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An Estimate of North Atlantic Basin Tropical Cyclone Activity for 2008

Robert M. Wilson
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August 2008

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LIST OF ACRONYMS AND SYMBOLS

AT	Armagh Observatory, Northern Ireland, surface air temperature
°C	degrees Celsius
CSU	Colorado State University
D	duration (in months)
EN	El Niño
ENR	El Niño-related
ENSO	El Niño Southern Oscillation
ERSST.v2	extended reconstructed sea surface temperature (version 2)
°F	degrees Fahrenheit
FD_{10}	first difference of the parametric 10-yr moving average
$<FD_{10}>$	average parametric value of the first difference of the 10-yr moving average
FSD	first storm day of the hurricane season
i	the year
kt	knot (one nautical mile per hour)
LN	La Niña
LP	lowest pressure (in millibars)
<LP>	average lowest pressure per storm
LSD	last storm day of the hurricane season
M	moderate strength
ma	moving average

LIST OF ACRONYMS AND SYMBOLS (Continued)

mb	millibar (a unit of atmospheric pressure)
mph	miles per hour
N4/5	number of category 4 and 5 hurricanes
NASA	National Aeronautics and Space Administration
NENR	non-El Niño-related
NH	number of hurricanes
NMH	number of major hurricanes (those of category 3 or higher)
NOAA	National Oceanic and Atmospheric Administration
NTC	number of tropical cyclones
NUSLFH	number of U.S. land-falling hurricanes
ONI	Oceanic Niño Index
P	proportion
PWS	peak wind speed (in kt)
<PWS>	average peak wind speed per storm
RR	recurrence rate
S	strong strength
SST	sea surface temperature
TSR	Tropical Storm Risk
U.S.	United States
W	weak strength
X	parametric value
yr	year

NOMENCLATURE

a	y-intercept in the inferred regression equation
b	slope in the inferred regression equation
cl	confidence level for the inferred regression equation
r	coefficient of correlation
r^2	coefficient of determination
sd	standard deviation
se	standard error of estimate
Σ	the summation symbol

TECHNICAL PUBLICATION

AN ESTIMATE OF NORTH ATLANTIC BASIN TROPICAL CYCLONE ACTIVITY FOR 2008

1. INTRODUCTION

A tropical cyclone is a non-frontal synoptic low-pressure system that forms over the warm tropical or subtropical waters (at least 27 °C, or 80 °F) and has organized convection and cyclonic surface wind circulation.[1,2] When the tropical cyclone has sustained winds of ≥34 kt (39 mph), it is referred to as a 'tropical storm.' When its sustained winds attain 64 kt (74 mph), it is referred to as a 'hurricane' (or 'typhoon' in the Northwest Pacific Ocean or 'severe' tropical cyclone in the Southwest Pacific Ocean and Southeast Indian Ocean), becoming a 'major,' or 'intense,' hurricane when its sustained winds reach 96 kt (111 mph). In terms of hurricane categories, a tropical cyclone is considered a major hurricane when it is category 3 or higher (the scale runs category 1–5). Based on past North Atlantic basin tropical cyclone activity (where the North Atlantic basin includes the North Atlantic Ocean, the Gulf of Mexico and the Caribbean Sea), a typical hurricane season extends 6 mo, from June 1 through November 30 in any given year (with the bulk of activity occurring in August–October), although occasionally tropical cyclones have been seen at other times outside this interval (in all months except March).[3]

Every year, various groups forecast the expected frequency of tropical cyclones for that particular season, including the expected number of storms, the expected number of hurricanes, and the expected number of intense hurricanes forming in the North Atlantic basin. For example, the Colorado State University (CSU) team[4] has predicted that the 2008 season should see 15 tropical cyclones forming in the North Atlantic basin, 8 becoming hurricanes and 4 becoming major hurricanes, whereas the official National Oceanic and Atmospheric Administration (NOAA) outlook[5] calls for 12–16 tropical cyclones forming in the North Atlantic basin, 6–9 becoming hurricanes and 2–5 becoming major hurricanes, and the Tropical Storm Risk (United Kingdom) team[6] predicts 14.8 ± 4.1 tropical cyclones, including 7.8 ± 2.7 hurricanes and 3.5 ± 1.8 major hurricanes for the 2008 season.

The purpose of this NASA Technical Publication (TP) is to reexamine the climatology associated with North Atlantic basin tropical cyclones, updating previous work[3,7–13] and offering a prediction of tropical cyclone activity for the current 2008 hurricane season.

2. RESULTS

Figure 1 displays the number of North Atlantic basin tropical cyclones (NTC), the number of hurricanes (NH), the number of major hurricanes (NMH), the number of category 4 and 5 major hurricanes (N4/5) and the number of U.S. land-falling hurricanes (NUSLFH) that have been reported for the interval 1945–2007, shown as the thin, jagged lines. The thicker, smoother lines are the 10-yr moving averages, and the horizontal lines are the median values. Also shown are the means and standard deviations (*sd*) for each group and the occurrences of El Niño (EN, the filled triangles) and La Niña (LN, the unfilled triangles) events based on the Oceanic Niño Index (ONI),[14] determined using the extended reconstructed sea surface temperature (version 2) database (ERSST.v2). The post-1945 North Atlantic basin data set of tropical cyclone activity is considered the most reliable, owing to routine use of aircraft reconnaissance and continuous satellite viewing (from the 1960s).[15,16]

For the interval of 1945–2007 (spanning some 63 yr), there have been, on average, about 11 tropical cyclones forming in the North Atlantic basin each year, of which about 6 become hurricanes, 2–3 become major hurricanes (1–2 becoming category 4 or 5 during their development), and about 1–2 become hurricanes striking the U.S. coastline (most often along the Florida coast).[3] It should be noted that the identified median values are the principal modal values, as well. Based on its 10-yr moving average, NTC has remained rather flat for most of the interval, at least for the subinterval of 1950–1990. Beginning in 1990, however, a substantial increase has been underway (perhaps peaking in the early 2000s), owing to the sharp increase in 1995 and thereafter. Prior to 1995, annual frequencies of NTC ranged typically between about 6 and 12 per year, with the largest frequency of occurrence in 1969 (18 tropical cyclones). From 1995, the rate has surpassed the median in 11 of the past 13 years, ranging between 8 and 28 (the infamous 2005 season) tropical cyclones per year.

For the other parameters (NH, NMH, N4/5, and NUSLFH), their 10-yr moving averages suggest a decreasing trend from the 1950s and an increasing trend from the 1990s, perhaps indicating a division of the decadal time interval into a simple bi-modal state: more active in the 1950s, 1960s, and the 1990s on, and less active during the 1970s and 1980s (this being especially true for NMH). While the current 10-yr moving averages of NTC, NH, and N4/5 are higher than ever seen in the record, those of NMH and NUSLFH remain slightly below the peaks of the 1950s. Should the upward trends continue, then clearly one should expect higher-than-average frequencies during the coming years, especially if the trends are related to global warming.[3,17–52]

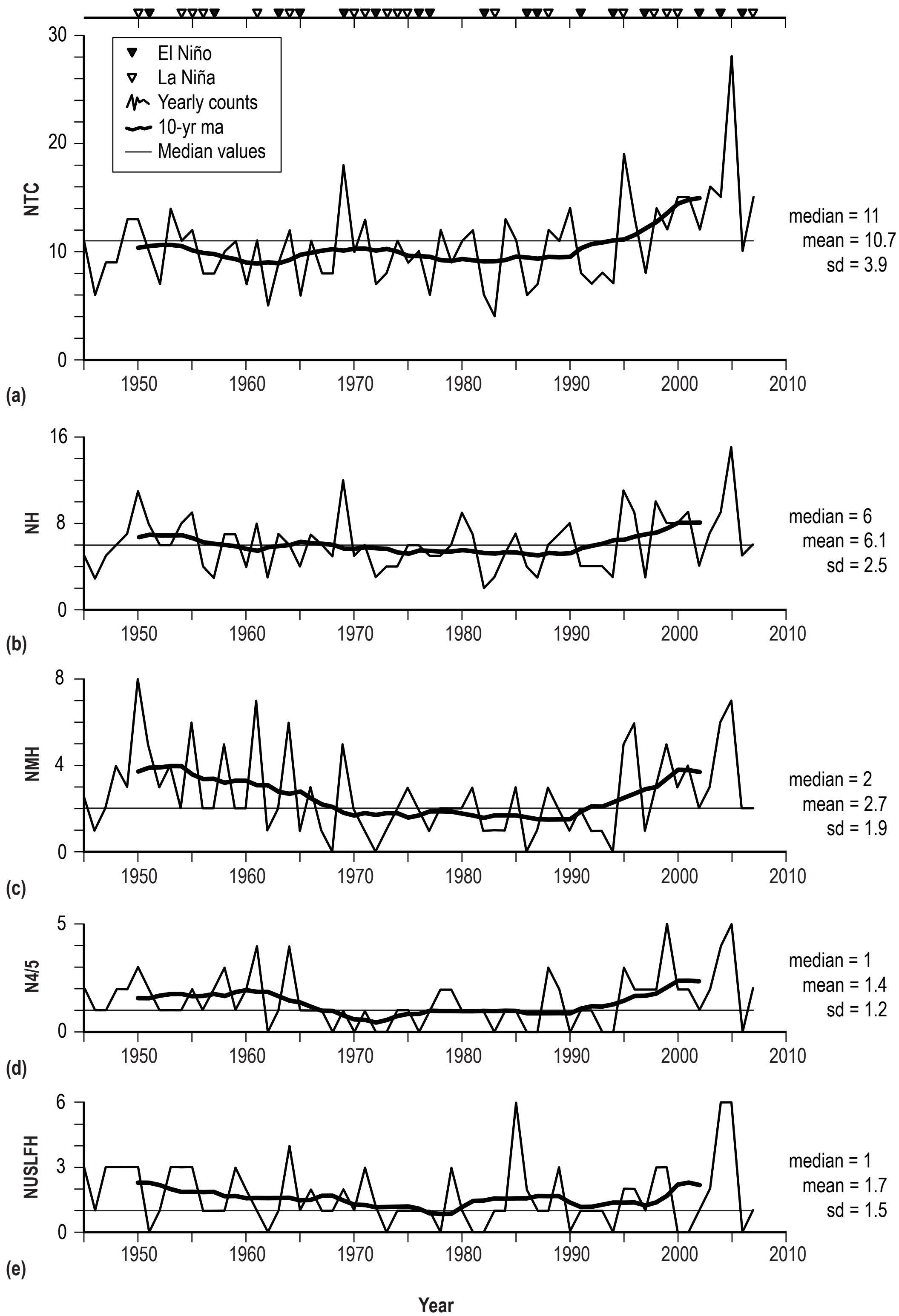

Figure 1. Variation of (a) NTC, (b) NH, (c) NMH, (d) N4/5, and (e) NUSLFH for the interval 1945–2007. Shown are the yearly counts (thin, jagged lines), 10-yr moving averages (thick, smoothed lines), median values (horizontal lines), means and standard deviations, and the occurrences of EN (filled triangles) and LN (unfilled triangles) events.

