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An Estimate of the North Atlantic Basin Tropical Cyclone Activity for the 2010 Hurricane Season

Robert M. Wilson
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May 2010

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LIST OF ACRONYMS AND SYMBOLS

<<ONI>>	Oceanic Niño Index event average
<AT>	annual mean surface-air temperature at Armagh Observatory
<ONI>	annual mean Oceanic Niño Index
10-yma	10-year moving average
2-mma	2-month moving average
CO_2	carbon dioxide
CSU	Colorado State University
EN	El Niño
ENSO	El Niño Southern Oscillation
ERSST.v3b	Extended Reconstruction of Sea Surface Temperature, version 3b
LN	La Niña
M	moderate
max ONI	maximum Oceanic Niño Index value
$MLCO_2$	Mauna Loa carbon dioxide atmospheric concentration
NENM	number of El Niño months
NH	number of hurricanes
NLNM	number of La Niña months
NMH	number of major hurricanes
NNM	number of El Niño Southern Oscillation neutral months
NOAA	National Oceanic and Atmospheric Administration
NTC	number of tropical cyclones
NUSLFH	number of United States land-falling hurricanes
ONI	Oceanic Niño Index
PWS	peak wind speed
RP	recurrence period
S	strong
SST	sea surface temperature
TSR	Tropical Storm Risk
U.S.	United States
W	weak

NOMENCLATURE

cl	confidence level
$fd(x)_{10}$	first difference of parameter x using 10-yma values
P	probability
r	coefficient of correlation
r^2	coefficient of determination
sd	standard deviation
se	standard error of estimate
x	x parameter
x	x regression
y	y regression
y_1	y regression based on current activity level (since 1995)
y_2	y regression based on overall interval (since 1950)
y_3	y regression based on first more active interval (1950–1965)

TECHNICAL PUBLICATION

AN ESTIMATE OF THE NORTH ATLANTIC BASIN TROPICAL CYCLONE ACTIVITY FOR THE 2010 HURRICANE SEASON

1. INTRODUCTION

Estimates are presented for the number of tropical cyclones (NTC), the number of hurricanes (NH), the number of major hurricanes (NMH), and the number of United States (U.S.) land-falling hurricanes (NUSLFH) expected for the North Atlantic basin during the 2010 hurricane season (June 1–November 30). The estimates are determined from long-term seasonal averages (1950–2009), the averages during the current high-activity interval (1995–present), the "usual" behavior of the first differences in the 10-yr moving averages (10-yma) of the parameters, correlations using 10-yma parametric values against 10-yma values of surface-air temperature at the Armagh Observatory in Northern Ireland, and a determination of the probable El Niño (EN) Southern Oscillation (ENSO) condition expected to prevail during the 2010 hurricane season (i.e., the likelihood of it being either ENSO-neutral or one of the extremes, EN or La Niña (LN)). The estimates are also compared against seasonal estimates recently given (December 2009) by the Colorado State University (CSU) team[1] and the Tropical Storm Risk (TSR) team[2] (United Kingdom). The official National Oceanic and Atmospheric Administration (NOAA) forecast is made each May, just prior to the start of hurricane season. The present work represents a continuation of nearly 2 decades of climate-related research performed at Marshall.[3–20] (The reader is reminded that a tropical cyclone is a "warm-core, nonfrontal, synoptic-scale cyclone that originates over tropical or subtropical waters, with organized deep convection and a closed surface wind circulation about a well-defined center" that has a sustained peak wind speed (PWS) ≥ 34 kt;[21] a hurricane is a tropical cyclone with sustained PWS ≥ 64 kt; and a major hurricane is a tropical cyclone with sustained PWS ≥ 96 kt.)

