storm.

Table 5 provides a convenient list of the 88 storms that attained a rating of category 4 or 5 during the span of 1945–2005. Given in the table are the SNBR; name; year; dates when WS ≥34 kt; D, hours of WS ≥34 kt; PWS in kt; LP in mb; category 4 or 5; and whether or not the storm was a U.S. landfalling hurricane, and if yes, the category it had at LF. The 18 most powerful storms (those having LP <925 mb,

Table 4. List of states having landfalling hurricanes 1945–2005.

State	Categories 1 and 2	Categories 3–5	Total	Proportion
FL	21	17	38	0.365
NC	14	8	22	0.212
LA	12	8	20	0.192
TX	12	6	18	0.173
SC	7	3	10	0.096
MS	2	5	7	0.067
AL	3	3	6	0.058
NY	3	3	6	0.058
ME	5	0	5	0.048
CT	3	1	4	0.038
MA	2	1	3	0.029
RI	2	1	3	0.029
GA	2	0	2	0.019
NH	2	0	2	0.019
VA	2	0	2	0.019
MD	1	0	1	0.010

Table 5. List of category 4 and 5 hurricanes 1945–2005.

SNBR	Name	Year	Begin	End	D	PWS	LP	Category	USLFH?/ Category
0712	Unnamed	1945	08/24–0600	08/29–0600	120	120	963	4	Yes/2
0716	Unnamed	1945	09/12–0000	09/18–1800	162	120	951	4	Yes/3
0723	Unnamed	1946	10/05–0600	10/09–0000	90	115	979	4	Yes/1
0728	Unnamed	1947	09/04–0600	09/20–1200	390	140	947	4	Yes/4
0739	Unnamed	1948	09/04–0600	09/16–1800*	300+	115	–	4	No
0741	Unnamed	1948	10/03–1800	10/16–0000*	294+	115	975	4	Yes/2
0744	Unnamed	1949	08/23–0600	08/30–0600	168	130	954	4	Yes/3
0752	Unnamed	1949	09/27–0600	10/06–0600	216	115	–	4	Yes/2
0756	Able	1950	08/12–0000	08/21–1800	198	120	–	4	No
0759	Dog	1950	08/30–1800	09/17–0000*	414+	160	–	5	No
0761	Fox	1950	09/08–0600	09/17–0600*	216+	120	–	4	No
0771	Charlie	1951	08/15–0000	08/23–1800	210	115	–	4	No
0773	Easy	1951	09/02–1800	09/13–1800*	264+	140	–	5	No
0785	Fox	1952	10/21–1200	10/28–0000	156	130	934	4	No
0789	Carol	1953	08/31–0600	09/09–1200*	222+	130	929	4	Yes/1
0808	Hazel	1954	10/05–0600	10/18–0000	306	120	937	4	Yes/4
0812	Connie	1955	08/03–1200	08/14–0000	252	125	936	4	Yes/3
0820	Janet**	1955	09/21–1800	09/30–0600*	204+	150	914	5	No

Table 5. List of category 4 and 5 hurricanes 1945–2005 (Continued).

SNBR	Name	Year	Begin	End	D	PWS	LP	Category	USLFH?/ Category
0830	Greta	1956	11/02–1200	11/07–0600*	114+	120	970	4	No
0832	Audrey	1957	06/25–0600	06/29–0600*	90+	125	946	4	Yes/4
0834	Carrie	1957	09/03–1200	09/24–1800*	510+	135	–	4/5	No
0841	Cleo	1958	08/11–0600	08/22–0000	258	140	948	5	No
0846	Helene	1958	09/23–0000	10/04–0600*	270+	115	934	4	Yes/3
0847	Ilsa	1958	09/24–1200	09/30–0600*	138+	115	998	4	No
0856	Gracie	1959	09/22–0000	10/01–0600	222	120	950	4	Yes/3
0864	Donna	1960	08/30–1200	09/14–0000*	348+	140	932	5	Yes/4
0865	Ethel	1960	09/14–1200	09/16–1800	60	140	981	5	Yes/1
0868	Betsy	1961	09/02–0600	09/12–0600*	240+	120	945	4	No
0869	Carla	1961	09/05–1200	09/13–1200	192	150	931	5	Yes/4
0871	Esther	1961	09/11–1200	09/26–1200	360	125	927	4	No
0875	Hattie**	1961	10/27–1200	11/01–0600	114	140	920	5	No
0889	Flora	1963	09/29–1200	10/13–1200*	336+	125	940	4	No
0896	Cleo	1964	08/21–0000	09/05–1200*	102+	135	950	4/5	Yes/2
0897	Dora	1964	09/05–1200	09/16–0000*	348+	115	942	4	Yes/2
0900	Gladys	1964	09/13–1200	09/25–0000*	276+	125	945	4	No
0901	Hilda	1964	09/29–1200	10/05–1800*	150+	130	941	4	Yes/3
0906	Betsy	1965	08/29–1200	09/11–0600	266	135	941	4/5	Yes/3
0918	Inez	1966	09/24–1800	10/11–0000	408	130	929	4	Yes/1
0922	Beulah**	1967	09/07–1200	09/22–1200	360	140	923	5	Yes/3
0939	Camille**	1969	08/14–1800	08/22–1200*	138+	165	905	5	Yes/5
0970	Edith	1971	09/07–1200	09/17–0600	234	140	943	5	Yes/2
0998	Carmen	1974	08/30–1200	09/0/–0000	228	130	928	4	Yes/3
1010	Gladys	1975	09/24–1800	10/04–0000*	222+	120	939	4	No
1023	Anita	1977	08/30–0600	09/03–0600	96	150	926	5	No
1034	Ella	1978	08/30–1800	09/05–1200*	138+	120	955	4	No
1036	Greta	1978	09/14–1200	09/19–1200	120	115	947	4	No
1044	David**	1979	08/26–0600	09/08–0000*	306+	150	924	5	Yes/2
1046	Frederic	1979	08/30–1200	09/14–1800	312	115	943	4	Yes/3
1050	Allen**	1980	08/02–0000	08/11–1200	228	163	899	5	Yes/3
1068	Harvey	1981	09/12–1800	09/19–0600	156	115	946	4	No
1077	Debby	1982	09/14–1200	09/20–1800*	150+	115	950	4	No
1087	Diana	1984	09/08–1200	09/16–0600*	186+	115	949	4	Yes/2
1102	Gloria**	1985	09/17–1200	10/02–0000*	318+	125	920	4	Yes/3
1127	Gilbert**	1988	09/09–1800	09/17–1800	192	160	888	5	No
1128	Helene	1988	09/20–0600	09/30–1200*	246+	125	938	4	No
1130	Joan	1988	10/11–0600	10/23–0600*	288+	125	932	4	No
1138	Gabrielle	1989	08/31–0000	09/12–1200	300	125	927	4	No
1139	Hugo**	1989	09/11–1800	09/25–1200*	330+	140	918	5	Yes/4
1159	Claudette	1991	09/05–1200	09/11–1800	150	115	946	4	No

Table 5. List of category 4 and 5 hurricanes 1945–2005 (Continued).

SNBR	Name	Year	Begin	End	D	PWS	LP	Category	USLFH?/ Category
1166	Andrew**	1992	08/17–1200	08/27–0600	234	150	922	5	Yes/5
1192	Felix	1995	08/08–1800	08/25–0000*	390+	120	929	4	No
1198	Luis	1995	08/29–0000	09/12–1800*	334+	120	935	4	No
1201	Opal**	1995	09/30–1200	10/06–1800	144	130	919	4	Yes/3
1210	Edouard	1996	08/22–0600	09/06–1800*	372+	125	933	4	No
1213	Hortense	1996	09/07–0600	09/16–0600*	216+	120	935	4	No
1233	Georges	1998	09/16–1200	09/29–1200	312	135	937	4/5	Yes/2
1239	Mitch**	1998	10/22–1800	11/09–1800*	354+	155	905	5	No
1242	Bret	1999	08/19–1800	08/24–0000	102	125	944	4	Yes/3
1243	Cindy	1999	08/20–1800	08/31–1200*	258+	120	943	4	No
1246	Floyd**	1999	09/08–0600	09/19–1200*	270+	135	921	4/5	Yes/2
1247	Gert	1999	09/12–1200	09/23–1200*	264+	130	930	4	No
1252	Lenny	1999	11/14–1200	11/21–0600	162	135	933	4/5	No
1261	Isaac	2000	09/22–0000	10/04–0600*	294+	120	943	4	No
1263	Keith	2000	09/29–1800	10/06–0600	132	120	941	4	No
1276	Iris	2001	10/05–1200	10/09–1200	96	125	948	4	No
1280	Michelle	2001	11/01–0000	11/06–1800*	138+	120	934	4	No
1294	Lili	2002	09/27–1200	10/04–0600	162	125	940	4	Yes/1
1300	Fabian	2003	08/28–1200	09/09–1800*	294+	125	941	4	No
1303	Isabel**	2003	09/06–0600	09/19–1800	324	145	915	5	Yes/2
1313	Charley	2004	08/10–0600	08/15–1200	126	125	947	4	Yes/4
1316	Frances	2004	08/25–1800	09/07–0600	300	125	937	4	Yes/2
1319	Ivan**	2004	09/03–0600	09/24–0000	378	145	910	5	Yes/3
1321	Karl	2004	09/16–1800	09/28–0000	270	125	938	4	No
1329	Dennis	2005	07/05–1200	07/11–0600	138	130	930	4	Yes/3
1330	Emily	2005	07/12–0000	07/21–0600	222	140	929	5	No
1336	Katrina**	2005	08/24–1200	08/30–1200	144	150	902	5	Yes/3
1342	Rita**	2005	09/18–1800	09/25–0600	156	255	897	5	Yes/3
1347	Wilma**	2005	10/17–0600	10/26–1800*	204+	160	882	5	Yes/3

are identified with two asterisks. The single asterisks given for some storm end times mean that at last observation the WS still exceeded 34 kt, so the durations for these storms are not precisely known. Ivan (SNBR 1319), which struck Alabama and Florida as a category 3 major hurricane on September 16, 2004, had the longest duration (240 hr) and attained category 5 status, with a PWS of 145 kt, and LP of 910 mb. Camille (SNBR 939, 1969) and Allen (SNBR 1050, 1980) had the highest PWS (165 kt), while Wilma (SNBR 1347, 2005) had the lowest LP (882 mb). Twenty-five of the 88 storms clearly were category 5 storms at some point in their development, with another 6 having PWS of 135 kt, a speed equal to the upper end of category 4 and the lower end of category 5 storms.

Regarding the naming of storms, this practice began in 1950. Storms before 1950 went unnamed. From 1950 to 1952, North Atlantic basin tropical cyclones were identified by the phonetic alphabet (Able, Baker, Charlie, etc.), but in 1953 the U.S. Weather Bureau switched to women's names and in 1979 men's names began to be used, as well. Even so, unnamed storms still occur, from none to as many as six per years, averaging about one per yr. The names of storms now follow a set list that recycles every 6 yr. The list for 2006 through 2011 can be found at <http://www.nhc.noaa.gov/aboutnames.shtml>. The names Dennis, Katrina, Rita, and Wilma from 2005 have been retired. If all names are used during the season, then the Greek alphabet is employed, as is what happened during the 2005 season.

Table 6 presents the probability of occurrence ($P(r)$) for various seasonal rates (r) for NS, NH, NMH, NUSLFH, and N4/5 presuming a Poisson distribution and neglecting any trending. Given at the bottom of the table is the number of seasons (N(s)), number of events (n), and seasonal mean (m) for each subgroup. Thus, there is a 95-percent probability that 16 or fewer storms will occur during any particular season, including about 10 or fewer hurricanes, about 5 or fewer major hurricanes, about 4 or fewer U.S. landfalling hurricanes, and about 3 or fewer category 4/5 storms. The 2005 season's 28 storms, 15 hurricanes, and 7 major hurricanes were all either of record or near record number, and therefore, were statistically unexpected, especially presuming seasonal rates to be randomly distributed. So, either the 2005 season was a statistical outlier (a fluke) or one must take into account natural variability and/or, perhaps, the effects of global warming.

2.2 Seasonal Variation of Storm Peak Wind Speed, Pressure, and Duration

Figure 4 (lower panel) displays the yearly PWS (kt) of the North Atlantic basin tropical cyclones during 1945–2005. Its format (also true for all subpanels) follows that of figures 1 and 2, with the thin jagged line being the observed yearly PWS values, the thin horizontal line being the long-term mean of the observed yearly PWS values, and the thick smooth line being the 10-yr moving average of the observed yearly PWS values. As an example, during 2005 Wilma had the highest recorded sustained WS, measuring 160 kt, and it is this value that is plotted for PWS in 2005. The long-term mean PWS for 1945–2005 equals 127.0 kt, *sd* equals 20.1 kt, and the range is 75 (1968, Gladys, SNBR 936) to 165 kt (1969, Camille, SNBR 939; 1980, Allen, SNBR 1050). The 10-yr moving average is above the long-term mean until the mid-1960s and stays below the long-term mean until the late 1990s (a slight rebound is observed between the mid-1970s and the mid-1980s). The 10-yr moving average in 2000 is near the peak that was seen in the mid-1950s, 133 kt versus 135 kt. Those storms with PWS ≥160 kt are identified.

Figure 4 (middle panel) displays the yearly average PWS per storm of the North Atlantic basin tropical cyclones (<PWS>s, in kt) during 1945–2005. As an example, the 28 storms of the 2005 season saw PWSs that ranged 35–160 kt. The sum of these PWS divided by the total NS in 2005 gives the <PWS>s for the 2005 season equal to 77 kt. The long-term mean <PWS>s for 1945–2005 equals 75.2 kt, the *sd* equals 9.2 kt, and the range is 56 (1997) to 100 kt (1950). The 10-yr moving average is above the long-term mean until the mid-1960s and has been below the long-term mean ever since, although it appears likely that it will once again rise above the long-term mean sometime in the early 2000s. Interestingly, a long-term decrease in <PWS>s is apparent from its peak in 1954 to 1989/1990, with a slight bump in 1978/1979. Values have generally been increasing since 1990, with the 10-yr moving average in 2000 very near the long-term mean, 75.1 kt versus 75.2 kt.