Figure 2 shows the peak wind speed (PWS, in kt), the average peak wind speed per storm (<PWS>, in kt), the lowest pressure (LP, in mb) and the average lowest pressure per storm (<LP>, in mb) for the interval 1945 – 2007. As in figure 1, shown are the yearly values (the thin, jagged lines), the 10-yr moving averages (the thicker, smoother lines), the medians (the horizontal lines), the means and standard deviations, and the occurrences of EN and LN. For the interval of 1945 – 2007, PWS has averaged about 127 kt, ranging typically between 100 and 150 kt, with the lowest PWS occurring in 1968 (75 kt) and the highest in 1969 and 1980 (165 kt, associated with Camille and Allen, respectively). Other notable years of PWS in excess of 150 kt include 1950 (160 kt, Dog), 1988 (160 kt, Gilbert), 1998 (155 kt, Mitch), and 2005 (155 kt, Rita, and 160 kt, Wilma; Katrina attained a PWS of 150 kt). While the overall trend (10-yr moving average) slowly decreased from the 1950s through the 1980s, it now appears to be trending upward, attaining values reminiscent of the 1950s. In fact, the last 10-yr moving average value (134.5 kt) is almost equal to the peak that was seen in 1954 (135 kt).

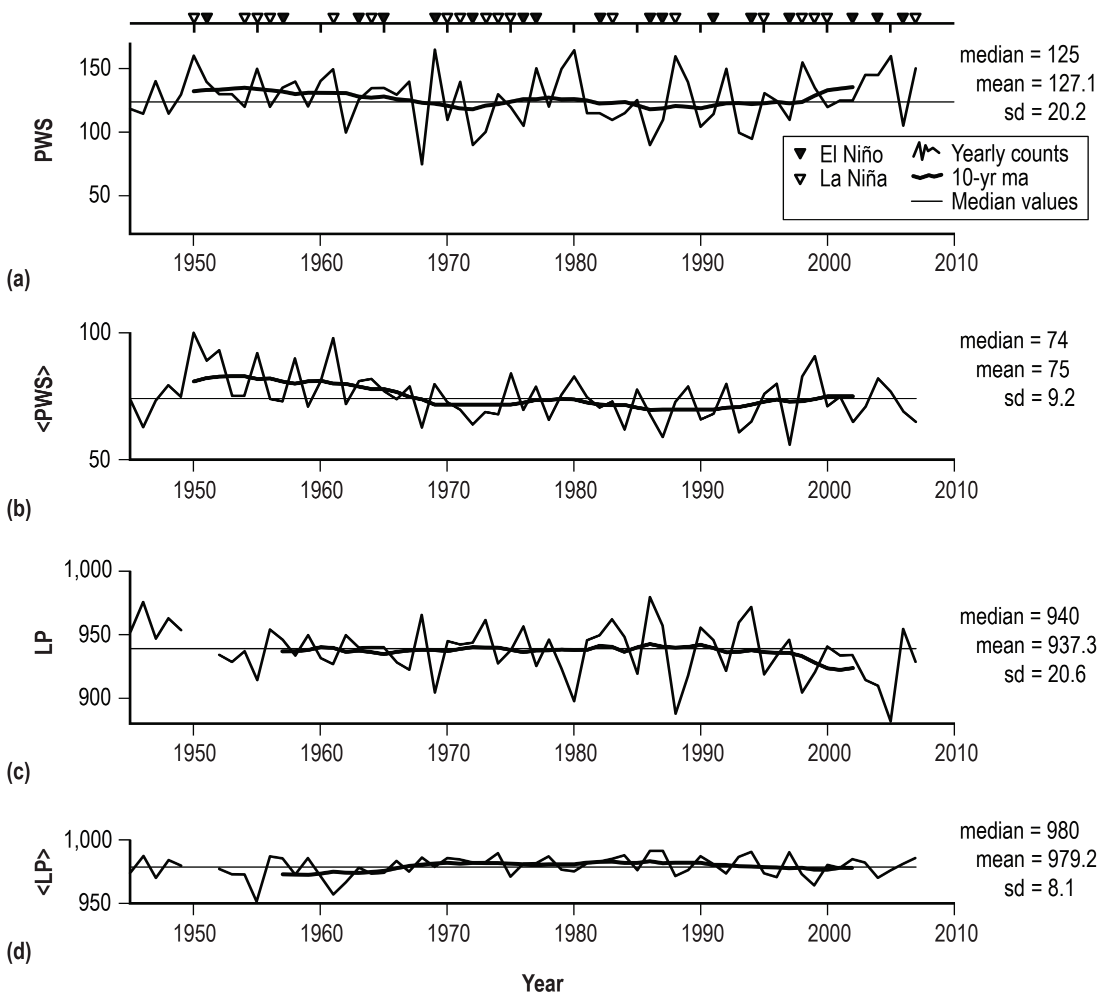

Figure 2. Variation of (a) PWS, (b) <PWS>, (c) LP, and (d) <LP> for the interval 1945–2007. Shown are the yearly values (thin, jagged lines), 10-yr moving averages (thick, smoothed lines), median values (horizontal lines), means and standard deviations, and the occurrences of EN (filled triangles) and LN (unfilled triangles) events.

Concerning <PWS>, a definite decrease occurred between the 1950s and the 1980s, with a slow rise beginning in the 1990s. While the trend is upward, current values pale in comparison to that found for the 1950s (74.5 kt in 2002 as compared to 83.4 kt in 1954).

For LP, the trend is relatively flat until about the 1990s. The value in 2002 measured 923.5 mb, being about 1.5% lower than the long-term average. Tropical cyclones having LPs < 900 mb include Allen (1980, 899 mb), Gilbert (1988, 888 mb), Rita (2005, 897 mb), and Wilma (2005, 882 mb). By comparison, Andrew in 1992 had LP = 922 mb and Katrina in 2005 had LP = 902 mb. Other noteworthy storms include Janet in 1955 (914 mb), Hattie in 1961 (920 mb), Beulah in 1967 (923 mb), Camille in 1969 (905 mb), David in 1979 (924 mb), Gloria in 1985 (920 mb), Hugo in 1989 (918 mb), Opal in 1995 (919 mb), Mitch in 1998 (905 mb), Floyd in 1999 (921 mb), Isabel in 2003 (915 mb) and Ivan in 2004 (910 mb). Of the 18 storms identified here, 13 have occurred since 1980, suggesting, perhaps, that an intensification of tropical cyclones is presently underway.

For <LP>, the overall trend is quite flat, although there was a slight increase (weakening) to values above the long-term average in the 1970s and 1980s and a slight decrease (strengthening) to values below the long-term average since the 1990s. In all fairness, however, it must be pointed out that the record of LPs in the 1940s and early 1950s is incomplete. Table 1 provides a detailed account of the yearly values plotted in figures 1 and 2. (The reader should remember that pressure and wind speed are inversely related, meaning that lower pressures are associated with faster wind speeds and vice versa.)

Table 1. North Atlantic basin tropical cyclone statistics (1945–present).