2. RESULTS AND DISCUSSION

2.1 Statistical Aspects of the North Atlantic Basin Tropical Cyclones (1950–2009)

Figure 1 displays the yearly (seasonal) frequencies of (a) NTC, (b) NH, (c) NMH, and (d) NUSLFH for the 60-yr interval 1950–2009 as observed for the North Atlantic basin. The thin-jagged lines are the yearly observed counts and the thick-smoothed lines are the 10-yma values, which indicate the current trend. The horizontal lines represent the long-term means. The mean, standard deviation (*sd*) and range appear to the right in each panel, as do the individual yearly frequency distributions. On average, one finds that about 11 tropical cyclones form in the North Atlantic basin during any given hurricane season (648 over the 60-yr interval), spanning a range of 4 to 28 and having an $sd=4$. The fewest number (4) formed in 1983 and the most (28) formed in 2005. Examination of the yearly frequency distribution indicates that 32 of 60 seasons (53%) had a yearly frequency of NTC = 8–12 per year, 16 of 60 seasons (27%) had a yearly frequency of NTC > 12 per year, and 12 of 60 seasons (20%) had a yearly frequency NTC < 8 per year. Since 1995, only 3 seasons (20%) have had a frequency of NTC < 11 per year, including the years 1997 (8), 2006 (10), and 2009 (9), all EN-related years.

For NH (fig. 1b), on average, one finds that about 6 hurricanes form in the North Atlantic basin during any given hurricane season (374 over the 60-yr interval), spanning a range of 2 to 15 and having an $sd=2.6$. The fewest number (2) formed in 1982 and the most (15) formed in 2005. Examination of the yearly frequency distribution indicates that 34 of 60 seasons (57%) had a yearly frequency of NH = 4–7 per year, 17 of 60 seasons (28%) had a yearly frequency of NH > 7 per year, and 9 of 60 seasons (15%) had a yearly frequency of NH < 4 per year. Since 1995, only two seasons (13%) have had a yearly frequency of NH < 4 per year, including the years 1997 (three) and 2009 (three), again, both being EN-related years.

For NMH (fig. 1c), on average, one finds that about 2–3 major hurricanes form in the North Atlantic basin during any given hurricane season (161 over the 60-yr interval), spanning a range of 0 to 8 and having an $sd=1.9$. The fewest number (zero) has occurred four times, in the years 1968, 1972, 1986, and 1994, while the most (eight) have occurred only once, in 1950. Examination of the yearly frequency distribution indicates that 32 of 60 seasons (53%) had a yearly frequency of NMH = 1–2 per year, 24 of 60 seasons (40%) had a yearly frequency of NMH > 2 per year, and 4 of 60 seasons (7%) never had a major hurricane, including the years 1968, 1972, 1986, and 1994, as mentioned above, all being EN-related years except 1968. Since 1995, there have been no years in which a major hurricane has not formed in the North Atlantic basin, with all years, except 1997, having a yearly frequency of NMH ≥ 2 per year.

For NUSLFH (fig. 1d), on average, one finds that about 1–2 hurricanes strike the U.S. coastline during any given hurricane season (95 over the 60-yr interval), spanning a range of 0 to 6 and having an $sd=1.5$. The fewest number (0) has occurred 12 times (in the years 1951, 1962, 1973, 1978, 1981,