Table 6. Poisson statistics for North Atlantic basin tropical cyclones 1945–2005.

	NS		NH		NMH		NUSLFH		N4/5	
r	Obs.	*P*(*r*)	Obs.	*P*(*r*)	Obs.	*P*(*r*)	Obs.	*P*(*r*)	Obs.	*P*(*r*)
0	0	0.0000	0	0.0021	4	0.0699	10	0.1827	13	0.2369
1	0	0.0003	0	0.0130	15	0.1861	26	0.3106	24	0.3412
2	0	0.0014	1	0.0401	16	0.2475	7	0.2640	15	0.2456
3	0	0.0050	8	0.0823	11	0.2194	14	0.1496	4	0.1179
4	1	0.0132	10	0.1267	3	0.1459	1	0.0636	3	0.0424
5	1	0.0279	7	0.1561	6	0.0776	0	0.0216	2	0.0122
6	5	0.0493	10	0.1603	3	0.0344	3	0.0061	0	0.0029
7	6	0.0746	9	0.1411	2	0.0131	0	0.0015	0	0.0006
8	8	0.0987	6	0.1086	1	0.0043	0	0.0003	0	0.0001
9	5	0.1162	5	0.0743	0	0.0013	0	0.0001	0	0.0000
10	4	0.1230	1	0.0458	0	0.0003	0	0.0000	0	0.0000
11	9	0.1184	2	0.0256	0	0.0001	0	0.0000	0	0.0000
12	7	0.1045	1	0.0132	0	0.0000	0	0.0000	0	0.0000
13	5	0.0852	0	0.0062	0	0.0000	0	0.0000	0	0.0000
14	3	0.0644	0	0.0027	0	0.0000	0	0.0000	0	0.0000
15	3	0.0455	1	0.0011	0	0.0000	0	0.0000	0	0.0000
16	1	0.0301	0	0.0004	0	0.0000	0	0.0000	0	0.0000
17	0	0.0187	0	0.0002	0	0.0000	0	0.0000	0	0.0000
18	1	0.0110	0	0.0001	0	0.0000	0	0.0000	0	0.0000
19	1	0.0061	0	0.0000	0	0.0000	0	0.0000	0	0.0000
20	0	0.0033	0	0.0000	0	0.0000	0	0.0000	0	0.0000
21	0	0.0016	0	0.0000	0	0.0000	0	0.0000	0	0.0000
22	0	0.0008	0	0.0000	0	0.0000	0	0.0000	0	0.0000
23	0	0.0004	0	0.0000	0	0.0000	0	0.0000	0	0.0000
24	0	0.0002	0	0.0000	0	0.0000	0	0.0000	0	0.0000
25	0	0.0001	0	0.0000	0	0.0000	0	0.0000	0	0.0000
26	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000
27	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000
28	1	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000
N(S)	61		61		61		61		61	
n	646		376		162		104		88	
m	10.59		6.16		2.66		1.70		1.44	

Figure 4 (upper panel) displays the yearly average PWS per hurricane (<PWS>h in kt) of the North Atlantic basin tropical cyclones during 1945–2005. As an example, the 15 hurricanes of 2005 saw PWSs that ranged 65–160 kt. The sum of these PWSs divided by the total NHs in 2005 gives the <PWS>h for the 2005 season, equal to 102 kt. The long-term mean <PWS>h for 1945–2005 equals 93.6 kt, the *sd* equals 10.4 kt, and the range is 68 (1968) to 119 kt (1964). The 10-yr moving average closely mimics the behavior observed for <PWS>s, except now the 10-yr moving average is above the long-term

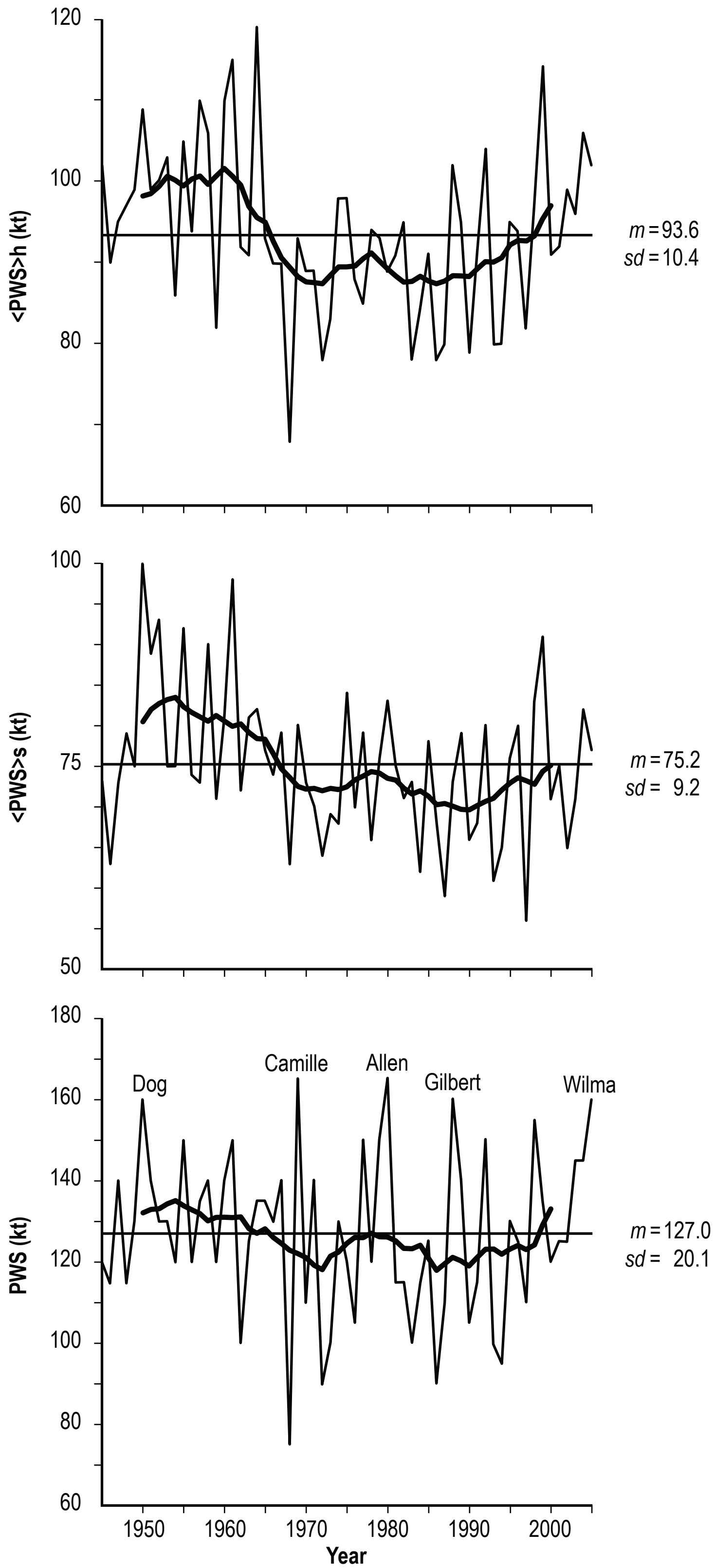


Figure 4. The yearly variation of PWS (lower panel), <PWS>s (middle panel), and <PWS>h (upper panel). The thin jagged lines are the yearly values, the thick smooth lines are the 10-yr moving averages, and the thin horizontal lines are the long-term means.

mean, continuing to track upward, but, as yet, has not attained values that were seen in the 1950s and 1960s, 97.0 kt versus 101.8 kt.

Figure 5 (lower panel) displays the yearly lowest reported pressure of the North Atlantic basin tropical cyclones for 1945–2005. There were no reported pressure readings in 1950–1951, and prior to 1979 pressure readings are spotty, at best; thus, the 10-yr moving averages are less reliable for years prior to about 1984. The format of figure 5 and all subpanels, follows that of figures 1, 2, and 4 with the thin jagged line being the observed yearly LP values, the thin horizontal line being the long-term mean of the observed yearly LP values, and the thick smooth line being the 10-yr moving average of the observed yearly LP values. As an example, in 2005 the storm having the lowest pressure was Wilma (882 mb), also having the lowest pressure ever recorded, beating out Gilbert's 888 mb in 1988. The long-term mean LP for 1945–2005 equals 937.6 mb, the *sd* equals 20.5 mb, and the range is 882 (Wilma, 2005, SNBR 1347) to 980 mb (Charley, 1986, SNBR 1,106). Interestingly the 10-yr moving average appears to be relatively flat between 1957–1997, staying between 935.9 and 942.8 mb. However, since 1997 the 10-yr moving average has dipped precipitously, falling to 924 mb. Another interesting observation is that storms having LP <925 mb (table 4) might be on the increase. For example, prior to 1980 there were only 5 such storms, whereas, since 1980 there have been 13 such storms, 8 having occurred since 1995 (the year 2005 actually had 3 such storms—Katrina, Rita, and Wilma). Overall, the average elapsed time between occurrences of these storms is about 3 yr (*sd*=2.6 yr).

Figure 5 (middle panel) displays the yearly average LP per storm (<LP>s) of the North Atlantic basin tropical cyclones for 1945–2005. As an example, the 28 storms of 2005 saw LPs that ranged between 882 (Wilma) and 1,006 mb (Lee). The sum of these LPs divided by the total NS in 2005 gives the <LP>s for the 2005 season, equal to 975 mb. The long-term mean equals 979.2 mb, the *sd* equals 8.1 mb, and the range is 951 (1955) to 992 mb (1986–1987). The 10-yr moving average is below the long-term mean until the late 1960s, when it rose above the long-term mean and continued above the mean until the mid-1990s, when it once again dipped below the long-term mean. The value in 2000 (977.2 mb), the LP that has been seen in the new more active interval, has not yet dipped below the lowest value that was seen in the previous active interval (972.9 mb in 1953).

Figure 5 (upper panel) displays the yearly average LP per hurricane (<LP>h) of the North Atlantic basin tropical cyclones for 1945–2005. As an example, the 15 hurricanes of 2005 saw LPs that ranged between 882 (Wilma) and 990 mb (Vince). The sum of these LPs divided by the total NH in 2005 gives <LP>h for the 2005 season, equal to 954 mb. The long-term mean equals 967.3 mb, the *sd* equals 9.6 mb, and the range is 946 (1988) to 988 mb (1986). The 10-yr moving average for <LP>h mimics that of the 10-yr moving average for <LP>s, except now the values in the current more active interval are the lowest on record and the trend remains sharply downward (since about 1982). The value in 2000 measured 960.4 mb, while the previous low in the first more active interval measured 964.1 mb (1960), a decrease (or intensification) of about 0.4 percent. Further intensification to values below 960 mb seems likely, given that 3 out of the past 4 years have had <LP>h <960 mb.

Figure 6 (left panel) displays the yearly average D per storm (<D>s) of North Atlantic basin tropical cyclones during 1945–2005, where the D of a storm is the total number of hours when its WS ≥34 kt. As an example, in 2005 the total number of hours that the 28 storms had WS ≥34 kt amounted to, at least, 3,564 hr, thereby, yielding <D>s=127 hr. The format of figure 6 is like that of figures 1, 2, 4,

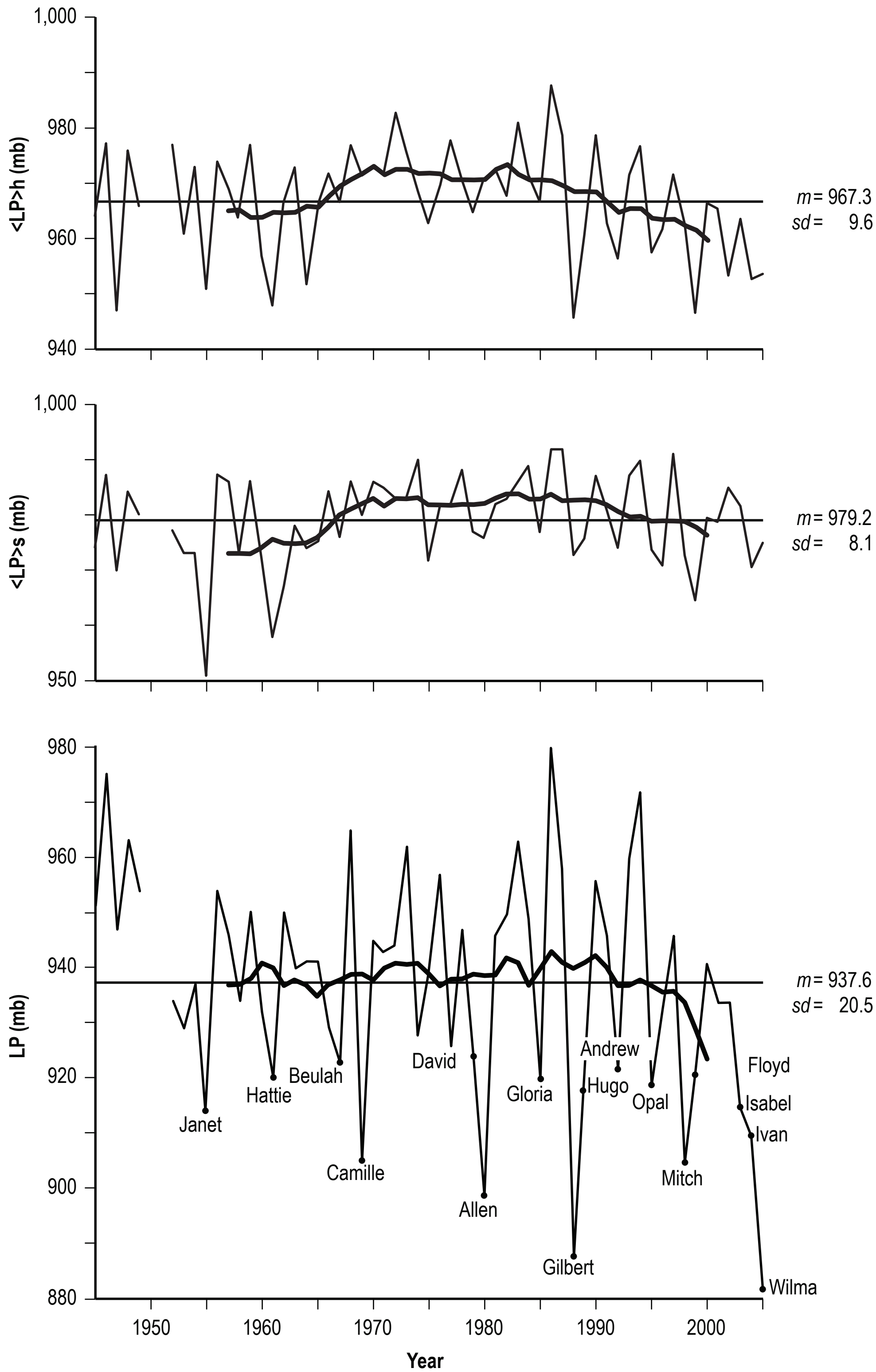


Figure 5. The yearly variation of LP (lower panel), <LP>s (middle panel), and <LP>h (upper panel). The thin jagged lines are the yearly values, the thick smooth lines are the 10-yr moving averages, and the thin horizontal lines are the long-term means.