			Yearly Counts					10-yr Moving Average					Yearly Values				10-yr Moving Average				
Year	FSD	LSD	NTC	NH	NMH	N4/5	NUSLFH	NTC	NH	NMH	N4/5	NUSLFH	PWS	<PWS>	LP	<LP>	PWS	<PWS>	LP	<LP>	EN/LN
1945	06-20	10-14	11	5	3	2	3	–	–	–	–	–	120	73	951	974	–	–	–	–	–
1946	06-13	11-02	6	3	1	1	1	–	–	–	–	–	115	63	975	987	–	–	–	–	–
1947	07-31	10-22	9	5	2	1	3#	–	–	–	–	–	140	73	947	970	–	–	–	–	–
1948	05-22	11-11	9	6	4	2	3	–	–	–	–	–	115	79	963	984	–	–	–	–	–
1949	08-21	11-04	13	7	3	2	3	–	–	–	–	–	130	75	954	980	133.8	82.3	–	–	–
1950	08-12	10-24	13	11	8	3	3	10.4	6.7	3.7	1.6	2.3	160	100	–	–	131.5	80.5	–	–	LN(M)
1951	05-16	10-20	10	8	5	2	0	10.5	7.0	3.9	1.6	2.3	140	89	–	–	133.3	82.0	–	–	EN(W)
1952	02-02	10-28	7	6	3	1	1	10.6	6.9	3.9	1.7	2.2	130	93	934	977	133.3	82.5	–	–	–
1953	05-25	12-09	14	6	4	1	3	10.6	6.9	4.0	1.8	2.0	130	75	929	973	134.3	83.1	–	–	–
1954	06-24	01-05*	11	8	2	1	3	10.5	6.9	4.0	1.8	1.9	120	75	937	973	135.0	83.4	–	–	LN(M)
1955	07-31	10-20	12	9	6	2	3	10.1	6.6	3.6	1.7	1.9	150	92	914	951	133.5	82.3	–	–	LN(S)
1956	06-12	11-07	8	4	2	1	1#	9.9	6.2	3.4	1.7	1.9	120	74	954	987	133.0	81.8	–	–	LN(W)
1957	06-08	10-27	8	3	2	2	1	9.8	6.1	3.4	1.8	1.9	135	73	945	979	132.0	81.2	935.7	972.3	EN(S)
1958	06-14	10-13	10	7	5	3	1	9.5	6.0	3.2	1.7	1.7	140	90	934	973	130.3	80.4	937.1	972.1	–
1959	05-29	10-21	11	7	2	1	3	9.3	5.9	3.3	1.9	1.7	120	71	950	986	130.8	81.1	937.8	972.4	–
1960	06-23	09-19	7	4	2	2	2#	9.0	5.6	3.3	2.0	1.6	140	81	932	972	130.8	80.7	939.4	973.6	–
1961	07-20	11-09	11	8	7	4	1	8.9	5.5	3.1	1.9	1.6	150	98	920	957	130.5	79.9	939.5	974.7	LN(W)
1962	08-27	10-23	5	3	1	0	0	9.0	5.8	3.1	1.9	1.6	100	72	950	967	131.3	80.2	937.1	974.4	–
1963	08-02	10-30	9	7	2	1	1	8.9	5.9	2.8	1.7	1.6	125	81	940	978	128.3	79.2	937.6	974.9	EN(M)
1964	06-07	11-08	12	6	6	4	4	9.2	6.0	2.7	1.5	1.6	135	82	941	974	127.3	78.3	936.9	975.2	LN(M)
1965	06-14	10-19	6	4	1	1	1#	9.7	6.3	2.8	1.4	1.5	135	77	941	975	128.0	78.3	935.3	975.6	EN(S)
1966	06-06	11-14	11	7	3	1	2	9.9	6.2	2.5	1.2	1.5	130	74	929	984	126.0	76.5	937.1	977.7	–
1967	08-30	11-01	8	6	1	1	1	10.1	6.1	2.2	1.0	1.7	140	79	923	976	125.0	74.7	937.9	979.9	–
1968	06-02	10-21	8	5	0	0	1	10.2	6.0	2.1	1.0	1.7	75	63	965	986	123.3	73.7	938.7	981.0	–
1969	07-27	11-25	18	12	5	1	2	10.1	5.7	1.8	0.8	1.5	165	80	905	980	121.8	72.4	939.2	982.0	EN(W)
1970	05-20	10-28	10	5	2	0	1	10.2	5.7	1.7	0.6	1.3	110	73	945	986	120.8	72.1	938.4	982.7	LN(W)
1971	07-05	11-22	13	6	1	1	3	10.3	5.8	1.8	0.6	1.3	140	70	943	985	118.8	72.2	939.7	982.4	LN(M)
1972	05-26	11-05	7	3	0	0	1	10.1	5.7	1.7	0.5	1.2	90	64	944	983	118.0	72.0	941.3	982.6	EN(S)
1973	07-03	10-30	8	4	1	0	0	10.2	5.6	1.8	0.6	1.2	100	69	962	983	120.8	72.2	940.5	983.0	LN(S)
1974	06-25	10-08	11	4	2	1	1	10.0	5.3	1.8	0.8	1.2	130	68	928	990	122.3	72.1	940.6	983.0	LN(W)
1975	06-29	12-12	9	6	3	1	1	9.6	5.2	1.6	0.9	1.2	120	84	939	972	124.3	72.4	939.2	982.3	LN(S)

Table 1. North Atlantic basin tropical cyclone statistics (1945–present). (Continued)

			Yearly Counts					10-yr Moving Average					Yearly Values				10-yr Moving Average				
Year	FSD	LSD	NTC	NH	NMH	N4/5	NUSLFH	NTC	NH	NMH	N4/5	NUSLFH	PWS	<PWS>	LP	<LP>	PWS	<PWS>	LP	<LP>	EN/LN
1976	05-23	10-29	10	6	2	0	1	9.6	5.5	1.7	0.9	1.1	105	70	957	982	125.8	73.2	937.1	981.7	EN(W)
1977	08-30	10-18	6	5	1	1	1	9.5	5.5	1.9	1.0	0.9	150	79	926	982	125.8	73.8	937.5	981.5	EN(W)
1978	01-19	11-03	12	5	2	2	0	9.2	5.4	1.9	1.0	0.9	120	66	947	988	127.0	74.3	937.9	981.7	–
1979	06-22	10-25	9	6	2	2	3#	9.1	5.4	1.9	1.0	0.9	150	76	924	977	126.3	74.2	939.0	981.8	–
1980	08-02	11-28	11	9	2	1	1	9.3	5.5	1.8	1.0	1.2	165	83	899	976	125.8	73.6	939.1	982.0	–
1981	05-07	11-17	12	7	3	1	0	9.2	5.4	1.7	1.0	1.5	115	75	946	982	125.3	73.2	939.2	982.7	–
1982	06-03	10-03	6	2	1	1	0	9.1	5.2	1.6	1.0	1.5	115	71	950	983	122.5	72.1	941.9	983.7	EN(S)
1983	08-15	09-30	4	3	1	0	1	9.1	5.2	1.7	1.0	1.6	100	73	963	986	122.5	71.5	940.6	983.5	LN(W)
1984	08-19	12-24	13	5	1	1	1	9.2	5.3	1.7	1.0	1.6	115	62	949	989	124.0	72.0	937.4	982.7	–
1985	07-16	11-23	11	7	3	1	6#	9.5	5.3	1.7	1.0	1.6	125	78	920	977	120.5	71.3	939.9	983.2	–
1986	06-06	11-21	6	4	0	0	2	9.4	5.1	1.6	0.9	1.6	90	68	979	992	117.5	70.1	942.8	983.7	EN(M)
1987	08-09	10-14	7	3	1	0	1	9.3	5.0	1.5	0.9	1.7	110	59	958	992	119.3	70.2	941.3	983.2	EN(S)
1988	08-07	11-26	12	6	3	3	1	9.5	5.2	1.5	0.9	1.7	160	73	888	973	121.0	70.0	939.8	982.8	LN(S)
1989	06-26	12-04	11	7	2	2	3	9.4	5.1	1.5	0.9	1.7	140	79	918	976	120.0	69.6	940.8	982.9	
1990	07-24	10-21	14	8	1	0	0	9.5	5.2	1.5	0.9	1.4	105	66	956	987	119.3	69.6	941.9	982.8	
1991	07-04	11-02	8	4	2	1	1	10.3	5.7	1.9	1.1	1.2	115	68	946	981	121.3	70.1	939.5	981.6	EN(M)
1992	04-22	10-29	7	4	1	1	1#	10.7	5.9	2.2	1.2	1.2	150	80	922	974	123.0	70.6	936.6	980.5	
1993	06-19	09-21	8	4	1	0	1	10.8	6.1	2.2	1.2	1.3	100	61	960	987	122.8	70.9	936.9	980.4	
1994	07-02	11-20	7	3	0	0	0	11.0	6.4	2.4	1.3	1.4	95	65	972	990	122.3	72.0	937.9	979.9	EN(M)
1995	06-03	11-03	19	11	5	3	2	11.1	6.4	2.6	1.5	1.4	130	76	919	974	122.8	72.9	937.3	979.0	LN(W)
1996	06-19	11-26	13	9	6	2	2	11.5	6.7	2.8	1.7	1.4	125	80	933	971	124.0	73.5	935.9	978.5	
1997	06-01	10-17	8	3	1	0	1#	12.1	6.9	3.0	1.7	1.3	110	56	946	991	123.3	73.1	935.9	979.0	EN(S)
1998	07-29	12-02	14	10	3	2	3	12.7	7.1	3.1	1.8	1.4	155	83	905	973	124.3	72.8	934.3	979.3	LN(M)
1999	06-12	11-21	12	8	5	5	3	13.5	7.5	3.5	2.1	1.7	135	91	921	965	129.0	74.2	928.9	978.1	LN(M)
2000	08-04	10-29	15	8	3	2	0	14.4	8.0	3.9	2.4	2.2	120	71	941	980	133.0	75.1	924.0	977.2	LN(W)
2001	06-05	12-04	15	9	4	2	0	14.7	8.0	3.8	2.4	2.3	125	75	934	979	133.5	74.6	923.2	977.7	
2002	07-15	10-12	12	4	2	1	1	14.9	8.0	3.7	2.4	2.2	125	65	934	985	134.5	74.5	923.5	978.0	EN(S)
2003	04-19	12-10	16	7	3	2	2						145	71	915	982					
2004	08-01	12-02	15	9	6	4	6#						145	82	910	971					EN(W)
2005	06-09	01-06*	28	15	7	5	6#						160	77	882	975					
2006	06-11	10-03	10	5	2	0	0						105	69	955	985					EN(M)

Table 1. North Atlantic basin tropical cyclone statistics (1945–present). (Continued)

			Yearly Counts					10-yr Moving Average					Yearly Values				10-yr Moving Average				
Year	**FSD**	**LSD**	**NTC**	**NH**	**NMH**	**N4/5**	**NUSLFH**	**NTC**	**NH**	**NMH**	**N4/5**	**NUSLFH**	**PWS**	**<PWS>**	**LP**	**<LP>**	**PWS**	**<PWS>**	**LP**	**<LP>**	**EN/LN**
2007	05-09	12-12	15	6	2	2	1						150	65	907	986					LN(M)
2008																					