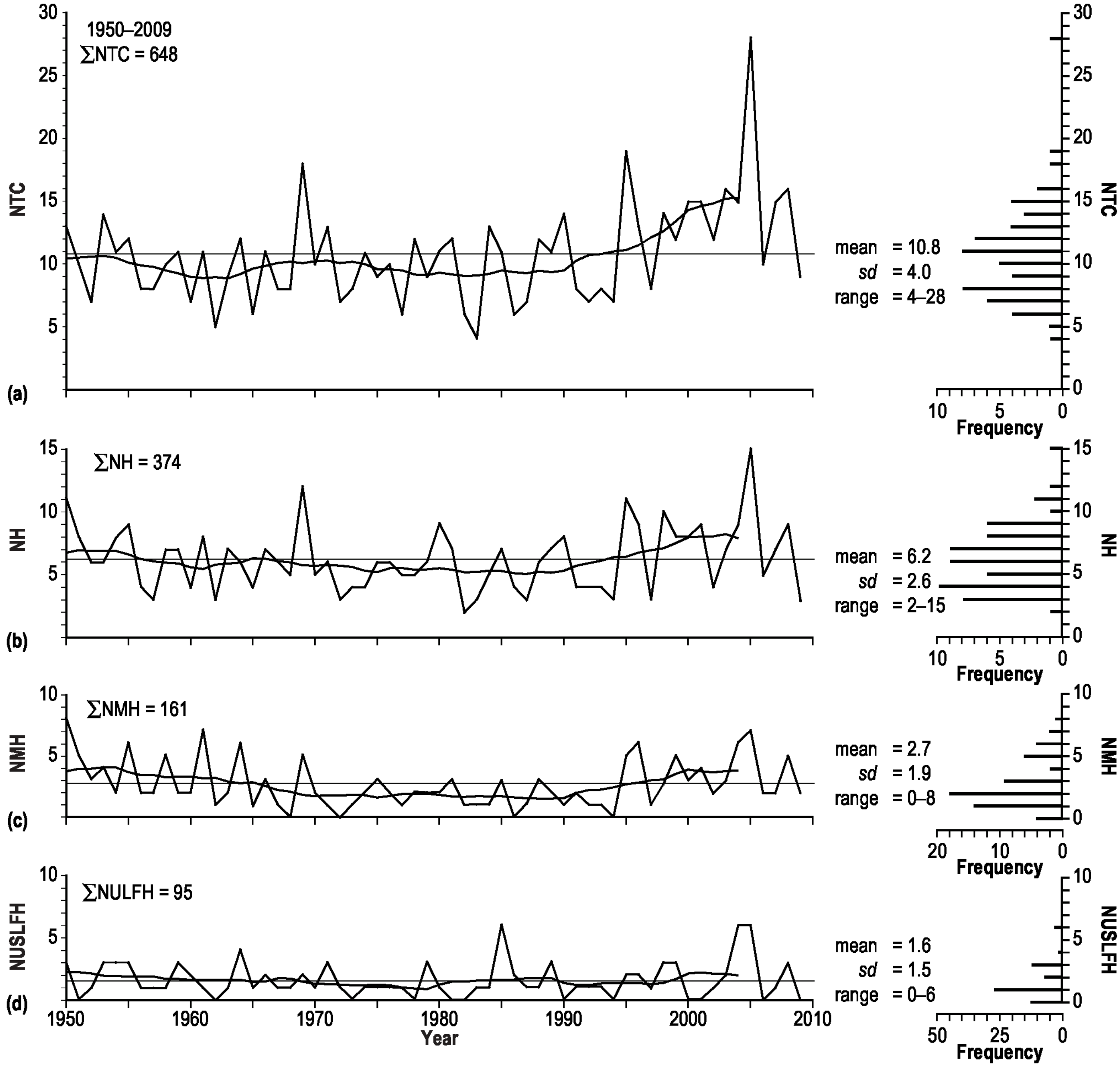

Figure 1. Yearly frequencies of (a) NTC, (b) NH, (c) NMH, and (d) NUSLFH for the North Atlantic basin (1950–2009).

1982, 1990, 1994, 2000, 2001, 2006, and 2009), while the most (6) have occurred only 3 times (in the years 1985, 2004, and 2005). The years 1951, 1982, 1994, 2006, and 2009 were EN-related years, while the years 1962, 1973, and 2000 were LN-related years. Examination of the yearly frequency distribution indicates that 38 of 60 seasons (63%) had no more than one land-falling hurricane to strike the U.S. coastline. Since 1995, there have been 8 years when the NUSLFH exceeded one per year and 5 years when the NUSLFH was three or more per year, with only the years 2000, 2001, 2006, and 2009 having no U.S. land-falling hurricanes