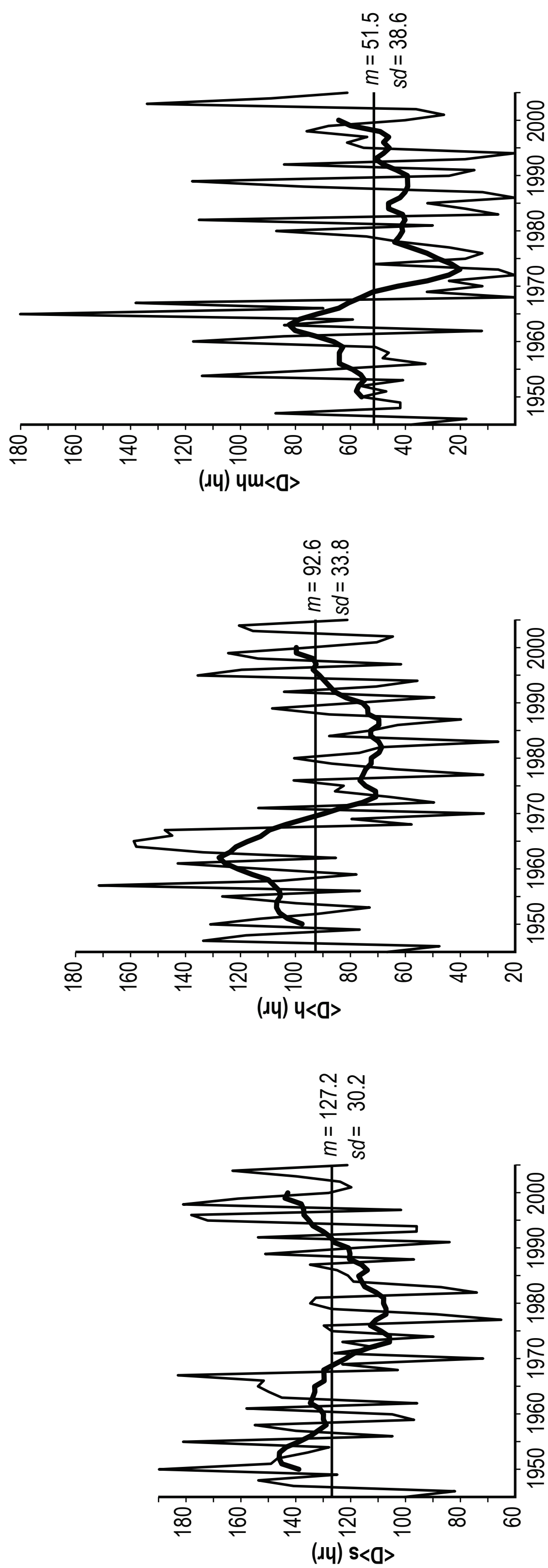


Figure 6. The yearly variation of <D>s (left panel), <D>h (middle panel), and <D>mh (right panel). The thin jagged lines are the yearly values, the thick smooth lines are the 10-yr moving averages, and the thin horizontal lines are the long-term means.

and 5 where the thin jagged line is the yearly average, the thin horizontal line is the long-term mean, and the thick smooth line is the 10-yr moving average. For 1945–2005, the long-term mean duration is 127.2 hr, the *sd* is 30.2 hr, and the range is 65 (1977) to 190 hr (1950). Clearly, during the first more active period (1950s and 1960s), the 10-yr moving average was above the long-term mean, while during the less active period (1970s and 1980s) it was below the long-term mean. Now, in the 1990s and 2000s, it has once again risen above the long-term mean. A peak seems to have occurred in the early 1950s and the value of the 10-yr moving average in 2000 is very close to that value, 144.7 hr versus 145.6 hr (1952/1953).

Figure 6 (middle panel) displays the yearly average D per hurricane (<D>h) of North Atlantic basin tropical cyclones during 1945–2005, where the D is the total number of hours when WS ≥64 kt. In 2005, the 15 hurricanes had WS ≥64 kt a total of 1,224 hr, thereby yielding <D>h=82 hr. The format follows that of <D>s. For 1945–2005, the long-term mean is 92.6 hr, the *sd* is 33.8 hr, and the range is 28 (1983) to 172 hr (1957). As noted for <D>s, the 10-yr moving average of <D>h is above the long-term mean during the 1950s and 1960s (actually peaking slightly later than was seen for <D>s, in the early 1960s rather than the early 1950s), dips below the long-term mean during 1970s and 1980s, and then rises again above the long-term mean in the late 1990s. As yet, the value of the 10-yr moving average for <D>h has not equaled or exceeded the peak value that was seen in the early 1960s, 100.1 hr versus 127.9 hr (1962).

Figure 6 (right panel) displays the yearly average D per major hurricane (<D>mh) of the North Atlantic basin tropical cyclones during 1945–2005, where the D is the total number of hours when WS ≥96 kt. In 2005, the seven major hurricanes had WS ≥96 kt a total of 426 hr, thus, yielding <D>mh=61 hr. Again, the format follows that of <D>s and <D>h. For 1945–2005, the long-term mean is 51.5 hr, the *sd* is 38.6 hr, and the range is 0 (there were no major hurricanes in 1968, 1972, 1986, and 1994) to 180 hr (1965). As before for <D>s and <D>h, the 10-yr moving average is above the long-term mean during the 1950s and 1960s (peaking in the early 1960s), dips below the long-term mean during the 1970s and 1980s, and then rises again above the long-term mean in the late-1990s. Also, as before, the value of the 10-yr moving average for <D>mh has not yet equaled or exceeded the peak value that was seen in the early 1960s, 64.2 hr versus 81.8 hr (1963).

2.3 Correlations of Lowest Pressure and Duration Against Peak Wind Speed

Figure 7 (lower-left panel) shows the scatterplot of <LP>s_{10} versus <PWS>s_{10}, where the subscript 10 indicates that the comparison is between the 10-yr moving averages, not the individual yearly averages. Not surprisingly, there is a very strong statistically significant correlation between <LP>s_{10} and <PWS>s_{10}, at *cl* >99.9 percent. Storms with the highest PWS generally are also the storms with the lowest pressure. The inferred regression indicates that about half the variance in the 10-yr moving average of <LP>s can be explained by the variation of the 10-yr moving average of <PWS>s. Recall, however, that pressures are less reliable prior to 1984, because of the spotty record of pressure recordings. Based strictly on the 1984–2000 timeframe, the regression is y=1058.713–1.086x, having r=–0.878, se=0.868, and cl=>99.9 percent. Thus, more than three-fourths of the variance can be explained by the inferred regression.

Figure 7 (upper left panel) shows the scatterplot of <D>s_{10} versus <PWS>s_{10}. While a statistically significant correlation is suggested between the two parameters (indicated by y), the inferred correlation

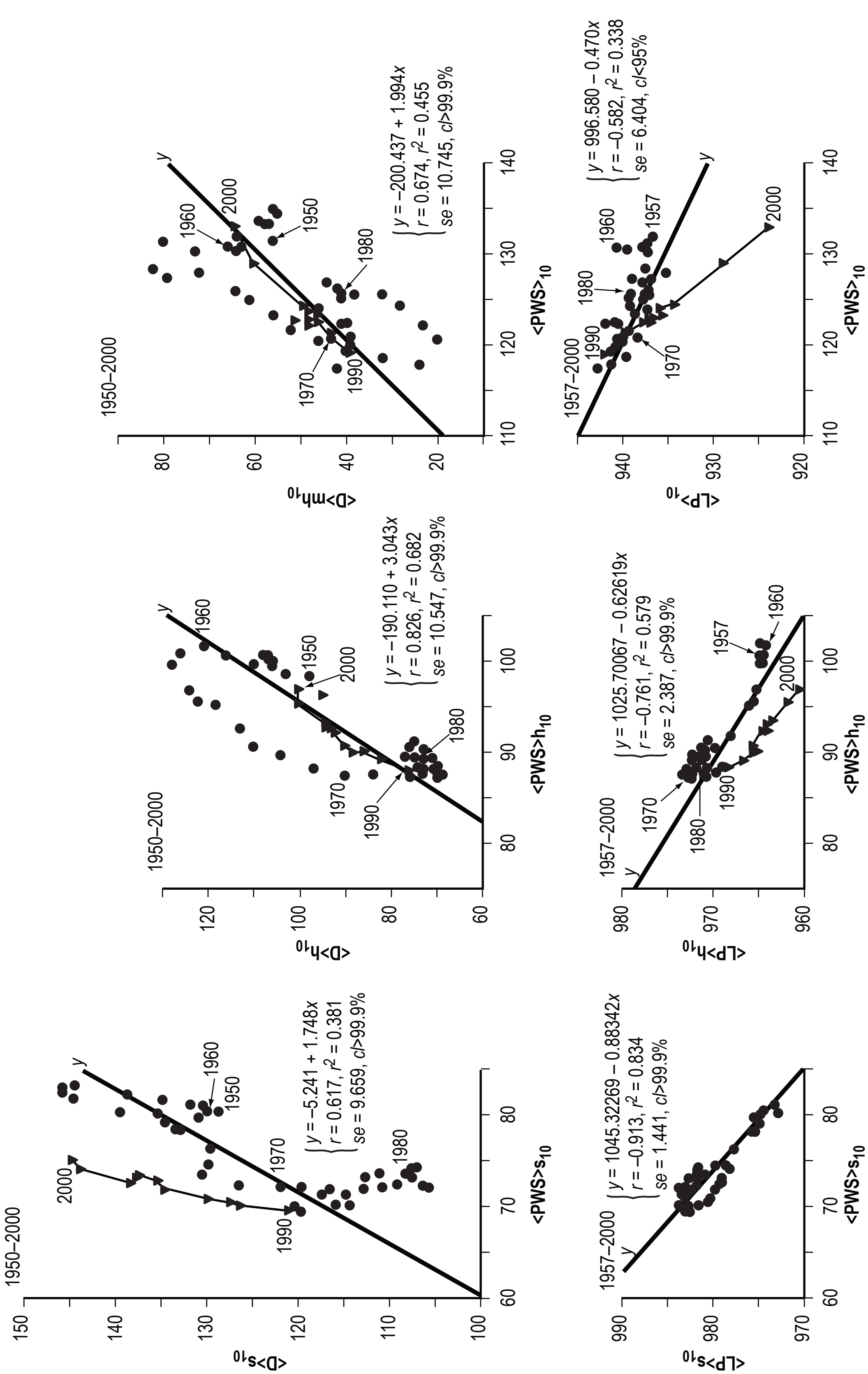


Figure 7. Scatterplots for various parametric combinations using 10-yr moving averages. See text for details.

since 1990 (denoted by the filled triangles) has been considerably stronger (the regression being given by y=–161.594+4.091x, having r=0.979, se=1.587, and cl>99.9 percent, and explaining about 96 percent of the variance). Since 1990, <PWS>s$_{10}$ has increased about 8 percent from 69.6 kt to 75.1 kt, while <D>s$_{10}$ has increased about 20 percent from 120.9 hr to 144.7 hr.

Figure 7 (lower middle panel) shows the scatterplot <LP>h$_{10}$ versus <PWS>h$_{10}$. Again, a strong statistical correlation is inferred between the two parameters, indicated by y, although for the more recent interval of 1990–2000, the inferred regression is again considerably stronger (the regression being given by y=1040.199–0.823x, having r=–0.979, se=0.513, and cl>99.9 percent, and explaining about 96 percent of the variance). Thus, over the past decade or so, there has been a marked intensification of hurricanes, with <PWS>h$_{10}$ increasing about 10 percent from 88.2 kt to 97.0 kt and <LP>h$_{10}$ decreasing about 1 percent from 968.5 mb to 960.4 mb.