Legend:

FSD	first storm day (wind speed 34+ kt), month-day
LSD	last storm day (wind speed 34+ kt), month-day
NTC	number of tropical cyclones (wind speed 34+ kt)
NH	number of hurricanes (wind speed 64+ kt)
NMH	number of major hurricanes (category 3-5, wind speed 96+ kt)
N4/5	number of category 4/5 major hurricanes (wind speed 114+ kt)
NUSLFH	number of U.S. land-falling hurricanes
*	LSD occurred in the following year
#	multiple U.S. land-falls by a hurricane
EN	El Niño (based on ONI, see http://ggweather.com/enso/oni.htm)
LN	La Niña (based on ONI, see http://ggweather.com/enso/oni.htm)
W	weak (based on ONI, see http://ggweather.com/enso/oni.htm)
M	moderate (based on ONI, see http://ggweather.com/enso/oni.htm)
S	strong (based on ONI, see http://ggweather.com/enso/oni.htm)
PWS	peak wind speed in kt
<PWS>	average peak wind speed per storm in kt
LP	lowest pressure in mb
<LP>	average lowest pressure per storm in mb

Note: In this report hurricane seasons are determined EN- or LN-related if at least 3 months during the season the ONI reflects EN or LN conditions, respectively. Table 2 gives dates of occurrence for EN and LN events since 1950.

El Niño conditions are known to affect the frequency of occurrence of tropical cyclones.[3,8–10,13,53–55] In particular, there usually is a reduction in the number of tropical cyclones forming in the North Atlantic basin when EN conditions prevail. Table 2 gives the start, peak, and end dates, duration (in months), event type (EN or LN), event strength (weak, moderate, or strong), peak ONI value (determined using the ERSST.v2 data set) and comments for specific events for those events occurring during the interval of 1950–2007. This listing of events is based on the ONI running 3-mo mean sea surface temperature (SST) anomaly for the Niño 3.4 region (located 5°N–5°S, 120°–170°W), which has become the de-facto standard that NOAA uses for identifying warm (EN) and cold (LN) events. In particular, events are determined when 5 or more months continuously have ONI values either 0.5 °C at or above SST anomaly (EN) or 0.5 °C at or below SST anomaly (LN). Weak events have ONI values between 0.5 and 0.9 °C SST anomaly for warm events and –0.5 and –0.9 °C SST anomaly for cold events; moderate events have ONI values between 1.0 and 1.4 °C SST anomaly for warm events and between –1.0 and –1.4 °C SST anomaly for cold events. Strong events have ONI values ≥1.5 °C SST anomaly for warm events and ≤–1.5 °C for cold events. In total, some 29 events are given, including 16 EN and 13 LN (however, the first and last events are incomplete, so complete knowledge is inferred for only 27 events), and these 29 events span 35 of the 58 yr between 1950 and 2007. The 23 non-extreme years are El Niño Southern Oscillation (ENSO)-neutral years, with ONI values neither warmer nor colder than their respective 5 °C thresholds. In the table, the first event is not completely discerned; hence, the letter B indicates that the event started before January 1950. Also, the peak date may have occurred before January 1950. Likewise, the last event is not completely discerned; hence, the letter A indicates that the event will end after January 2008 and its peak may be colder than indicated. Also, it should be noted that this event listing is much richer than the one used in Wilson (2007).[3] In it, extreme events were determined from the combined effects of both atmospheric and oceanic signals, using the ENSO Index developed by Catherine Smith and Prashant Sardeshmukh (available at <http://www.cdc.noaa.gov/people/cathy.smith/best/>).[56] Consequently, only 8 EN and 5 LN years were ascertained.

Table 3 gives the means, standard deviations, and ranges for each of the parameters (NTC, NH, NMH, N4/5, NUSLFH, PWS, <PWS>, LP, and <LP>) for all three ENSO conditions: EN, LN, and neutral. Clearly, when EN conditions prevail, the frequency of tropical cyclones is typically depressed below long-term averages. Also, when LN conditions prevail, a slight enhancement above the long-term averages is apparent. On average, there appear to be about three additional storms forming during a typical LN season, as compared to a typical EN season, and the difference is statistically important at the 5% level of significance (confidence level, $cl > 95\%$). A statistically significant difference in the means of the two groups is also true for NH, NMH, N4/5, <PWS>, and <LP>, but not true for NUSLFH, PWS, or LP. Hence, while the numbers of storms might be depressed during an EN season and the <PWS> and <LP> might be indicative of weaker storms, the number striking the U.S. and the storm with highest PWS and lowest pressure are statistically no different from when neutral or LN conditions prevail. A case in point is 1969, when EN conditions prevailed both before the hurricane season and during the latter half of the hurricane season. (It should be noted that in tables 1 and 2, a year is denoted EN or LN when at least 3 consecutive months occur during the interval June–November that are indicative of EN or LN, respectively, based on the ONI descriptor. As an example, ONI spanned –0.1 to –1.2 during the June–November 2007 hurricane season, being –0.8, –1.1, and –1.2 during the 3-mo span of September–November 2007, indicative of LN conditions of moderate strength, so noted as LN(M) in table 1. Also, the actual strength of the LN event at the end of 2007 is denoted strong, based on the ONI value of –1.5 in January 2008, and is so noted in table 2.)

Table 2. Occurrence dates for EN and LN events based on the ONI for 1950–2007.

Start	Peak	End	Duration (mo)	Type	Strength	Peak ONI Value	Comment
B01-1950	01-1950?	03-1951	15+	LN	Strong	–1.8	
08-1951	10/11-1951	12-1951	5	EN	Weak	0.7	
04-1954	11-1955	01-1957	34	LN	Strong	–2.1	Secondary local peak of –1.1 in 10/11-1954
04-1957	01-1958	06-1958	15	EN	Strong	1.6	
09-1961	09/10-1961	04-1962	8	LN	Weak	–0.6	
07-1963	11/12-1963	01-1964	7	EN	Moderate	1.0	
04-1964	10/11-1964	02-1965	11	LN	Moderate	–1.1	
06-1965	11-1965	04-1966	11	EN	Strong	1.6	
10-1967	02-1968	04-1968	7	LN	Weak	–0.9	
11-1968	01/02-1969	01-1970	15*	EN	Moderate	1.0	Secondary local peak of 0.7 in 10/11-1969
07-1970	01/02-1971	01-1972	19	LN	Moderate	–1.4	
05-1972	12-1972	03-1973	11	EN	Strong	2.1	
05-1973	11-1973	05-1976	36#	LN	Strong	–1.9	Secondary local peak of –1.8 in 12-1975
09-1976	11/12-1976	02-1977	6	EN	Weak	0.8	
09-1977	11/12-1977	01-1978	5	EN	Weak	0.8	
05-1982	12-1982/01-1983	06-1983	14	EN	Strong	2.3	
09-1983	11-1983	01-1984	5	LN	Weak	–0.9	
10-1984	12-1984	06-1985	9	LN	Moderate	–1.1	
08-1986	08/09-1987	02-1988	19	EN	Strong	1.6	Secondary local peak of 1.3 in 01-1987
05-1988	11/12-1988	05-1989	13	LN	Strong	–1.9	
05-1991	01-1992	06-1992	14	EN	Strong	1.8	
04-1994	12-1994	03-1995	12	EN	Moderate	1.3	
09-1995	12-1995/01-1996	03-1996	7	LN	Weak	–0.8	
05-1997	11/12-1997	04-1998	12	EN	Strong	2.5	
07-1998	01-1999$	02-2001	32$	LN	Strong	–1.6	
05-2002	11-2002	03-2003	11	EN	Strong	1.5	
07-2004	09/10/11-2004	02-2005	8	EN	Weak	0.9	
09-2006	11/12-2006	01-2007	5	EN	Moderate	1.1	
09-2007	01-2008?	A01-2008	5+	LN	Strong	–1.5?	

Note: ONI values based on ERSST.v2 SST anomalies in the Niño 3.4 region
* ONI dipped below 0.5 threshold to 0.4 for 3 months (06-1969 – 08-1969)
# ONI dipped below 0.5 threshold to –0.4 for 1 month (08-1974)
$ ONI dipped below 0.5 threshold to –0.3 for 3 months (07-2000 – 09-2000); Attained same peak value (–1.6) in 12-1999 and 01-2000
B Before
A After
? Questionable

Table 3. Statistics of North Atlantic basin tropical cyclones based on ONI conditions (1950–2007).

Statistic	EN–Related Seasons(17)					LN–Related Seasons(18)					Neutral Seasons(23)				
	NTC	NH	NMH	N4/5	NUSLFH	NTC	NH	NMH	N4/5	NUSLFH	NTC	NH	NMH	N4/5	NUSLFH
mean	9.0	5.0	1.9	0.9	1.2	11.6	6.8	3.2	1.9	1.8	11.3	6.7	2.6	1.2	1.7
sd	3.4	2.6	1.8	1.1	1.4	3.3	2.4	1.9	1.5	1.2	4.6	2.5	1.7	0.8	1.7
range	6–18	2–12	0–6	0–4	0–6	4–19	3–11	1–8	0–5	0–4	5–28	3–15	0–7	0–5	0–6

Statistic	EN–Related Seasons(17)				LN–Related Seasons(18)				Neutral Seasons(23)			
	PWS	<PWS>	LP	<LP>	PWS	<PWS>	LP	<LP>	PWS	<PWS>	LP	<LP>
mean	120.9	71.5	944.3	983.1	132.5	78.7	931.0	976.2	128.0	75.1	932.7	978.9
sd	21.7	8.8	19.4	6.0	19.2	10.5	20.8	11.0	20.9	8.1	19.4	6.2
range	90–165	56–89	905–980	971–992	100–160	65–100	888–963	951–990	75–165	61–93	882–966	967–989

As previously mentioned, values have been substantially higher (stronger) since 1995. Table 4 compares means, standard deviations, and ranges for each of the parameters, comparing post-1995 values against pre-1995 values. Plainly, all parameters, except <PWS> and <LP>, show that since 1995 the frequency of occurrence and peak strength of North Atlantic basin tropical cyclones have increased dramatically.