An interesting aspect of the yearly frequencies, true in particular for NMH, is that there is the hint of a strong decadal signal imbedded in the yearly frequencies with numbers being greater (more active) in the 1950s to the mid-1960s and again from the mid-1990s to the present and lesser (less active) between the mid-1960s and the mid-1990s. For the first more active interval, 1950–1965, the mean (± 1 *sd*) for each of the parameters measures 9.6 ± 2.6, 6.3 ± 2.3, 3.6 ± 2.2, and 1.8 ± 1.2, respectively. For the second more active interval, 1995–2009, the mean (± 1 *sd*) for each of the parameters measures 14.5 ± 4.7, 7.8 ± 3.2, 3.7 ± 1.8, and 2 ± 2, respectively. Statistical testing (the t-test for independent samples) reveals that the difference in means for NTC is highly statistically significant,[22] indicating that the present second more active interval has seen a greater number of tropical cyclones forming in the North Atlantic basin than in the former first more active interval (an increase of about 50%). While true, statistical testing also reveals that the difference in means for NH, NMH, and NUSLFH is not statistically important between the two perceived more active intervals. Therefore, while the number of tropical cyclones forming in the North Atlantic basin has increased over time, there appears to have been no statistically significant increase in the number of hurricanes, major hurricanes, or U.S. land-falling hurricanes when comparing the two more active intervals; however, increases of 20%, 3%, and 10%, respectively, have occurred. (One speculates that the significant difference in NTC between the two more active intervals might merely reflect better observations today as compared to the past, owing to the use of satellites.)

For the less active interval (1966–1994), the mean (± 1 *sd*) for each of the parameters measures 9.6 ± 3, 5.4 ± 2.1, 1.6 ± 1.1, and 1.3 ± 1.3, respectively. Statistical testing, comparing this less active interval with the first more active interval, reveals that the difference in means for NTC is not statistically important nor is it statistically important for NH or NUSLFH. However, the difference in means is highly statistically significant for NMH. Comparison of this less active interval with the current more active interval reveals that the difference in means is statistically important for all parameters except NUSLFH. Hence, on the basis of NMH, there appears a highly statistically significant difference in the means between the less active and the more active intervals, indicating that the current more active interval is more than twice as active as the less active interval. For NTC, the current interval is more than 50% more active than the less active interval; for NH, the current active interval is more than 40% more active than the less active interval; and for NUSLFH, the current more active interval is about 50% more active than the less active interval, although this difference is not statistically important.

Since the less active interval lasted approximately 3 decades in length, presuming that the transitioning from more-to-less-to-more active states is quasi-periodic in nature, one speculates that the current more active interval likely will persist for another 1–2 decades. However, if the current more active interval is now being driven by increased temperature due to climatic change, then the current active state might persist longer.

2.2 First Differences of Parametric 10-yma Values

A simple means for estimating the expected NTC, NH, NMH, and NUSLFH for the 2010 hurricane season can easily be accomplished by examining the "usual" behavior of their 10-yma values (from one year to the next). Figure 2 plots the first differences of the 10-yma values ($fd(x)_{10}$, where x is the parameter of interest) for (a) NTC, (b) NH, (c) NMH, and (d) NUSLFH. For NTC