Figure 7 (upper middle panel) shows the scatterplot of <D>h$_{10}$ versus <PWS>h$_{10}$. While there is a strong inferred statistical correlation between the two parameters, indicated by y, an interesting observation is that the behavior of the data points hints of an additional systematic variation. Identified in the scatterplot are the values observed specifically for the years 1950, 1960, 1970, 1980, 1990, and 2000. Notice that the values progressively move upward and to the right from 1950 to 1960, attaining a peak in 1962 (127.9 hr). Then, the values progressively move downward and to the left through 1970 (with the values consistently lying above the regression) and then downward and to the right through 1980 (below the regression). The lowest value occurs in 1982 (68.6 hr). This value is then followed by generally increasing values (upward and to the right), such that the values for 1999–2000 are located very close in value to the value for 1950, perhaps, suggesting the near completion of an inherent natural cycle of activity. The values for 1990–2000 line along the inferred regression.

Figure 7 (lower right panel) shows the scatterplot of <LP>$_{10}$ versus <PWS>$_{10}$ (essentially, equivalent to values for major hurricanes, since major hurricanes always have the highest value of PWS and lowest value of LP). As for <LP>h$_{10}$, the inferred regression for 1990–2000 is stronger than the general inferred regression, which is not statistically significant, owing to the unreliability of the 10-yr moving averages of LP for the years preceding 1984, and is given by y=1098.682–1.316x, having r=0.996, se=0.401, and cl>99.9 percent, and explaining about 99 percent of the variance. For 1990–2000, <PWS>$_{10}$ increased about 11 percent from 119.3 kt to 133 kt, while <LP>$_{10}$ decreased about 2 percent from 942.0 mb to 924 mb.

Figure 7 (upper right panel) shows the scatterplot of <D>mh$_{10}$ versus <PWS>$_{10}$. As found for <D>h$_{10}$, there appears to be embedded in the scatterplot an inherent systematic variation—The values tend to move upward and to the left from 1950, peaking in 1963 (81.8 hr), then moving downward and to the left to its lowest value (20.0 hr) in 1973. Afterwards, they move upward and slightly to the right through 1980, then slightly leftward, followed by a strongly linear upward and rightward movement for 1990–2000, with the 2000 value exceeding the 1950 value, 64.2 hr versus 55.7 hr, an increase of about 15 percent.

2.4 Correlations Against Global Surface Air Temperature

The association of tropical cyclone activity with climatic change and/or global warming has produced mixed results.[1,2,11] For example, Evans has examined the 20-yr interval of 1967–1986, now known to be a predominantly less active interval, and found that while SST does influence tropical cyclone development and provides an upper bound to intensity, it is not the overriding factor for determining the maximum intensity of a storm.[32] Additionally, Landsea et al. have noted that, for the North Atlantic basin, warmer than average waters are usually accompanied by lower than average surface pressures, weaker trade winds, and reduced shear while cooler than average waters are usually accompanied by higher surface pressures, stronger trade winds, and increased shear further noting that the interannual variability of Atlantic basin tropical cyclones is directly related to wet/dry years associated with the West African monsoon.[11,33–35] They also have noted that the interdecadal variability is related to changes in the dipole structure of the Atlantic Ocean SST structure, with warmer (cooler) than average SST north of the equator being coupled with cooler (warmer) than average SST south of the equator, this favoring increased (decreased) intense hurricane activity in the North Atlantic basin, with ENSO and the quasi-biennial oscillation (QBO) also serving as moderating factors.[42–44]

Furthermore, Landsea has noted that studies have suggested that increases in anthropogenic greenhouse gases, chiefly CO_2, might lead to increased tropical SST and increased tropical rainfall with a slightly stronger intertropical convergence zone (ITCZ), possibly leading to increased frequency of occurrence and increased storm intensity, although other studies have indicated decreases associated with warmer SST.[13] Goldenberg et al. have associated the greater activity experienced during 1995–2000 directly with increased North Atlantic SST and decreased vertical wind shear, suggesting further that the high level of tropical cyclonic activity likely will continue for some 10–40 yr presuming a natural multidecadal variability, called the Atlantic multidecadal oscillation (AMO).[14] Emanuel, on the basis of his power dissipation index (PDI), has argued that since the mid-1970s tropical cyclones have increased in their destructiveness, owing to the observed increased SST and hence, global warming.[16] Pielke et al. have argued that claims of linkages between global warming and hurricane impacts are, at present, premature, in particular, because no connection has, as yet, been firmly established between greenhouse gas emissions and the observed behavior of hurricanes and because the peer-reviewed literature reflects that a scientific consensus exists that any future changes in hurricane intensities will likely be small in the context of observed variability, concluding that the expectation of finding a conclusive link between global warming and hurricanes or their impacts in the near term is highly unlikely.[17]

More recently, Michaels, Knappenberger, and Davis have reported that a rising SST appears to act by increasing the percentage of major hurricanes, but not the ultimate intensity of the storms.[26] Mann and Emanuel, using a formal analysis to separate the estimated influences of anthropogenic climate change from possible natural cyclical influences, have presented results indicating that anthropogenic factors are likely responsible for long-term trends in the Atlantic SST and tropical cyclonic activity.[23] Landsea et al. have argued that currently available databases, especially regarding worldwide cyclonic activity, are insufficiently reliable to ascertain long-term trends in tropical storm intensity, especially, as being linked to global warming, noting that, while routine aircraft reconnaissance dates from the 1940s, it can monitor only about half the North Atlantic basin, but not on a continuous basis; hence, heavy reliance has been placed on satellite monitoring, which has been of inhomogeneous quality.[22] They conclude that real trends might exist in tropical cyclone intensity, but that such trends may be so small as to be considered insignificant, noting that Klotzbach has shown that extreme tropical cyclones and overall tropical cyclone activity have globally been flat from 1986 until 2005, despite a rise of 0.25 °C in SST warming.[45] Finally, Elsner has provided evidence that the power of Atlantic tropical cyclones is rising, being correlated with an increase in the late summer/early fall SST over the North Atlantic, thus, indicating that it is the rising global mean near-surface AT that causes the rising North Atlantic SST and increased North Atlantic basin tropical cyclonic intensification.[21]

The Armagh Observatory (Armagh, Northern Ireland) surface AT record is one of the longest available for study.[46–49] Mean temperature readings, based on maximum and minimum thermometers, extend from 1844 to the present, where mean temperature is defined as the mean of the daily maximum and minimum temperatures. The entire dataset is available at <http://climate.arm.ac.uk/calibrated.html>. Previous studies have shown that its rural environment has ensured that the observatory suffers from little or no urban microclimatic effects and that the temperature record can be used as a proxy for studying long-term trends in northern hemispheric and global annual mean surface AT.[47,50]

Figure 8 (lower panel) displays the annual mean temperature (AT) in °C at the Armagh Observatory for the interval 1945–2004 (the readings for 2005 have not yet been published). The format follows that of figures 1, 2, 4, 5, and 6 with the thin jagged line representing the annual means, the thin horizontal line representing the mean for the 1945–2004 interval, and the thick smooth line representing the 10-yr moving average. For the interval 1945–2004, the mean equals 9.43 °C, the *sd* equals 0.49 °C, and the range is 8.35 °C (in 1979) to 10.32 °C (in 1949 and 1997). The general shape of the 10-yr moving average of AT is reminiscent of those previously presented. Hence, there may be, at least a loose correlation between the NS, PWS, LP (an anticorrelation), and D against global temperature, as represented using AT. The 10-yr moving averages of AT are found to have cooled between 1945 (first entry) and 1982 (with small recoveries about 1957 and 1971), and to have sharply warmed thereafter through 1999 (last entry). It seems worth mentioning that between 1844–2004, AT (the yearly means) has exceeded 10 °C in only 14 years as follows: 1846 (which had the highest yearly reading, 10.40 °C), 1857, 1921, 1945, 1949, 1959, 1989, 1995, 1997, 1998, 1999, 2002, 2003, and 2004—half of these having occurred since 1995. From 1995, AT has been above the mean every yr except 1996. In the span of 1945–2004, AT dipped by one or more *sd* (≤8.94 °C) in only 9 years: 1952, 1963, 1965, 1969, 1972, 1974, 1979 (the lowest AT = 8.35 °C), 1985, and 1986—more than half of these having occurred in the 1970s and 1980s, the time span corresponding to depressed hurricane activity in the North Atlantic basin.

Figure 8 (upper panel) displays the annual August–October average temperatures (corresponding to late summer-early fall temperatures and the interval of greatest frequency of North Atlantic basin tropical cyclones) at the Armagh Observatory for the interval 1945–2004. Again, the thin jagged line represents the yearly August–October averages, the thin horizontal line represents the overall mean (12.73 °C, *sd*=0.78 °C), and the thick smooth line represents the 10-yr moving average. Whereas, the yearly January–December 10-yr moving averages (lower panel) display a slowly decreasing temperature trend from 1945 to 1982 followed by a sharp rise thereafter, the August–October 10-yr moving averages display a relatively flat variation from 1945 to about 1973 followed by a slight downward shift through about 1989 and a sharp rise thereafter. Thus, both the yearly January–December and August–October trends are sharply upward from about 1989, this time corresponding to the start of increases in the 10-yr moving averages of NS, NH, NMH, and N4/5 (fig. 1); PWS (fig. 4); duration (fig. 6); and to decreases in the 10-yr moving averages of LP (fig. 5).

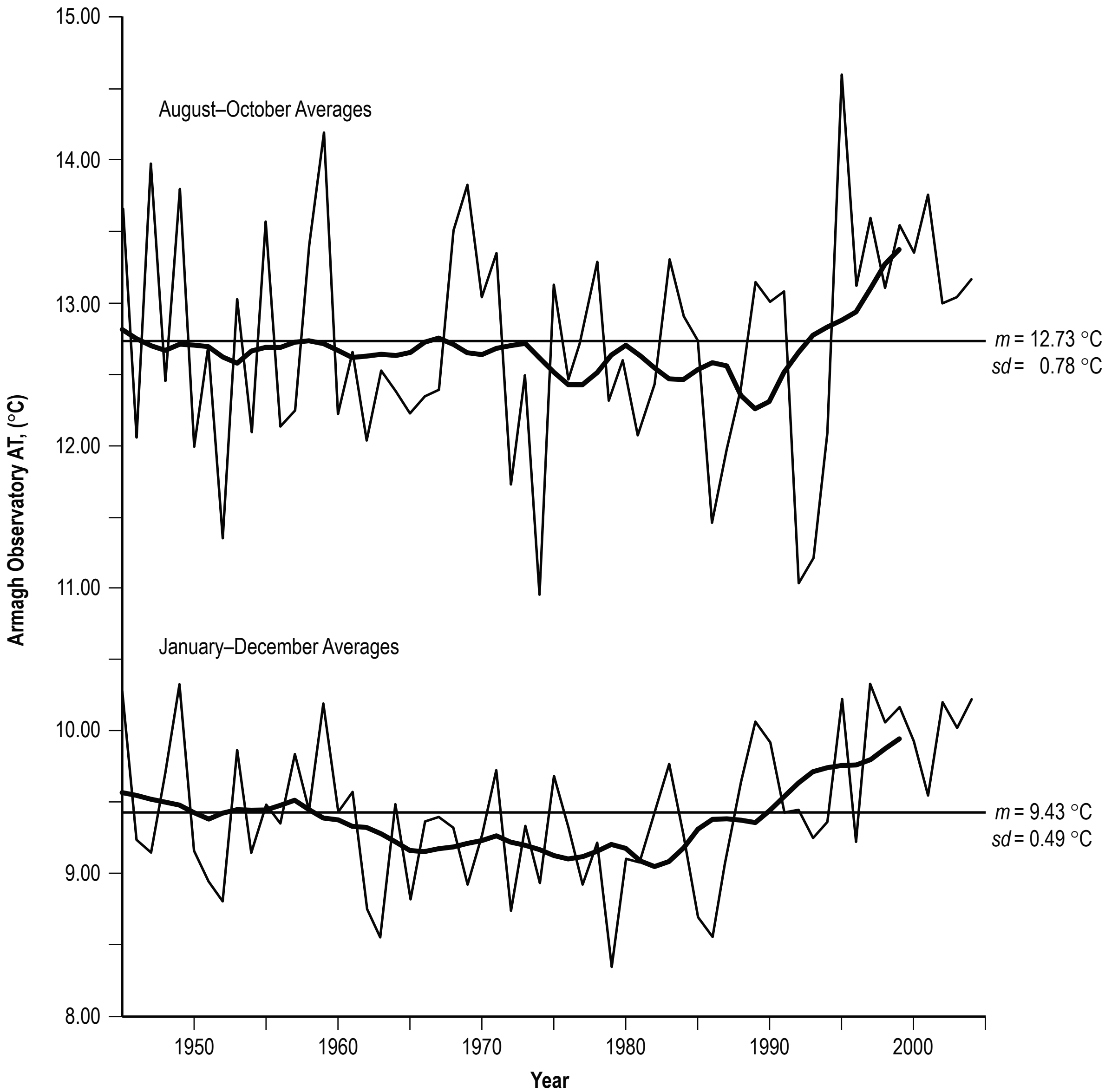


Figure 8. The yearly variation of AT, January–December (lower panel) August–October (upper panel). The thin jagged lines are the yearly values, the thick smooth lines are the 10-yr moving averages, and the thin horizontal lines are the long-term means.

Figure 9 shows the scatterplots of 10-yr moving averages of NS (lower panels), <PWS>s (lower middle panels), <LP>s (upper middle panels), and <D>s (upper panels) against the 10-yr moving averages of AT January–December (left panels) and AT August–October (right panels) for the interval 1989–1999. Similarly, figure 10 shows the scatterplots of 10-yr moving averages of NH (lower panels), <PWS>h (lower middle panels), <LP>h (upper middle panels), and <D>h (upper panels) against the 10-yr moving average of AT January–December (left panels) and AT August–October (right panels) for the interval 1989–1999. All scatterplots are highly statistically significant (*cl*>99.9 percent), suggesting very strong correlations between the yearly average NS and NH, PWS, LP, and D against average yearly and late summer-early fall temperature, at least, over the most recent years. The 10-yr moving averages for the interval 1989–1999 are based on yearly values for 1984–2004.