Table 4. Comparison of pre- and post-1995 statistical values.

	NTC		NH		NMH		N4/5		NUSLFH		PWS		<PWS>		LP		<LP>	
Statistic	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
mean	9.6	14.8	5.7	8.0	2.4	3.9	1.2	2.3	1.6	2.1	125.5	133.1	75.2	73.9	941.1	923.2	979.5	978.2
sd	2.8	4.9	2.1	3.2	1.8	1.9	1.0	1.6	1.3	2.0	20.8	17.0	9.2	9.2	19.3	19.9	8.3	7.5
range	4–18	8–28	2–12	3–15	0–8	1–7	0–4	0–5	0–6	0–6	75–165	105–160	59–100	56–91	888–980	882–955	951–992	965–991

Table 5 identifies the recurrence rate (RR) and duration (D) of EN and LN events since 1950. Of the 29 EN and LN events listed in table 2, information is sufficient to characterize RR and D for 26 of the events. The LN event of 1950 could not be used because no start date is given, and the D for the LN event of 2007 is presently unknown (since the event continues). Also, the RR for the EN event of 2006 is unknown, since another EN has yet to occur. (The reader should note that the recurrence rate is determined from the start of a particular event to the start of the next same type event, disregarding event strength. As an example, the August 1951 start of an EN was followed by the next start of an EN event in April 1957, 68 mo later; thus, the RR is 68 mo. Similarly the April 1954 start of a LN event was followed by the next start of a LN event in September 1961, 89 mo later; thus, its RR is 89 mo.)

Table 6 compares the mean, standard deviation, and range for EN and LN events, according to event strength and in total. Hence, EN events appear to recur, on average, about every 58 mo (range: 13–124 mo), while LN events appear to recur, on average, about every 44 mo (range: 12–75 mo). If an ongoing EN event is of weak strength, then one would expect the next EN (of any strength) to occur, on average, about 21 mo later (range: 13–34 mo). If an ongoing EN event is of moderate strength, then one would expect the next EN (of any strength) to occur, on average, about 40 mo later (range: 34–43 mo). Last, if an ongoing EN event is of strong strength, then one would expect the next EN (of any strength) to occur, on average, about 103 mo later (range: 88–124 mo). Similarly, if an ongoing LN event is of weak strength, then one would expect the next LN (of any strength) to occur, on average, about 41 mo later (range: 12–68 mo). If an ongoing LN event is of moderate strength, then one would expect the next LN (of any strength) to occur, on average, about 34 mo later (range: 23–42 mo). Last, if an ongoing LN event is of strong strength, then one would expect the next LN (of any strength) to occur, on average, about 50 mo later (range: 12–75 mo).

Table 5. Recurrence rates and durations of extreme events.

LN Events*				EN Events**			
Start (Mo-Yr)	RR (mo)	D (mo)	Strength	Start (Mo-Yr)	RR (mo)	D (mo)	Strength
04-1954	89	34	S	08-1951	68	5	W
09-1961	31	8	W	04-1957	75	15	S
04-1964	42	11	M	07-1963	23	7	M
10-1967	33	7	W	06-1965	41	11	S
07-1970	34	19	M	11-1968	42	15	M
05-1973	124	36	S	05-1972	52	11	S
09-1983	13	5	W	09-1976	12	6	W
10-1984	43	9	M	09-1977	56	5	W
05-1988	88	13	S	05-1982	51	14	S
09-1995	34	7	W	08-1996	57	19	S
07-1998	110	32	S	05-1991	35	14	S
09-2007	–	5+	S	04-1994	37	12	M
				05-1997	60	12	S
				05-2002	26	11	S
				07-2004	26	8	W
				09-2006	–	5	M

Note:
* Excludes LN events of 1950 and 2007
** Excludes EN event of 2006 (for RR)
RR Recurrence Rate (in months)
D Duration (in months)
W Weak
M Moderate
S Strong

Table 6. Statistics of recurrence rates and durations for EN and LN events.

	RR* (mo)			D (mo)		
Grouping	mean	sd	range	mean	sd	range
LN(W)	21.0	13.0	13–34	6.8	1.3	5–8
LN(M)	39.7	4.9	34–43	13.0	5.3	9–19
LN(S)	102.8	17.4	88–124	28.8	10.6	13–36
All LN events	58.3	37.3	13–124	16.5	11.9	5–36
EN(W)	40.5	25.9	12–68	6.0	1.4	5–8
EN(M)	34.0	9.8	23–42	9.8	4.6	5–15
EN(S)	49.6	15.4	26–75	13.4	2.8	11–19
All EN events	44.1	17.9	12–75	10.6	4.3	5–19

Note:
* RR is from the start of the event to the start of the next event, regardless of event strength

Concerning the duration of the extreme events, on average, EN events (disregarding strength) last about 11 mo (range: 5–19 mo) and LN events (disregarding strength) last about 17 mo (range: 5–36 mo). If the ongoing EN is of weak strength, then one would expect its duration, on average, to be about 6 mo from start to end (range: 5–8 mo). If the ongoing EN is of moderate strength, then one would expect its duration, on average, to be about 10 mo (range: 5–15 mo). Last, if the ongoing EN is of strong strength, then one would expect its duration, on average, to be about 13 mo (range: 11–19 mo). Similarly, if the ongoing LN is of weak strength, then one would expect its duration, on average, to be about 7 mo from start to end (range: 5–8 mo). If the ongoing LN is of moderate strength, then one would expect its duration, on average, to be about 13 mo (range: 9–19 mo). Last, if the ongoing LN is of strong strength, then one would expect its duration, on average, to be about 29 mo (range: 13–36 mo).

Presently, a strong LN continues that began in September 2007. Since the LN event is of strong strength, one anticipates that its duration will be at least 13 mo (from the shortest observed duration reported for strong LN events since 1950; see tables 5 and 6). If true, then LN conditions will prevail well into and possibly through the current 2008 hurricane season. Thus, prediction of the frequencies of occurrence and strengths of the tropical cyclones for the 2008 hurricane season should be based on the statistics of LN-related seasons. It should be noted, however, that, according to the May 8, 2008, ENSO Diagnostics Discussion, NOAA forecasters[57] have reported that LN conditions have weakened considerably since February, but presently remain indicative of a continuing weak LN through April. Hence, a transition to ENSO-neutral conditions appears to be underway. If neutral conditions manifest themselves prior to August 2008, then the duration of the presently ongoing LN will be <11 mo, which is outside the experiential database of strong LN since 1950 (but not outside the 90% prediction interval of duration based on the four known LN(S) events, which is about 29 ± 23 mo), and the season would be best described as ENSO-neutral.

Presuming that LN conditions will prevail during the 2008 hurricane season, from table 3 one finds that, on average, previous (since 1950) LN-related seasons have had about 12 tropical cyclones forming in the North Atlantic basin, with about 7 becoming hurricanes, 3 becoming major hurricanes, 2 attaining category 4/5 status, and 2 striking the U.S. coastal areas. The 90% prediction intervals (correcting for sample size) for the 2008 hurricane season for each of the parameters are as follows: $NTC_{90} = 11.6 \pm 5.7$, $NH_{90} = 6.8 \pm 4.2$, $NMH_{90} = 3.2 \pm 3.3$, $N4/5_{90} = 1.9 \pm 2.6$, $NUSLFH_{90} = 1.8 \pm 2.1$, $PWS_{90} = 132.5 \pm 33.4$ kt, $\langle PWS \rangle_{90} = 78.7 \pm 18.3$ kt, $LP_{90} = 932.7 \pm 34.3$ mb, and $\langle LP \rangle_{90} = 976.2 \pm 18.8$ mb. Thus, there appears to be only a 5% chance that NTC will exceed 17 (unless the current season proves to be a statistical outlier, as was the 2005 season), NH will exceed about 11, NMH will exceed about 6, N4/5 will exceed about 5, NUSLFH will exceed about 4, PWS will exceed about 166 kt, <PWS> will exceed about 97 kt, LP will be lower than about 898 mb, and <LP> will be lower than about 957 mb. (Should neutral conditions prevail, one would have to slightly adjust the prediction interval accordingly.)

Another approach is simply to disregard the ENSO condition and use the post-1995 statistical values (a more active state). The 90% prediction intervals (correcting for sample size) for the 2008 hurricane season for each of the parameters are as follows: $NTC_{90} = 14.8 \pm 8.8$, $NH_{90} = 8.0 \pm 5.7$, $NMH_{90} = 3.7 \pm 3.2$, $N4/5_{90} = 2.3 \pm 2.9$, $NUSLFH_{90} = 2.1 \pm 3.6$, $PWS_{90} = 133.1 \pm 30.5$ kt, $\langle PWS \rangle_{90} = 73.9 \pm 16.5$ kt, $LP_{90} = 924.5 \pm 34.7$ mb, and $\langle LP \rangle_{90} = 977.9 \pm 12.9$ mb. Thus, presuming that the 2008 hurricane season is statistically similar to the post-1995 seasons, there appears to be only a 5% chance that NTC will exceed about 24, NH will exceed about 14, NMH will exceed about 7, N4/5 will exceed about 5, NUSLFH will exceed about 6, PWS will exceed about 164 kt, <PWS> will exceed about 90 kt, LP will be lower than about 890 mb, and <LP> will be lower than about 965 mb.