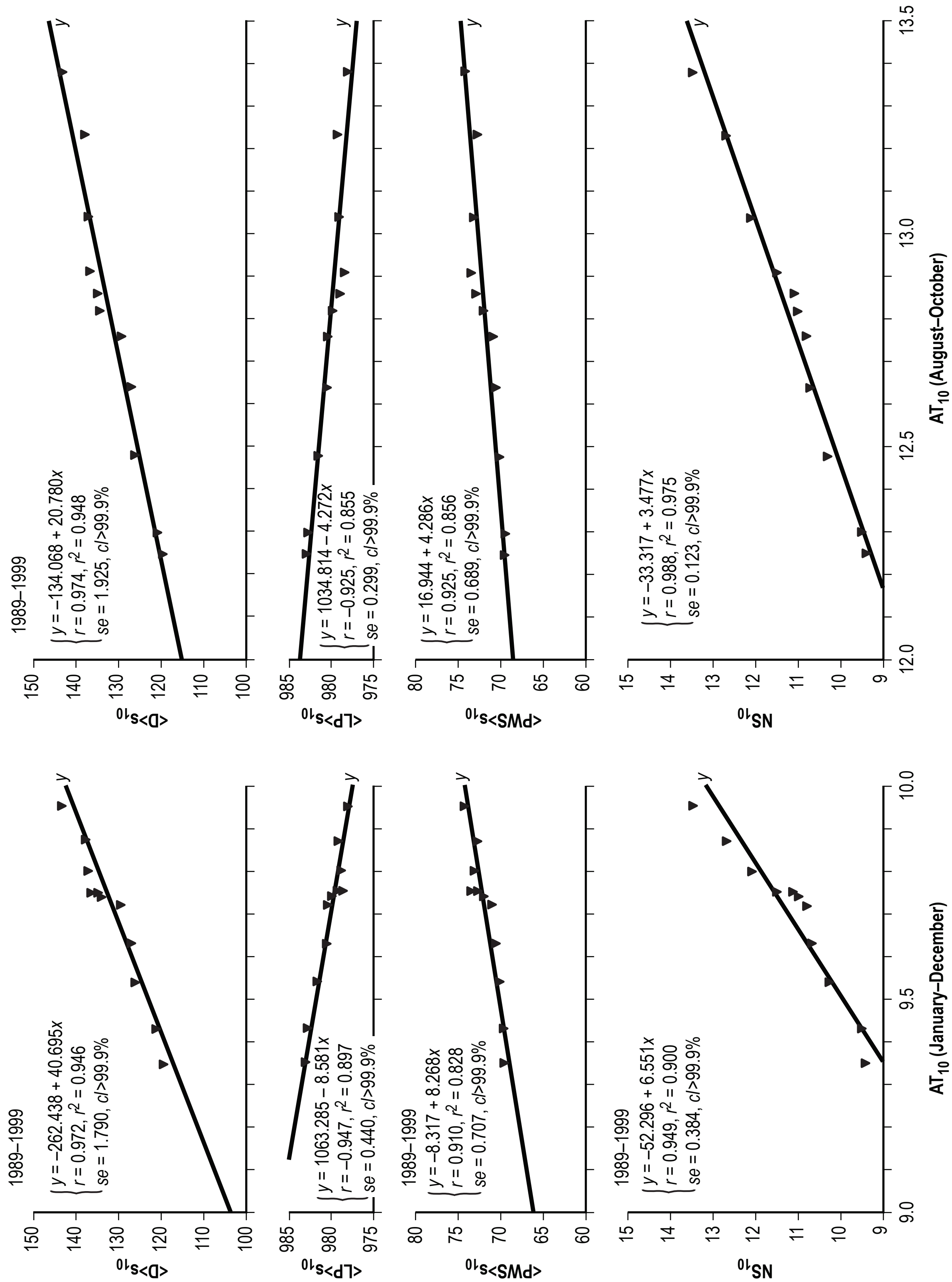


Figure 9. Scatterplots for various parametric combinations using 10-yr moving averages for 1989–1999. See text for details.

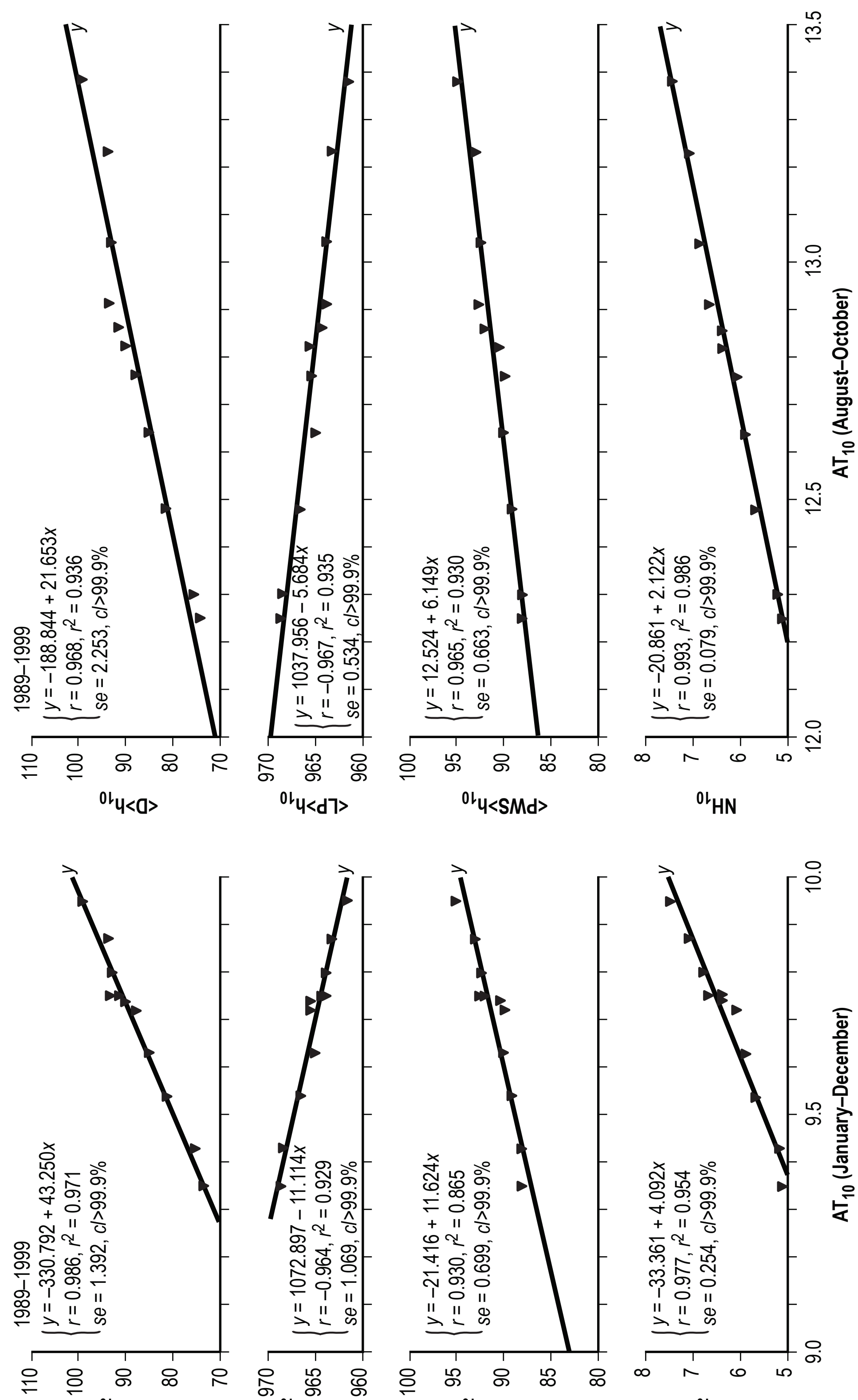


Figure 10. Scatterplots for various parametric combinations using 10-yr moving averages for 1989–1999. See text for details.

Figure 11 displays scatterplots of 10-yr moving averages of NS, <PWS>s, <LP>s, and <D>s against the 10-yr moving average of AT January–December (left panels) and AT August–October (right panels), and figure 12 displays scatterplots of 10-yr moving averages of NH, <PWS>h, <LP>h, and <D>h against the 10-yr moving average of AT January–December (left panels) and AT August–October (right panels), both for the data available intervals 1950–1999 or 1957–1999 (for <LP>s and <LP>h). For the interval 1950–1999, both NS_{10} and NH_{10} are found to strongly correlate against either AT_{10} (January–December or August–October) although for both, the correlations are strongest for the more recent interval 1989–1999. Concerning <PWS>s_{10} and <PWS>h_{10}, only the correlations between <PWS>h_{10} and AT_{10} are of marginal statistical significance (*cl*>90 percent). For <LP>s_{10}, the correlations against AT_{10} are of marginal statistical significance, although they are statistically important for <LP>h_{10} against AT_{10}. For <D>s_{10}, the correlation against AT_{10} is statistically important, while the correlation is not statistically important between <D>h_{10} and AT_{10}. Thus, the suggestion by Elsner that the power of Atlantic tropical cyclones is rising, being correlated with an increase in the late summer-early fall SST (and, hence, global mean near-surface AT) over the North Atlantic basin seems plausible, in that rising WS and falling pressure correlates with both yearly means and late summer-early fall averages of Armagh mean surface ATs, especially for the past two decades.[21] It should be noted that some of the general correlations are much stronger if one ignores data prior to about 1970.

Figure 13 displays the residuals, the observed 10-yr moving average minus predicted 10-yr moving average, of NS, <PWS>s, <LP>s, and <D>s based on the inferred regressions, as given in figure 11, using 10-yr moving averages of AT (January–December left panels; August–October right panels). Hence, the residuals show the effects on the parameters now having removed temperature as a forcing agent. When the residual is positive, this means that the observed parametric value is slightly larger than expected, given the observed surface AT, and when it is negative, this means that the observed parametric value is slightly smaller than expected, given the observed surface AT. There is a strong hint of episodic (quasi-periodic) behavior. Of particular interest is the behavior of <PWS>s_{10} and <LP>s_{10}, which suggests the existence of long-term intervals (>30 yr) where yearly average PWS (LP) tends to be consistently larger (smaller) than normal, and vice versa, with the transition from one mode to the other being rather quick (in the mid-to-late 1960s). The current mode seems to be one having positive residuals for NS_{10} and <LP>s_{10} and negative residuals for <PWS>s_{10} and <D>s_{10}. Thus, the North Atlantic basin seems to be producing, on average, more tropical cyclones now than can be accounted for strictly by temperature alone, and the relative flatness of the PWS and pressure residuals suggest that temperature (warming) now seems to be the dominant factor during the present epoch (at least, based on yearly AT). Also, whereas the 1950s and 1960s together represent an interval of high activity in the North Atlantic basin, with storms generally being of higher PWS and longer durations, and the 1970s and 1980s together represent an interval of lower activity in the North Atlantic basin, with storms generally being of lower PWS and shorter durations, surprisingly, the 1990s and 2000s (now having removed the effects of temperature) suggest that, though the trend is toward the occurrence of another more active interval, as yet, it has not fully arrived. Hence, future seasons may be even more active, due to the strengthening of the presumed quasi-periodic component, the AMO.

Figure 14 similarly displays the residuals, but this time for hurricanes. Again, the observed behavior of the residuals suggests episodic behavior (due to a quasi-periodic component), with trends in the residuals indicating the imminent occurrence of another more active interval.

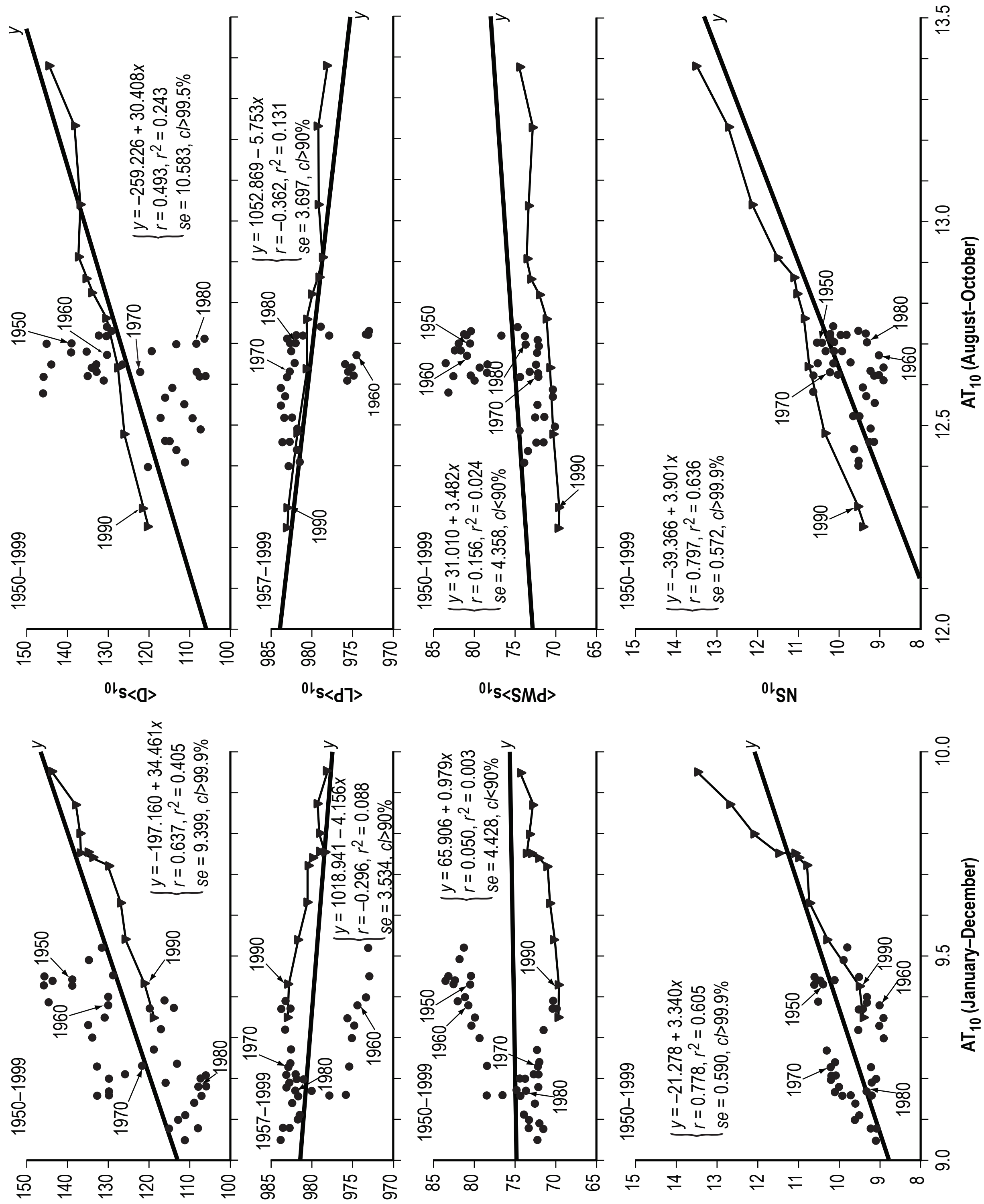


Figure 11. Scatterplots for various parametric combinations using 10-yr moving averages. See text for details.

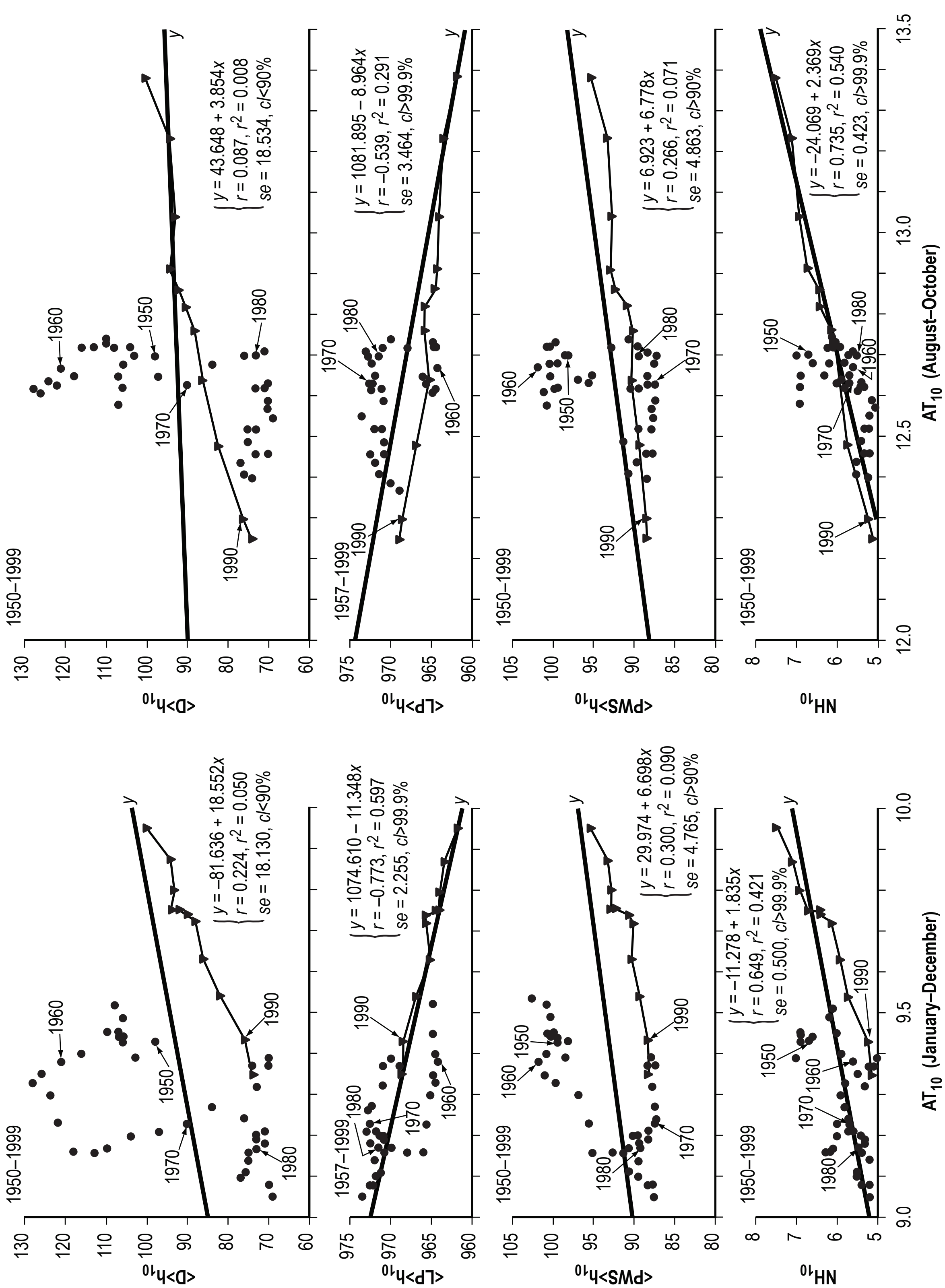


Figure 12. Scatterplots for various parametric combinations using 10-yr moving averages. See text for details.

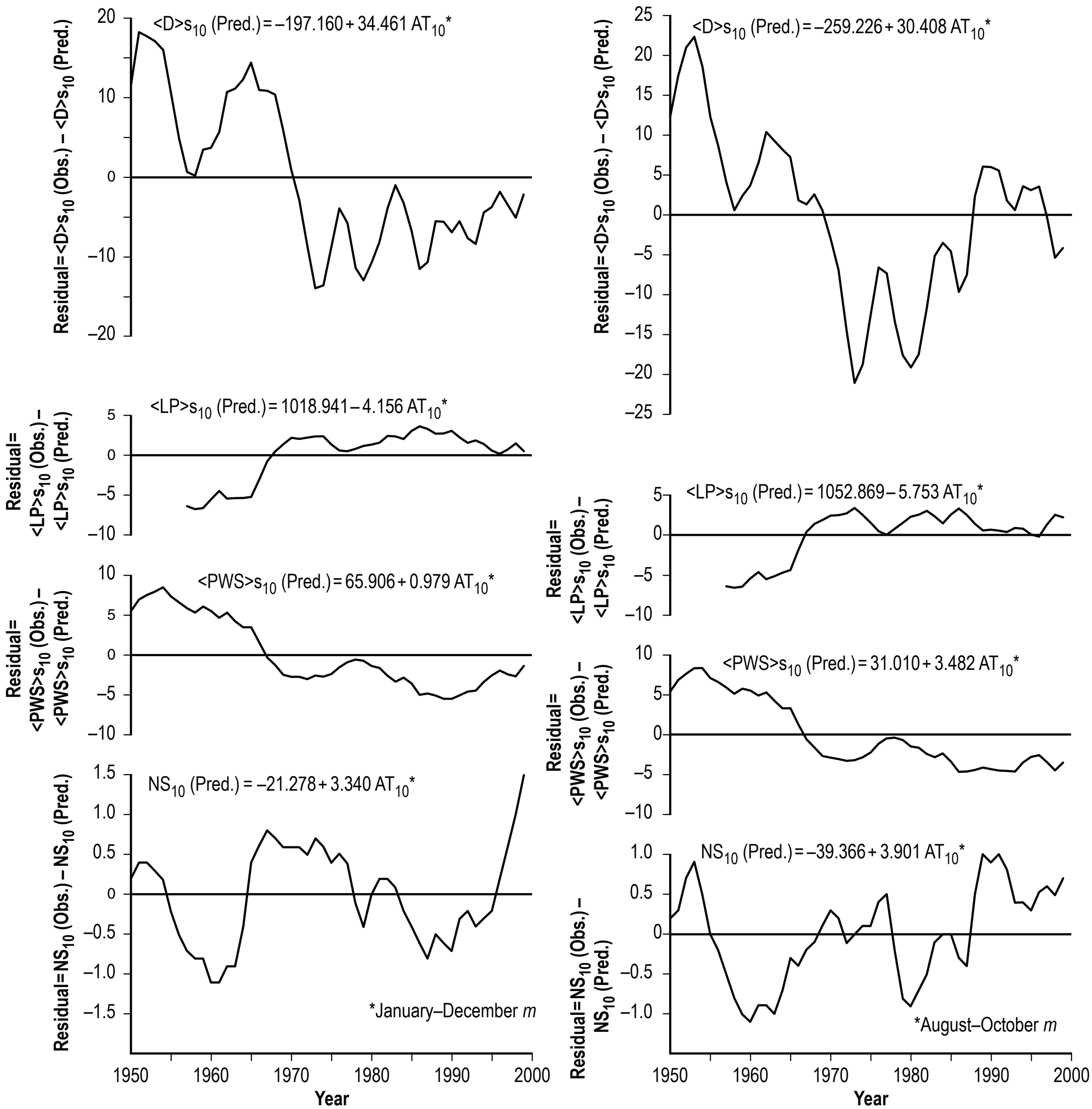


Figure 13. The yearly variation of residuals, having removed the temperature dependency.

2.5 Predicting the Next Season

In this section, simple statistical means will be given for crudely estimating NS, NH, NMH, NUSLFH, and N4/5 for the following (next) annual North Atlantic basin tropical cyclone season, given the statistics of the last completed annual season and anticipated behavioral constraints for the upcoming season (that is, whether it will be an El Niño or non-El Niño year and/or whether it is part of a less or more

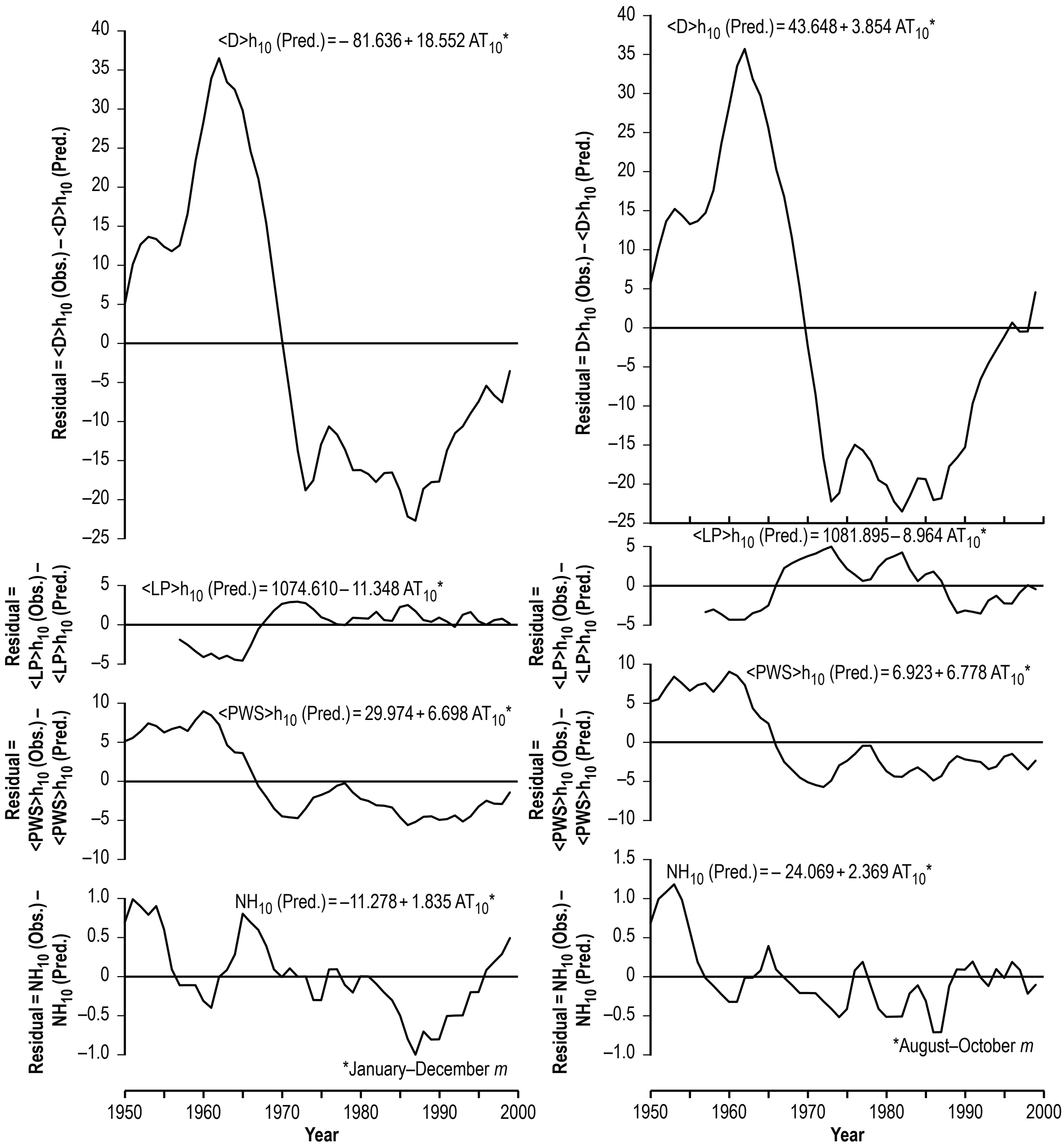


Figure 14. The yearly variation of residuals, having removed the temperature dependency.

active interval). Recall from section 2.1 (table 6) that for any given year, ignoring the phase of ENSO and inferred trends, one anticipates that, on average, about 10 or 11 tropical cyclones will occur in the North Atlantic basin, of which 6 or 7 will become hurricanes (with 3 or 4 becoming major hurricanes and 1 or 2 attaining category 4 or 5 status during some portion of their development) and with about 2 striking the

U.S. coastline, probably Florida. Furthermore, based on the past 61 years (1945–2005), Poisson statistics show that the central 50-percent probability interval is NS=9–13, NH=5–8, NMH=2–4, NUSLFH=1–2, and N4/5=1–2, while the observed range is NS=4–28, NH=2–15, NMH=0–8, NUSLFH=0–6, and N4/5=0–5. If, however, one correctly anticipates that the yr will be characterized as an El Niño yr, then the prediction will be slightly reduced, while if one correctly anticipates that the yr will be characterized as a non-El Niño yr (either a neutral yr or a La Niña yr), then the prediction likely will be either about average or slightly larger than average. During the previous eight El Niño years (defined using the best ENSO Index), the range is NS=6–12, NH=2–4, NMH=0–2, NUSFLH=0–1, and N4/5=0–1, while during the previous five La Niña years, the range is NS=8–13, NH=4–11, NMH=1–8, NUSLFH=0–3, and N4/5=0–3. Similarly, if one correctly anticipates that the yr is part of a long-term interval of less activity, the prediction likely will be slightly reduced, while if one correctly anticipates that the yr is part of a long-term interval of more activity, the prediction likely will be slightly augmented. For the 25 years spanning 1970–1994 (an interval indicative of less activity), the range is NS=4–14, NH=2–9, NMH=0–3, NUSLFH=0–6, and N4/5=0–3; while for the 36 years spanning 1945–1969 and 1995–2005 (intervals indicative of more activity), the range is NS=5–28, NH=3–15, NMH=0–8, NUSLFH=0–6, and N4/5=0–5. The central 50-percent probability intervals for these two activity related states (less/more) are NS=7–11/9–13, NH=3–6/5–8, NMH=1–2/2–4, NUSLFH=0–1/1–2, and N4/5=0–1/1–2. Tables 7 and 8 give the Poisson statistics for the less and more activity intervals, respectively, for each of the aforementioned parameters.