In Wilson (2007),[3] a method for predicting the expected frequencies based on the distribution of the rates of change in the parametric 10-yr moving averages was described. Figure 3 displays the first difference in the 10-yr moving averages (FD_{10}) of NTC, NH, and NMH for 1950–2001. By estimating the change in the parametric 10-yr moving average value, one effectively establishes a prediction for the current hurricane season. As described here, the first difference (FD_{10}) is defined as the change in the 10-yr moving average (ma) from one year to the next. As an example, the 10-yr moving average for NTC for the year 2001 is 14.7 and the 10-yr moving average for NTC for the year 2002 is 14.9, so one can infer that FD_{10} equals 0.2 for NTC for the year 2001 (that is, the 10-yr moving average value for NTC increased by 0.2 unit), and this is the value plotted in figure 3. To the right in figure 3 are the distributions of the parametric first differences and proportions (P) of the 52 FD_{10} values that fall within ± 0.1 unit and within ± 0.2 unit of the preceding 10-yr moving average value. For NTC, 50% of the time, its FD_{10} lies within ± 0.1 unit, and 69% of the time, it lies within ± 0.2 unit. Hence, one can use these proportions to approximate the expected frequency of occurrence of NTC for the 2008 hurricane season.

The 10-yr moving average for NTC for the year 2003 is calculated simply as

$$NTC_{10}(2003) = [NTC(1998) + NTC(2008) + 2\,(\Sigma NTC(i) \text{ for } i = 1999 \text{ through } 2007)]/20 \quad . \qquad (1)$$

In equation (1), there are two unknowns: $NTC_{10}(2003)$ and NTC(2008). However, one can approximate $NTC_{10}(2003)$ from the distribution of $FD_{10}(NTC)$, as follows:

$$NTC_{10}(2003) = NTC_{10}(2002) \pm x \quad , \qquad (2)$$

where $NTC_{10}(2002)$ is known and x is the estimate for the first difference (usually equal to ± 0.1 or ± 0.2, having occurred 50 and 69% of the time, respectively). As an example, $NTC_{10}(2002) = 14.9$. Assuming that the $FD_{10}(NTC)$ for 2003 will be ± 0.1, one determines $NTC(2008) = 8 \pm 2$, inferring only a 25% chance that NTC(2008) will exceed 10. On the other hand, assuming that $FD_{10}(NTC)$ for 2003 will be ± 0.2, one determines $NTC(2008) = 8 \pm 4$, inferring only about a 15% chance that NTC(2008) will exceed 12. Both predictions presume a normal distribution for $FD_{10}(NTC)$, though plainly the observed distribution has a noticeable rightward skew (towards higher first difference values), perhaps indicating that a first difference larger than 0.2 is a distinct possibility. In fact, rather than having 15% of the values higher than 0.2, one finds that the observed distribution exceeds 0.2 about 21% of the time. It should be noted that the mean FD_{10} value since 1990 is about 0.4, and one can infer that if the first difference in the 10-yr moving average of NTC for 2003 happens to equal 0.4, then one finds that NTC (2008) could be as high as 16. Only six times in the span of 52 years has the $FD_{10}(NTC)$ exceeded 0.4, all occurrences except one taking place since 1990.

For NH and NMH, their FD_{10} values have $P(\pm 0.1)$ equal to about 60 and 64%, respectively, and their FD_{10} values have $P(\pm 0.2)$ equal to about 73 and 85%, respectively. Also, the mean FD_{10} values since 1990 for both NH and NMH are about 0.2. Presuming that FD_{10} for both NH and NMH equals 0.2 for 2003, one expects 12 or fewer hurricanes and 7 or fewer major hurricanes to form in the North Atlantic basin in 2008. First differences larger than 0.2 have occurred only nine times for hurricanes (five times since 1990) and only three times for major hurricanes (all since 1990).

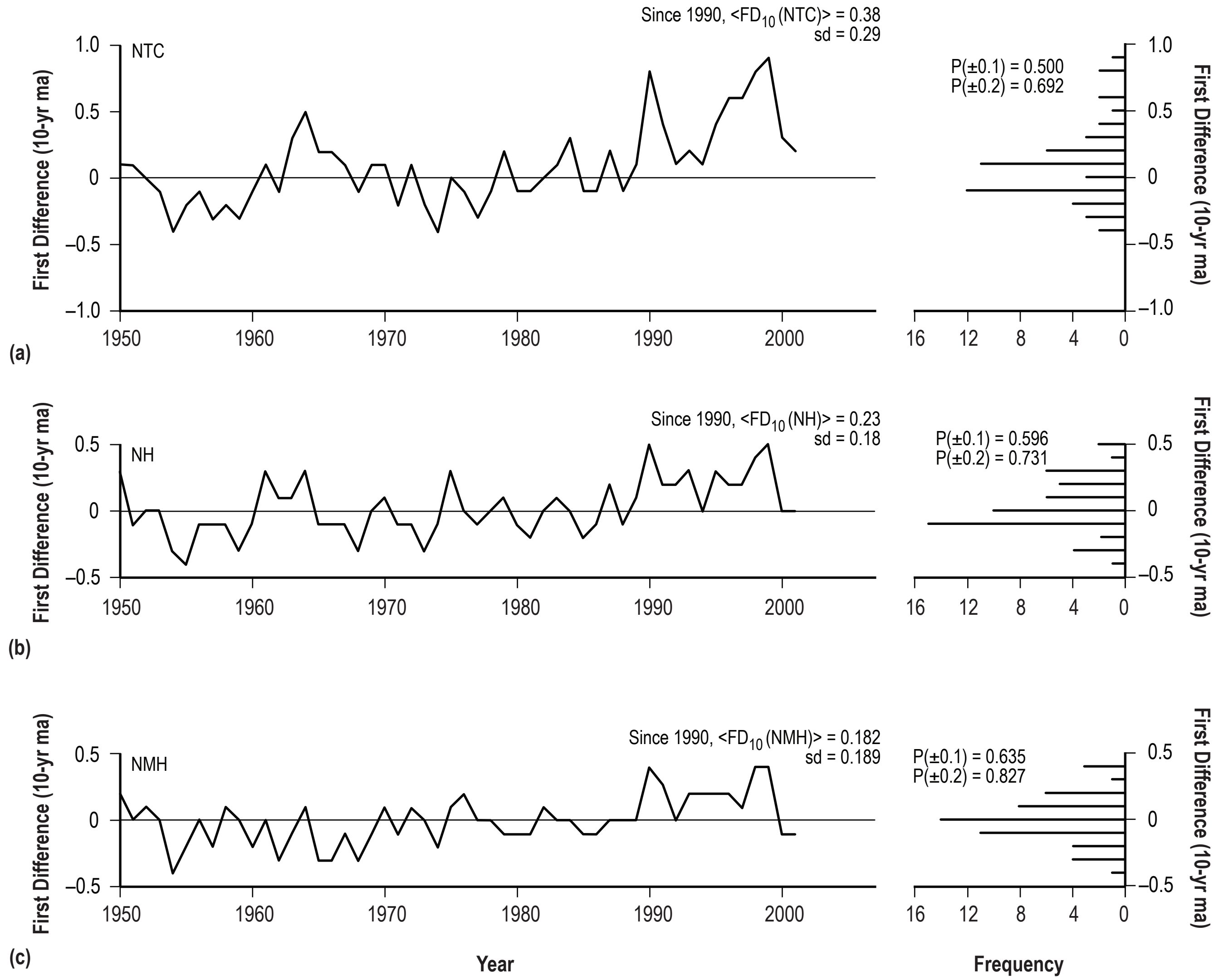

Figure 3. Variation of the yearly first difference of 10-yr moving average values for (a) NTC, (b) NH, and (c) NMH for the interval 1950–2001. Also shown are the distribution of first difference values, the proportions for ±0.1 and ±0.2 first difference values, and the average first difference value (and standard deviation) for values since 1990.

Figure 4 shows a similar plot for the first differences for N4/5 and NUSLFH. The ±0.1 and ±0.2 proportions for N4/5 are about 75 and 96%, respectively. For NUSLFH, the proportions are about 77 and 90%, respectively. Since 1990, the mean FD_{10} for both N4/5 and NUSLFH is about 0.1. Therefore, presuming that FD_{10} for both N4/5 and NUSLFH equals 0.1 for 2003, one expects two or fewer category 4 or 5 storms and five or fewer hurricanes to strike the U.S. coastline during the 2008 hurricane season. If instead one accepts 0.0 for the FD_{10} for 2003 for both N4/5 and NUSLFH, then one expects no category 4 or 5 storms and three or fewer hurricanes to strike the U.S. coastline during the 2008 hurricane season. (A value of 0.0 has occurred 44% of the time for N4/5 and 48% of the time for NUSLFH.)

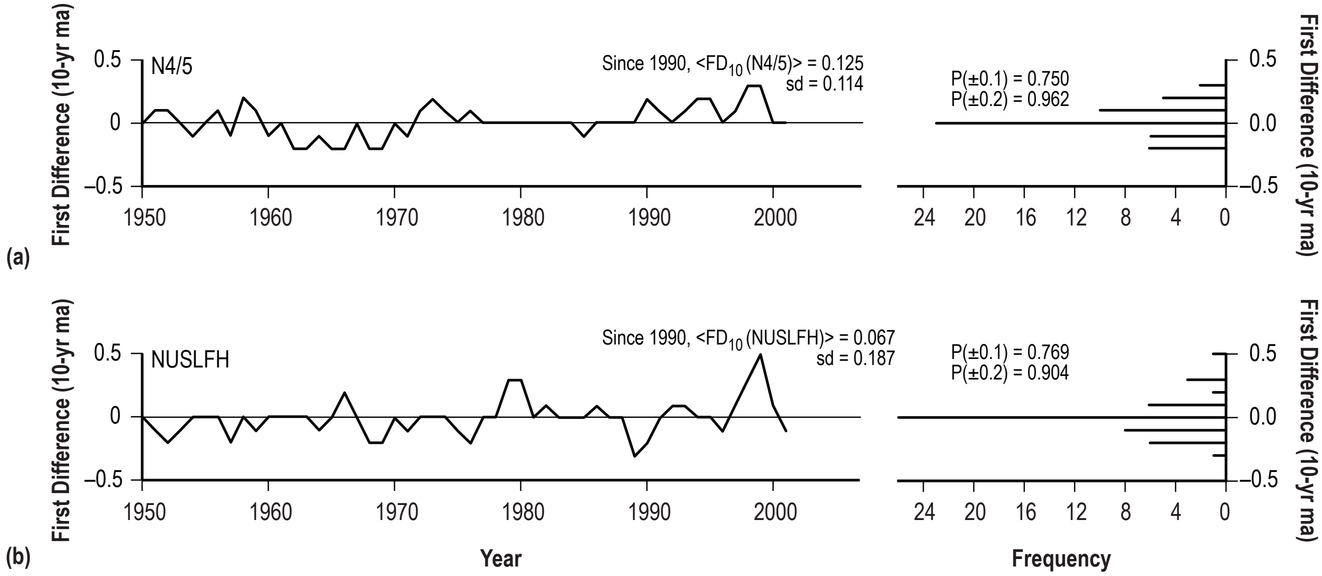

Figure 4. Variation of the yearly first difference of 10-yr moving averages for (a) N4/5 and (b) NUSLFH. Also shown are the distribution of first difference values and the first difference value (and standard deviation) for values since 1990.

3. DISCUSSION AND SUMMARY

Examined in this study were the statistical aspects of the North Atlantic basin tropical cyclones for the past 63 seasons (1945–2007), an interval considered the most reliably determined because of routine aircraft reconnaissance and continuous satellite viewing. In particular, both yearly values and 10-yr moving averages were ascertained, and the effects of ENSO on them were described. Last, estimates of the expected tropical cyclone activity for the current season were given, based on expected trends in the 10-yr moving averages.

For 1945–2007, the mean number of tropical cyclones forming in the North Atlantic basin measured 10.7, having a standard deviation of 3.9 and ranging between 4 (in 1982) and 28 (in 2005). Thus, presuming a normal distribution and no trending, the 90% prediction interval is 10.7 ± 6.5, which suggests only a 5% chance that 18 or more storms should be expected during any given season. In fact, 18 or more storms have occurred on only three occasions (which happen to be 5% of the samples): 1969 (18), 1995 (19), and 2005 (28).

Because the 10-yr moving average of the number of tropical cyclones has been trending upward since 1990, it is apparent that the number of tropical cyclones since 1995 has increased markedly. Indeed, the mean number of tropical cyclones post-1995 measures 14.8, having a standard deviation of 4.9 and ranging between 8 (1997) and 28 (2005). The 90% prediction interval post-1995 is 14.8 ± 8.7, which suggests only a 5% chance that 24 or more storms should be expected during the post-1995 era (also, there is only a 5% chance that fewer than 6 storms should be expected during the post-1995 era). Compared to the pre-1995 era, on average, about five additional storms per season have occurred during the post-1995 era. The difference in means (14.8 vs. 9.6) is statistically important at <0.1% level of significance (that is, greater than the 99.9% *cl*). Hence, it appears that since 1995, the likelihood of enhanced tropical cyclone activity in the North Atlantic basin has substantially increased.

Likewise, it is quite apparent that non-EN-related seasons tend to be more active than EN-related seasons, especially if the season is deemed LN-related. On average, based on the 17 prior EN-related seasons since 1950 (determined by the ONI), during an EN-related season one expects about 9 tropical cyclones, having a standard deviation of 3.4 and ranging between 6 and 18, thus yielding the 90% prediction interval of 9 ± 5.9. For LN-related seasons (18 since 1950), on average one expects 11.6 tropical cyclones, having a standard deviation of 3.3 and ranging between 4 and 19, thus yielding the 90% prediction interval of 11.6 ± 5.7. The difference in means (LN vs. EN) is statistically important at the 5% level of significance (95% *cl*). The difference in means between LN-related seasons and ENSO-neutral seasons is not statistically important.

Presently, a formerly strong LN, which began in September 2007, continues as a weak LN (through early 2008). Because strong LN events, on average (since 1950), persist about 29 mo (ranging in duration between 13 and 36 mo), it seems highly likely that the 2008 hurricane season will be a non-EN-related season (either an LN-related season or possibly an ENSO-neutral season). Hence, one should expect greater-than-average frequency of tropical cyclones this hurricane season.

Supporting this view is the fact that the trend in the 10-yr moving average has risen from 9.5 in 1990 to 14.9 in 2002, and the first difference in 10-yr moving average value has been positive (>0.0) since 1989, averaging about 0.4 (ranging between 0.1 and 0.9) since 1990. Hence, one expects the 10-yr moving average for 2003 to be 15 or higher. Presuming the 10-yr moving average will be exactly 15, the number of tropical cyclones expected in 2008 would be 10. Should the 10-yr moving average be 15.3 (reflecting the average increase of 0.4 since 1990), the number of tropical cyclones expected in 2008 will be 16. Only 6 of 52 first differences have been >0.4, all except one having occurred since 1990. So, it appears highly likely that the expected first difference for 2002 will be positive and that the 10-yr moving average will be greater than 15 for 2003, suggesting that one should expect more than the average number of tropical cyclones during the present season. (First differences tend to cluster about a value of 0.0, ranging from –0.4 to 0.9, with 11.5% being of value >0.4. For 69%, the values are ±0.2.)

Table 7 summarizes the expected frequency of occurrences for selected groupings of tropical cyclones for the 2008 hurricane season, based on the statistics of the North Atlantic basin tropical cyclone record for 1945–2007. Recall that the CSU team[4] predicts that the 2008 hurricane season will see 15 tropical cyclones, 8 hurricanes, and 4 major hurricanes. The official NOAA outlook[5] calls for 12–16 tropical cyclones, 6–9 hurricanes, and 2–5 major hurricanes. The TSR team[6] predicts about 11–19 tropical cyclones, 5–11 hurricanes, and 2–5 major hurricanes. Comparison of these values with those of table 7 reveals that all of these predictions essentially reflect mean post-1995 behavior. Thus, given that the 2008 hurricane season is one that is post-1995 and in all likelihood a non-EN-related season (see the appendix), above-average frequencies of occurrence should be expected for the current hurricane season.

Table 8 gives the decadal means, standard deviations, and ranges for each subgrouping of tropical cyclone activity. As an example, the decade of 1950–1959 averaged 10.4 tropical cyclones, having a standard deviation of 2.3 and ranging between 7 and 14 storms per season; it averaged 6.9 hurricanes, having a standard deviation of 2.3 and ranging between 3 and 11; and so forth. Compared to the 2000–2007 partial decade, none of the mean decadal rates are statistically different except the ones for NTC. For the partial decade of 2000–2007, NTC averages 15.8 tropical cyclones, having a standard deviation of 5.3 and ranging between 10 and 28. The difference in means is statistically important at the 0.2% level of significance (98% *cl*). Comparing the partial decade of 2000–2007 with the decade of the 1970s (or the 1960s or 1980s), one finds that all mean decadal rates are statistically different except the one for NUSLFH. Thus, the current epoch of tropical cyclone activity is statistically more active than the decades of the 1960s–1980s (less active), and similar to the decade of the 1950s (with the lone exception of NTC, with about five additional tropical cyclones, on average, than in the 1950s). The number of U.S. land-falling hurricanes has remained relatively constant for the past 5+ decades.

Table 7. Summary of expected frequency of occurrences for selected groupings of tropical cyclones for the 2008 hurricane season.

Parameter	NTC	NH	NMH	N4/5	NUSLFH
mean (1945–2007)	10.7	6.1	2.7	1.4	1.7
range (1945–2007)	4–28	2–15	0–7	0–5	0–6
mean (LN-related season)	11.6	6.8	3.2	1.9	1.8
range (LN-related season)	4–19	3–11	1–8	0–5	0–4
mean (post-1995)	14.8	8.0	3.9	2.3	2.1
range (post-1995)	8–28	3–15	1–7	0–5	0–6
FD = mean post-1990	16	12	7	2	5
FD = 0.0	8	8	3	0	3

Table 8. Decadal statistics of North Atlantic basin tropical cyclones.

Decade	NTC	NH	NMH	N4/5	NUSLFH	AT*
1950–1959	10.4,2.3,7–14	6.9,2.3,3–11	3.9,2.1,2–8	1.7,0.8,1–3	1.9,1.2,0–3	9.43,0.44,8.81–10.20
1960–1969	9.5,3.7,5–18	6.2,2.6.3–12	2.8,2.4,0–7	1.5,1.4,0–4	1.5,1.1,0–4	9.17,0.36,8.57–9.58
1970–1979	9.5,2.2,7–13	5.0,1.1,3–6	1.6,0.8,0–3	0.8,0.8,0–2	1.2,1.0,0–3	9.15,0.42,8.35–9.72
1980–1989	9.3,3.2,4–13	5.3,2.3,2–9	1.7,1.1,0–3	1.0,0.9,0–3	1.6,1.8,0–6	9.28,0.47,8.57–10.07
1990–1999	11.0,4.0,7–19	6.4,3.1,3–11	2.5,2.1,0–6	1.4,1.6,0–5	1.4,1.1,0–3	9.75,0.44,9.22–10.32
2000–2007	15.8,5.3,10–28	7.9,3.4,4–15	3.6,1.9,2–7	2.3,1.6,0–5	2.0,2.6,0–6	10.15,0.31,9.57–10.59

Note: The three sets of numbers given for each grouping are the mean, standard deviation, and range, respectively.
* Armagh Observatory, Northern Ireland, surface air mean temperature in degrees C (calibrated data 2004; provisional data 2005–2007)

Included in table 8 is the decadal mean surface air temperature at Armagh Observatory, Northern Ireland (AT), to show the effects of global warming. During the 1950s the average AT measured about 9.4 °C. The decadal average declined in the 1960s and 1970s before increasing in the 1980s and 1990s. In the partial decade of 2000–2007, the average temperature reached about 10.2 °C. A comparison of the behaviors of the decadal means of the tropical cyclone groupings with the AT behavior shows strong similarity, suggesting a close association between them.