Another simple means for estimating yearly values for the parameters is based on determining the expected rate of change in the parametric 10-yr moving average (from one yr to the next). Figure 15 displays the yearly rates of change in the 10-yr moving averages of NS (lower panel), NH (lower middle panel), NMH (middle panel), NUSLFH (upper middle panel), and N4/5 (upper panel) for 1950–1999. Here, the parametric rate of change is computed as the difference in the 10-yr moving averages between two consecutive years for a particular parameter (specifically, the following yr value minus the current yr value). As an example, the NS_{10} for the yr 2000 is 14.4 (based upon the string of NS values spanning 1995–2005) and the NS_{10} for the yr 1999 is 13.5 (based upon the string of NS values spanning 1994–2004). The rate of change ΔNS_{10} for 1999 then equals 14.4 minus 13.5, or 0.9, which is the highest yearly rate of change observed during 1950–1999, and it is the 11th consecutive positive value in a string of positive values. Typically, the greatest concentration of parametric rates of change is –0.1 to +0.1, accounting for 26 of the 50 (52 percent) yearly rates of change for ΔNS_{10}, 29 of 50 (58 percent) for ΔNH_{10}, 31 of 50 (62 percent) for ΔNMH_{10}, 38 of 50 (76 percent) for $\Delta NUSLFH_{10}$, and 37 of 50 (74 percent) for $\Delta N4/5_{10}$. Table 9 gives the distributions for the parametric rates of change.

Presuming ΔNS_{10} for the yr 2000 equals –0.1 to +0.1 implies that NS_{10} for the yr 2001 will equal 14.3 to 14.5. Because the 10-yr moving average is calculated by summing the central nine values of NS, centered on the yr of interest (here, the central yr being 2001 and the central nine values being those for the years 1997–2005), then multiplying the sum by two and adding the values of NS for the yr 1996 and 2006, and then dividing by 20, plainly one can crudely estimate (with about 50-percent accuracy) the NS for 2006. The sum of NS for 1997–2005 equals 135 and NS for 1996 equals 13; hence, NS for 2006 would be estimated to be about 5 ± 2, presuming that NS_{10} for the yr 2000 is 14.4 ± 0.1. If, however, ΔNS_{10} is slightly enlarged to ± 0.2 (which captures about 70 percent of the known years), then the estimate for NS_{10} for the yr 2000 would be 14.4 ± 0.2, and the estimate for NS for the yr 2006 would be 5 ± 4. It should be noted that ΔNS_{10} has been positive in value for 11 consecutive years, averaging about 0.5; using NS_{10} equal to 14.9, one would estimate NS for the yr 2006 to be about 15.

Table 7. Poisson statistics for the less active interval 1970–1994.

r	NS		NH		NMH		NUSLFH		N4/5	
	Obs.	*P*(*r*)	Obs.	*P*(*r*)	Obs.	*P*(*r*)	Obs.	*P*(*r*)	Obs.	*P*(*r*)
0	0	0.0001	0	0.0065	3	0.2187	6	0.2894	10	0.4493
1	0	0.0009	0	0.0326	10	0.3324	14	0.3588	11	0.3595
2	0	0.0040	1	0.0822	8	0.2527	1	0.2225	3	0.1438
3	0	0.0124	4	0.1381	4	0.1280	3	0.0920	1	0.0383
4	1	0.0288	6	0.1740	0	0.0486	0	0.0285	0	0.0077
5	0	0.0535	4	0.1754	0	0.0148	0	0.0071	0	0.0012
6	3	0.0827	5	0.1474	0	0.0037	1	0.0015	0	0.0002
7	4	0.1097	3	0.1061	0	0.0008	0	0.0003	0	0.0000
8	3	0.1272	1	0.0668	0	0.0002	0	0.0000	0	0.0000
9	2	0.1312	1	0.0374	0	0.0000	0	0.0000	0	0.0000
10	2	0.1217	0	0.0189	0	0.0000	0	0.0000	0	0.0000
11	4	0.1027	0	0.0086	0	0.0000	0	0.0000	0	0.0000
12	3	0.0794	0	0.0036	0	0.0000	0	0.0000	0	0.0000
13	2	0.0567	0	0.0014	0	0.0000	0	0.0000	0	0.0000
14	1	0.0376	0	0.0005	0	0.0000	0	0.0000	0	0.0000
15	0	0.0233	0	0.0002	0	0.0000	0	0.0000	0	0.0000
16	0	0.0135	0	0.0001	0	0.0000	0	0.0000	0	0.0000
17	0	0.0074	0	0.0000	0	0.0000	0	0.0000	0	0.0000
18	0	0.0038	0	0.0000	0	0.0000	0	0.0000	0	0.0000
19	0	0.0019	0	0.0000	0	0.0000	0	0.0000	0	0.0000
20	0	0.0009	0	0.0000	0	0.0000	0	0.0000	0	0.0000
21	0	0.0004	0	0.0000	0	0.0000	0	0.0000	0	0.0000
22	0	0.0002	0	0.0000	0	0.0000	0	0.0000	0	0.0000
23	0	0.0001	0	0.0000	0	0.0000	0	0.0000	0	0.0000
24	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000
25	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000
26	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000
27	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000
28	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000
N(S)	25		25		25		25		25	
n	232		126		38		31		20	
m	9.28		5.04		1.52		1.24		0.80	

Similarly, one can estimate NH, NMH, NUSLFH, and N4/5 for the yr 2006, following the same procedure used for NS, using the greatest concentration intervals for the rates of change. Thus, for NH, presuming NH_{10} for 2000 to be about 8.0 ± 0.1, one computes NH for the yr 2006 to be about 5 ± 2; for NMH, presuming NMH_{10} for 2000 to be about 3.8 ± 0.1, one computes NMH for the yr 2006 to be about 3 ± 2; for NUSLFH, presuming $NUSLFH_{10}$ for 2000 to be about 2.2 ± 0.1, one computes NUSLFH for the yr 2006 to be about 0 (actually, -2 ± 2); and, for N4/5, presuming $N4/5_{10}$ for 2000 to be about 2.4 ± 0.1, one computes N4/5 for the yr 2006 to be ≤ 2 (actually, 0 ± 2).

Table 8. Poisson statistics for the more active intervals 1945–1969 and 1995–2005.

r	NS		NH		NMH		NUSLFH		N4/5	
	Obs.	*P*(*r*)	Obs.	*P*(*r*)	Obs.	*P*(*r*)	Obs.	*P*(*r*)	Obs.	*P*(*r*)
0	0	0.0000	0	0.0010	1	0.0321	4	0.1313	3	0.1511
1	0	0.0001	0	0.0067	15	0.1103	12	0.2666	13	0.2855
2	0	0.0007	0	0.0233	8	0.1897	6	0.2706	12	0.2698
3	0	0.0026	4	0.0539	7	0.2175	11	0.1831	3	0.1700
4	0	0.0074	4	0.0936	3	0.1871	1	0.0929	3	0.0803
5	1	0.0170	3	0.1299	6	0.1287	0	0.0377	2	0.0304
6	2	0.0325	5	0.1503	3	0.0738	2	0.0128	0	0.0096
7	2	0.0535	6	0.1490	2	0.0363	0	0.0037	0	0.0026
8	5	0.0769	5	0.1292	1	0.0156	0	0.0009	0	0.0006
9	3	0.0982	4	0.0996	0	0.0060	0	0.0002	0	0.0001
10	2	0.1129	1	0.0692	0	0.0021	0	0.0000	0	0.0000
11	5	0.1181	2	0.0436	0	0.0006	0	0.0000	0	0.0000
12	4	0.1131	1	0.0252	0	0.0002	0	0.0000	0	0.0000
13	3	0.1001	0	0.0135	0	0.0000	0	0.0000	0	0.0000
14	2	0.0822	0	0.0067	0	0.0000	0	0.0000	0	0.0000
15	3	0.0630	1	0.0031	0	0.0000	0	0.0000	0	0.0000
16	1	0.0453	0	0.0013	0	0.0000	0	0.0000	0	0.0000
17	0	0.0306	0	0.0005	0	0.0000	0	0.0000	0	0.0000
18	1	0.0196	0	0.0002	0	0.0000	0	0.0000	0	0.0000
19	1	0.0119	0	0.0001	0	0.0000	0	0.0000	0	0.0000
20	0	0.0068	0	0.0000	0	0.0000	0	0.0000	0	0.0000
21	0	0.0037	0	0.0000	0	0.0000	0	0.0000	0	0.0000
22	0	0.0020	0	0.0000	0	0.0000	0	0.0000	0	0.0000
23	0	0.0010	0	0.0000	0	0.0000	0	0.0000	0	0.0000
24	0	0.0005	0	0.0000	0	0.0000	0	0.0000	0	0.0000
25	0	0.0002	0	0.0000	0	0.0000	0	0.0000	0	0.0000
26	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000
27	0	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000
28	1	0.0000	0	0.0000	0	0.0000	0	0.0000	0	0.0000
N(S)	36		36		36		36		36	
n	414		250		124		73		68	
m	11.50		6.94		3.44		2.03		1.89	

At the time of writing this TP (December 2006) the 2006 North Atlantic basin tropical cyclone season is officially over. To date, there have been nine storms, including no unnamed storms, five hurricanes, two major hurricanes, no U.S. landfalling hurricanes, and no category 4/5 storms. At the beginning of the season, it was generally thought that because the current season is one that is part of a second long-term more active cycle and because of the robustness of the 2005 season, numbers for the 2006 season probably would be higher than average, especially since ENSO appeared to be in the neutral phase. The initial "NOAA: 2006 Atlantic Hurricane Outlook" (issued May 22, 2006; see <http://www.cpc.noaa.gov/products/outlooks/hurricane.shtml>) called for

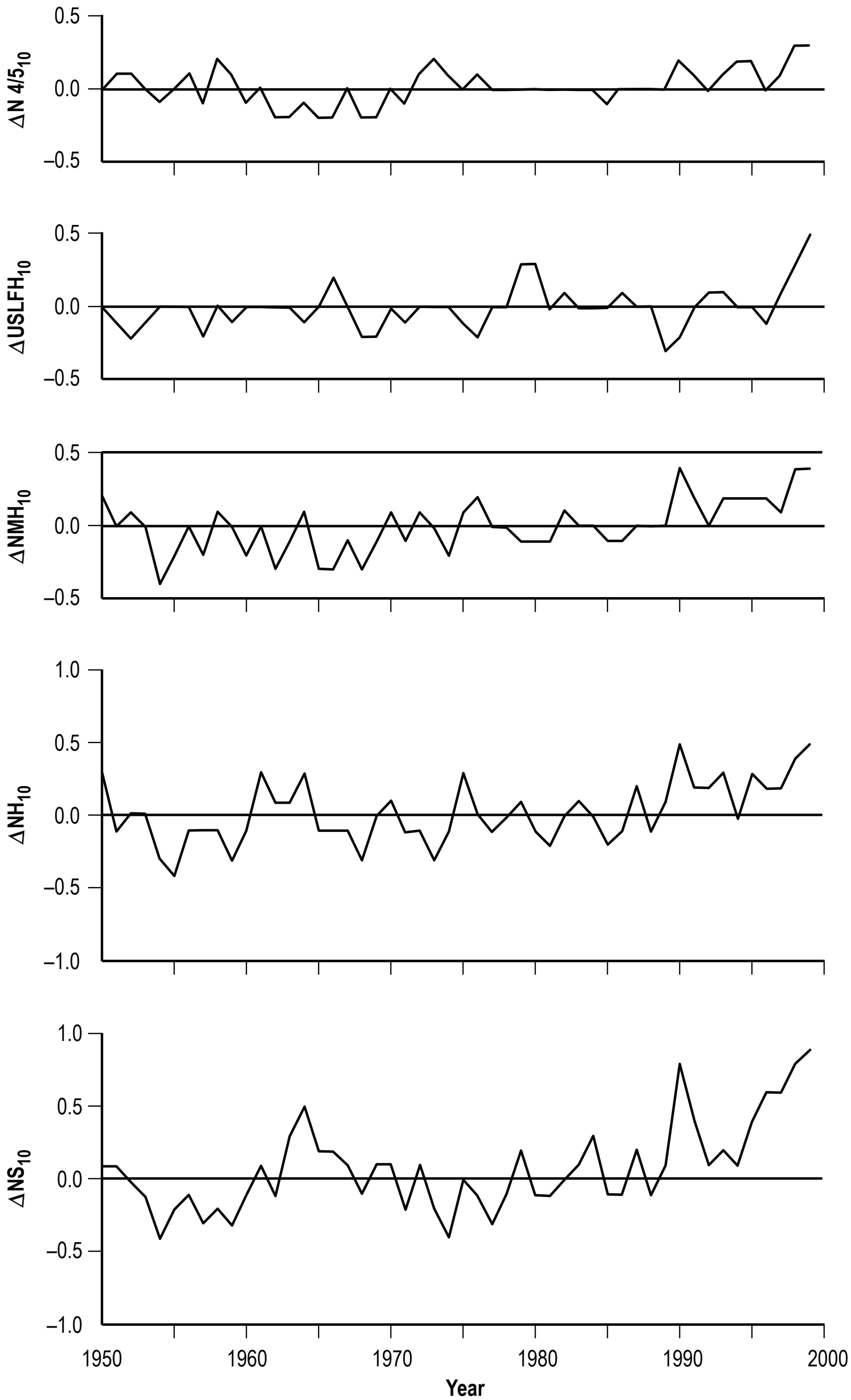


Figure 15. The yearly variation of the parametric 10-yr moving average rates of change.

a very active season, with 13–16 named storms, 8–10 hurricanes, and 4–6 major hurricanes. The bases for the very active season (though less active than the 2005 season) were the warmer than normal SST, lower wind shear, reduced sea-level pressure, and a more conducive structure of the African easterly jet. The official NOAA

Table 9. Distribution of parametric 10-yr moving average rates of change.