Figure 5 displays a visual depiction of the mean decadal behaviors presented in table 8. Notice that the less active 1960s and 1970s seem to be associated with a cooling in temperature, while the 1950s and 1980s onward seem to be associated with a long-term warming in temperature. Table 9 gives the correlative results comparing tropical cyclone decadal means against AT decadal means. For NTC there is a very strong statistical correlation ($r=0.94$ at >99% *cl*) against temperature, one that explains nearly 90% of its variance; for NH, there is a strong statistical correlation ($r=0.83$ at >95% *cl*) against temperature, one that explains more than two-thirds of its variance. Statistically important inferred correlations, however, are lacking for NMH, N4/5 (the inferred correlation, $r=0.80$, is only of marginally statistical strength, *cl* >90%), and NUSLFH. Some other factor(s), therefore, must also be at work, most likely wind shear associated with the ENSO events.

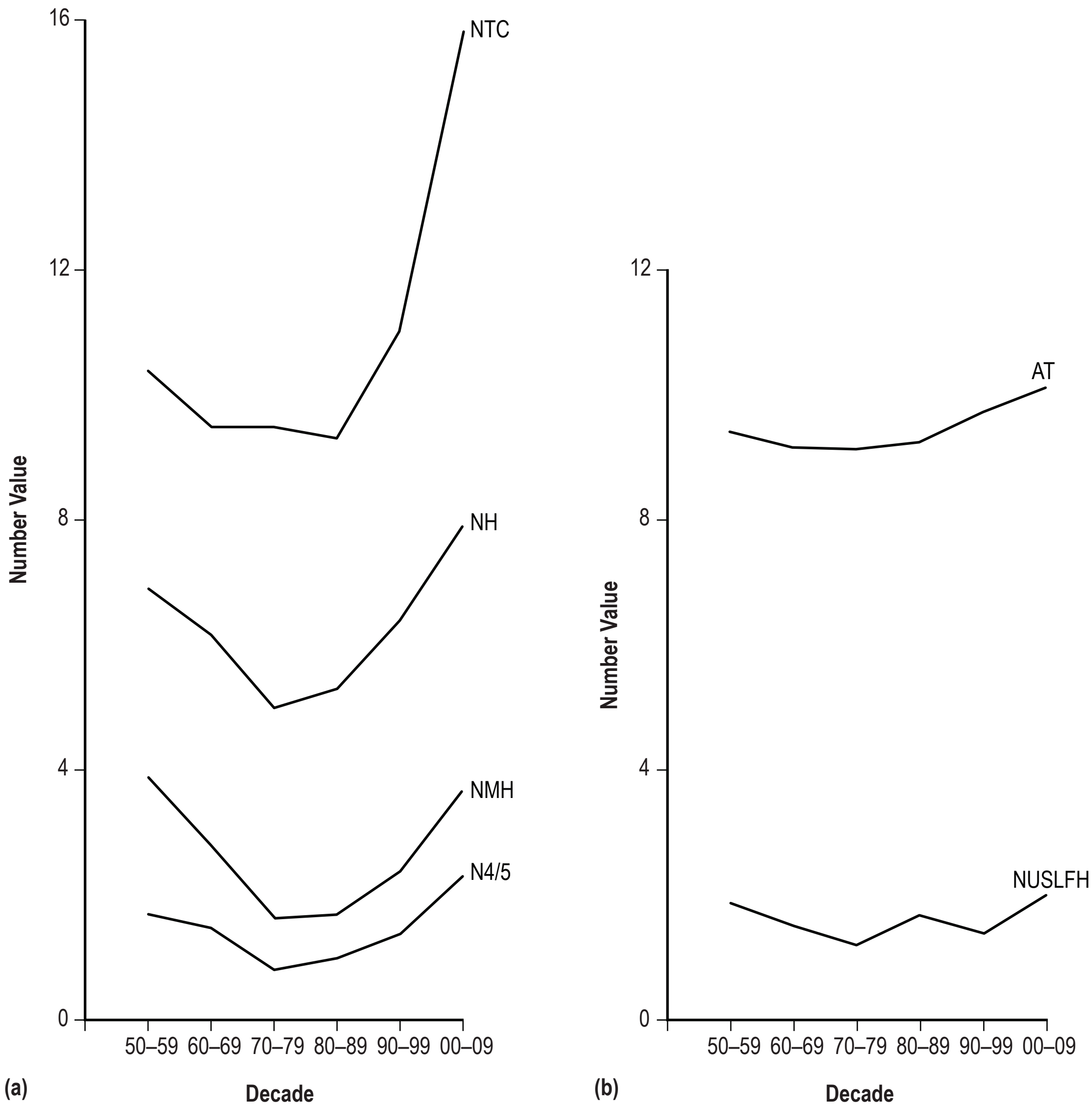

Figure 5. Decadal variation of (a) (NTC, NH, NMH, N4/5), and (b) (AT, NUSLFH).

Table 9. Correlative results based on the decadal statistics of numbers of tropical cyclones, hurricanes, major hurricanes, category 4/5 hurricanes, and U.S. land-falling hurricanes vs. Armagh temperature.

Statistic	NTC	NH	NMH	N4/5	NUSLFH
r	0.936	0.832	0.549	0.798	0.609
rxr	0.876	0.691	0.301	0.637	0.371
a	−45.234	−15.064	−9.927	−8.823	−2.867
b	5.918	2.250	1.329	1.083	0.471
se	0.966	0.649	0.888	0.349	0.260
cl	>99%	>95%	<90%	>90%	<90%

In conclusion, this study supports the previous predictions proffered by the CSU, NOAA, and TSR teams calling for a continued increased activity during the 2008 hurricane season. The 2008 season is a post-1995 season that also will be non-EN-related, both conditions indicative of increased activity in the North Atlantic basin during the current epoch of activity, especially when coupled with continued global warming. Presuming first differences comparable to the post-1990 means, one should expect about 16 tropical cyclones to form in the North Atlantic basin, including 12 hurricanes and 7 major hurricanes, of which 2 should attain category 4 or 5. While the long-term average is about two hurricanes striking the U.S. coastline, as many as six have struck in a single season. One anticipates that as many as five could strike if the first difference in the 10-yr moving average NUSLFH is indeed comparable to the post-1990 mean first difference.

APPENDIX—EL NIÑO-RELATED AND NON-EL NIÑO-RELATED SEASONS

According to the running 3-mo ONI, an El Niño is said to occur when five consecutive monthly values at or above the threshold of a +0.5 °C SST anomaly are seen. For this study, a hurricane season (June – November) is designated El Niño-related (ENR) when at least 3 consecutive months during the hurricane season have been identified as being an El Niño by ONI. Otherwise, the season is termed non-El Niño-related (NENR). Of the preceding 58 hurricane seasons (1950 – 2007), there have been 17 ENR seasons and 41 NENR seasons.

Table 10 gives the frequencies of occurrence of ENR and NENR seasons based on a single question (event): Is ONI ≥0.5 SST anomaly during the month of interest? Hence, the table provides a means whereby one can determine on a monthly basis the likelihood that a hurricane season will be ENR or NENR from early-year ONI values. As an example, January 2008 has a value of ONI = –1.5. Hence, the answer to the question is "no." Of the 40 past January ONI values that answered "no," 26 (65%) had following hurricane seasons that were described as NENR. A continued "no" answer in February increases the percentage to 70%, and increases it further to 82% in June. So, it seems very likely that the 2008 hurricane season will be NENR.

Table 10. Frequencies of occurrence of ENR seasons and NENR seasons based on monthly running 3-mo ONI averages.

Event: Is ONI >/= 0.5 SST anomaly during month of interest?				
Decision	**Month**	**ENR-Season (17)**	**NENR-Season (41)**	**Total (58)**
YES	01	3	15	18
	02	4	10	14
	03	2	9	11
	04	4	7	11
	05	9	7	16
	06	9	4	13
	All	31	52	83
NO	01	14	26	40
	02	13	31	44
	03	15	32	47
	04	13	34	47
	05	8	34	42
	06	8	37	45
	All	71	194	265
	Total	102	246	348

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The statistics of North Atlantic basin tropical cyclones for the interval 1945–2007 are examined and estimates are given for the frequencies of occurrence of the number of tropical cyclones, number of hurricanes, number of major hurricanes, number of category 4/5 hurricanes, and number of U.S. land-falling hurricanes for the 2008 hurricane season. Also examined are the variations of peak wind speed, average peak wind speed per storm, lowest pressure, average lowest pressure per storm, recurrence rate and duration of extreme events (El Niño and La Niña), the variation of 10-yr moving averages of parametric first differences, and the association of decadal averages of frequencies of occurrence of North Atlantic basin tropical cyclones against decadal averages of Armagh Observatory, Northern Ireland, annual mean temperature (found to be extremely important for number of tropical cyclones and number of hurricanes). Because the 2008 hurricane season seems destined to be one that is non-El Niño-related and is a post-1995 season, estimates of the frequencies of occurrence for the various subsets of storms should be above long-term averages.

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