Rate of Change	NS	NH	NMH	NUSLFH	N4/5
–0.5	0	0	0	0	0
–0.4	2	1	1	0	0
–0.3	3	4	4	1	0
–0.2	4	2	4	6	6
–0.1	12	15	9	7	6
0.0	3	8	14	26	21
0.1	11	6	8	5	10
0.2	5	5	7	1	5
0.3	2	6	0	3	2
0.4	2	1	3	0	0
0.5	1	2	0	1	0
0.6	2	0	0	0	0
0.7	0	0	0	0	0
0.8	2	0	0	0	0
0.9	1	0	0	0	0
1.0	0	0	0	0	0
Total	**50**	**50**	**50**	**50**	**50**
<–0.1	9	7	9	7	6
–0.1 to +0.1	26	29	31	38	37
>+0.1	15	14	10	5	7

prediction, in fact, echoed earlier predictions by the team at Colorado State University in December 2005 and April 2006, which called for the 2006 Atlantic hurricane season to be much more active than the 1950–2000 averages, including 17 named storms, 9 hurricanes, 5 major hurricanes, and the probability of a U.S. landfalling hurricane being 55 percent above the long-term average (this being increased to 60 percent above the long-term average in their May 2006 update; see <http://typhoon.atmos.colostate.edu/forecasts/>).

Things began to change, however, with the August update. In August 2006, the NOAA outlook still called for an above normal 2006 Atlantic hurricane season, but now called for fewer storms: 12–15 named storms, 7–9 hurricanes, and 3–4 major hurricanes. The reasons cited for the reductions were a lessening of the atmospheric and oceanic conditions conducive to a more active forecast, a faster transition from La Niña-like rainfall patterns, and a very persistent upper-level ridge pattern over the eastern U.S. and western Atlantic basin.

Similarly, updates from Colorado State University also began to reflect a lessening of activity for the 2006 season. In their August 2006 forecast, they estimated 15 named storms, 7 hurricanes, and 3 major hurricanes, with the likelihood of a U.S. landfalling hurricane being reduced to a probability of about 40 percent above the long-term average. In their September update, the numbers were further reduced to 13 named storms, 5 hurricanes, and 2 major hurricanes blaming the reduced activity to an unexpected increase in tropical Atlantic mid-level dryness (owing to large amounts of African dust) and a continued trend toward El Niño-like conditions in the eastern and central Pacific. The numbers were again reduced in their October update to 11 named storms, 6 hurricanes (an increase), and 2 major hurricanes, noting the rapid late summer development of an El Niño event that had not been anticipated.

Obviously, predicting exactly the number of named storms, hurricanes, major hurricanes, and U.S. landfalling hurricanes during a season remains a most difficult proposition to accomplish, with unforeseen (unpredicted) events, like El Niño and the effects of the African dust, having a dramatic effect on the final outcome. Even so, it is a worthwhile endeavor yielding insight into the vagaries of Earth's climate.[51–53]

As previously noted, the 2006 North Atlantic basin tropical cyclone season (yr) ended with NS=9, NH=5, NMH=2, NUSLFH=0, and N4/5=0. These numbers allow for the exact determination of the 10-yr moving averages of the parameters for the yr 2001—Namely, NS_{10}=14.6, NH_{10}=8.0, NMH_{10}=3.8, $NUSLFH_{10}$=2.3, and $N4/5_{10}$=2.4. Such values yield parametric rates of change for the yr 2000, respectively, equal to +0.2, 0.0, 0.0, +0.1, and 0.0. Thus, for the 51 years spanning 1950–2000, the distribution of the rate of change in the 10-yr moving average of NS (table 9) is now <–0.1:9, –0.1 to +0.1:26, and >+0.1:16, indicating that the expected NS_{10} for 2002 should be about 14.6 ± 0.1, with about 51-percent accuracy, and inferring NS=12 ± 2 for the 2007 season, indicative of a continued above average (more active) hurricane season. The positive rate of change for ΔNS_{10} for the yr 2000 is the 12th consecutive year having a positive value, the longest string of same sign values in the span of 1950–2000.

Similarly, following the same procedure, NH_{10} for 2002 should be about 8.0 ± 0.1, with about 59-percent accuracy, inferring NH=7 ± 2 for the 2007 season; NMH_{10} for 2002 should be about 3.8 ± 0.1, with about 63-percent accuracy, inferring NMH=5 ± 2 for the 2007 season; $NUSLFH_{10}$ for 2002 should be about 2.3 ± 0.1, with about 76-percent accuracy, inferring NUSLFH=3 ± 2 for the 2007 season; and $N4/5_{10}$ for 2002 should be about 2.4 ± 0.1, with about 75-percent accuracy, inferring N4/5=2 ± 2 for the 2007 season. If El Niño continues for several months into 2007 (as predicted by the Climate Prediction Center in December 2006—El Niño conditions are likely to persist through May 2007), then the numbers forecast for the 2007 season, should be slightly reduced. If, however, El Niño dissipates quickly and is not a modulating factor, then the numbers might be slightly augmented, reflecting the continued more active state that has been apparent since the mid-1990s. In fact, the early December prediction issued by Colorado State University researchers William Gray and Philip Klotzbach calls for 14 named storms, 7 hurricanes, and 3 major hurricanes during the 2007 season (see <www.coloradoan.com> for December 8, 2006). Likewise, Mark Saunders of the University College of London predicts 16 named storms, 9 hurricanes, and 4 major hurricanes for the 2007 season (see <www.heraldtribune.com> for December 8, 2006). These predictions, as well as the one presented above, based on the simple statistical expected rates of change, all suggest a return to higher than average NS in the 2007 season. So, once again, predicting the 2007 season appears fraught with uncertainty, at least in these early stages of the prediction process, not knowing whether El Niño will or will not be a factor in the 2007 hurricane season. It should be noted that the recurrence rates of the extremes in the ENSO cycle, using the best ENSO index, favors a return of La Niña very soon. (For forecasts of the ENSO, see <http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory/index.shtml>).

3. SUMMARY

More than half the U.S. population lives along the narrow coastal fringe of the U.S. (see <http://oceanservice.noaa.gov/programs/mb/supp_cstl_population.html>), a large portion of this population living along the coasts from Texas to Maine. Found here are many of the nation's shipping ports and air-transportation hubs, energy-related endeavors, food/fishing industries, and vacation spots all of which can be affected—sometimes quite harshly—by hurricanes, as evidenced by 2005's Katrina.

Each year various commercial, educational, and governmental agencies provide educated guesses (predictions, forecasts, estimates) as to what might be expected for the next hurricane season—how many storms, how many hurricanes, how many major hurricanes, the likelihood of a landfalling hurricane along the coastal U.S., etc. These valiant attempts are required both to advance our understanding of climate and to alert the public as to the potential for damage and loss of life. As Max Mayfield, former Director of the National Hurricane Center, once quoted, "It only takes one hurricane to make a really bad year."[54]

In this study, the statistical aspects of the North Atlantic basin tropical cyclones during the interval 1945–2005 have been described, looking specifically for inferred trends and examining the roles of natural variability and global warming as related to them. On average, there have been about 10.6 tropical cyclones in any given yr during the span of 1945–2005, with yearly rates ranging between 4 in 1983 and 28 in 2005. Also, on average, there have been about 6.2 hurricanes per yr, ranging between 2 and 15 per yr; 2.7 major hurricanes per yr (those of category 3–5, having peak sustained WS ≥111 mph) and ranging between 0 and 8 per yr; 1.6 U.S. landfalling hurricanes per yr, ranging between 0 and 6 per yr, and 1.4 category 4/5 events per yr (having sustained WS ≥131 mph and ranging between 0 and 5 per yr). On the basis of the best ENSO Index, there have been eight El Niño years and five La Niña years during the span of 1945–2005. During El Niño years, the frequency of tropical cyclones in the North Atlantic basin is reduced, while during La Niña years the frequency tends to be augmented. Prior to the 2006 season, El Niño last occurred in 2002 and La Niña last occurred in 1988. Based on their average rates of recurrence, either type event could have occurred during the 2006 season, although at the start of the year atmospheric and oceanic conditions reflected a continuing neutral phase for the ENSO cycle; as yet, there has not been a La Niña event during the current more active cycle, and a short-lived El Niño was observed at year's end.

On the basis of 5-yr averages, the 5-yr intervals of 1995–1999 and 2000–2004 had the greatest number of tropical cyclones during the twelve 5-yr intervals spanning 1945–2004, averaging about 69–70 storms, including 39 hurricanes, 18–19 major hurricanes, 10 U.S. landfalling hurricanes (3 striking as major hurricanes), 11–12 category 4/5 hurricanes, and 2–3 storms having LP<925 mb. The next 5-yr interval, 2005–2009, seems poised to have numbers comparable to or even higher than the previous two 5-yr intervals.

While the bulk of the tropical cyclones have occurred during the months of June–November, on rare occasions (19 events) they have occurred during December–May, with none, as yet, having occurred in March. The months of August–October have accounted for 78 percent of all tropical cyclones, 84 percent of all hurricanes, 93 percent of all major hurricanes, 86 percent of all U.S. landfalling hurricanes, 93 percent of all category 4/5 hurricanes, and 100 percent of all hurricanes having LP<925 mb. The state of Florida has been struck more times (38) by hurricanes than any other state, nearly twice as much as the states of North Carolina (22) and Louisana (20), the second and third most frequently hit states.

Based on the movement of the mean yearly GL, the average GL of tropical cyclones was southward of 22.2° N latitude and westward of 65.4° W longitude during the first more active interval (1945–1969). During the less active interval (1970–1994), the average GL was northward of 22.2° N latitude and eastward of 65.4° W longitude. Now, in this second more active interval (since 1995), while there has been a return to latitudes southward of the long-term average latitude, the GL remains eastward of the long-term average longitude.

Interestingly, PWS, <PWS>s, and <PWS>h, as well as, <D>s, <D>h, and <D>mh (with LP, <LP>s, and <LP>h varying inversely) display variations that suggest higher values during the more active years and lower values during the less active years. Indeed, the various parameters are strongly correlated and all appear highly correlated against surface AT as determined by the Armagh Observatory in Northern Ireland, particularly since 1989. Thus, the less active years appear to associate with a cooling, while the recent more active years appear to associate with a warming. Removal of the temperature dependency, however, yields residuals that still appear to vary systematically (cyclic variations of decadal or multidecadal lengths).

The distribution of parametric 10-yr moving average rates of change is strongly centered on a yr-to-yr rate of change between –0.1 and +0.1. Hence, one can use it to crudely estimate the numbers of tropical cyclones and hurricanes for the upcoming season. Based on that simple statistical technique, the 2007 season should be one above average and more robust than the 2006 season, but not as robust as the 2005 season, having about 12 ± 2 tropical cyclones, 7 ± 2 hurricanes, 5 ± 2 major hurricanes, 3 ± 2 U.S. landfalling hurricanes, and 2 ± 2 category 4/5 hurricanes. Dependent upon whether El Niño persists into the first several months of 2007, these numbers will be slightly reduced or augmented, if El Niño abruptly ends.

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Statistical aspects of the North Atlantic basin tropical cyclones for the interval 1945–2005 are examined, including the variation of the yearly frequency of occurrence for various subgroups of storms (all tropical cyclones, hurricanes, major hurricanes, U.S. landfalling hurricanes, and category 4/5 hurricanes); the yearly variation of the mean latitude and longitude (genesis location) of all tropical cyclones and hurricanes; and the yearly variation of the mean peak wind speeds, lowest pressures, and durations for all tropical cyclones, hurricanes, and major hurricanes. Also examined is the relationship between inferred trends found in the North Atlantic basin tropical cyclonic activity and natural variability and global warming, the latter described using surface air temperatures from the Armagh Observatory in Armagh, Northern Ireland. Lastly, a simple statistical technique is employed to ascertain the expected level of North Atlantic basin tropical cyclonic activity for the upcoming 2007 season.

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