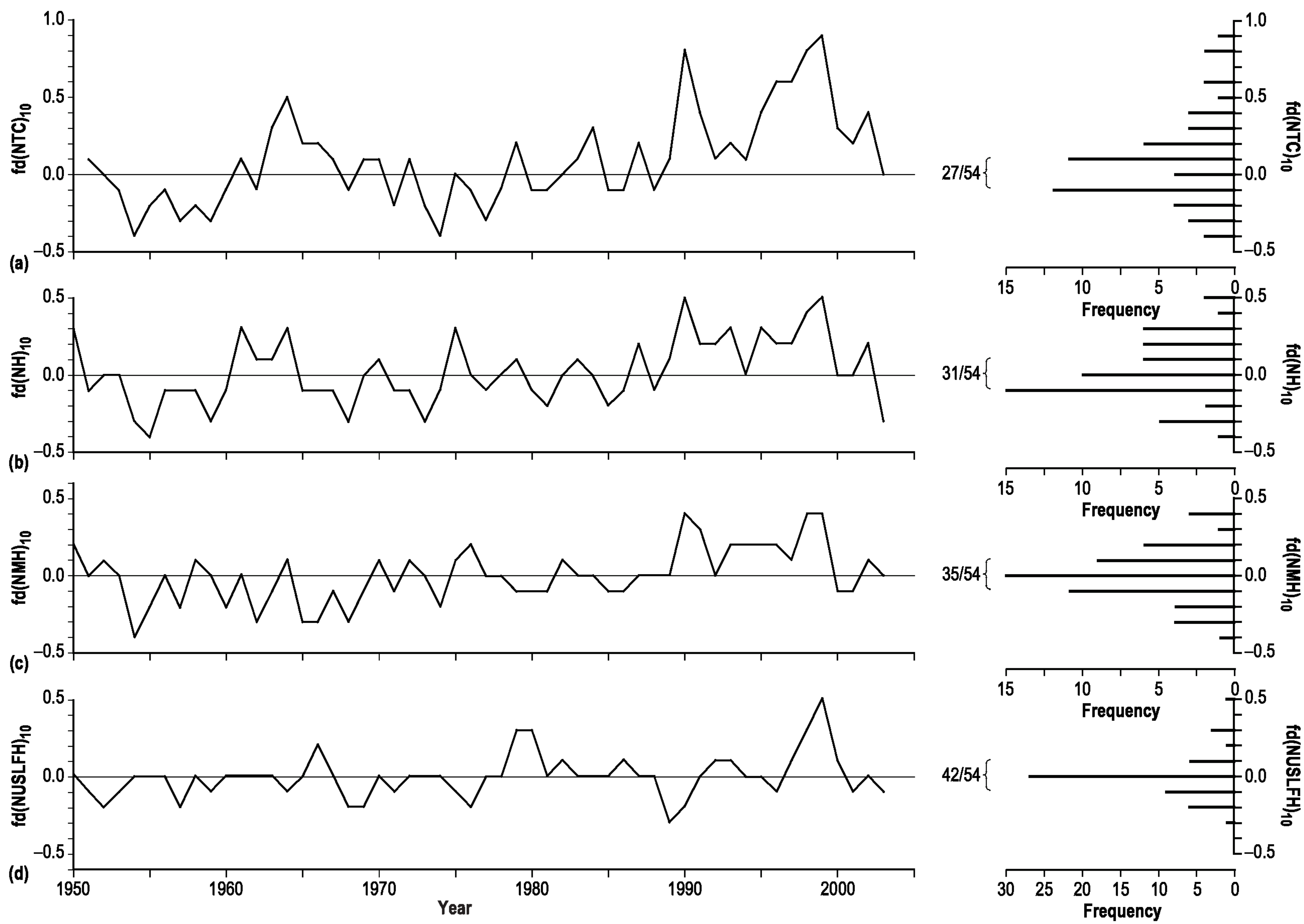

Figure 2. First differences of the 10-yma values of (a) NTC, (b) NH, (c) NMH, and (d) NUSLFH.

(fig. 2a), the first difference in its 10-yma values between 2003 and 2004 is zero. The distribution of first difference values (shown to the right in each panel) reveals that a first difference of ± 0.1 is the "usual" value, occurring 27 out of 54 years (50%). For 9 of 54 years (17%), the first difference has measured –0.4 to –0.2, and for 18 of 54 years (33%), the first difference has measured ≥ 0.2, with the largest first difference (0.9) occurring in 1999. Presuming that the first difference of the 10-yma values for NTC will fall within the "usual" range, one estimates the 10-yma value of NTC for 2005 to be 15.3 ± 0.1, further suggesting that the yearly value of NTC for 2010 should be about 19 ± 2 (i.e., $19 \pm 2 = 20(15.3 \pm 0.1) - 2(136) - 15$, where 136 represents the sum of NTC for the interval 2001–2009 and 15 is the NTC for 2000). Past behavior indicates that the proportion of first differences equal to ± 0.1 is 50%, suggesting that there is about a 50% chance that NTC for 2010 will be 19 ± 2; there is about a 67% chance that NTC for 2010 will be 21 or fewer and about an 83% chance that NTC for 2010 will be 17 or more. (The reader should note that a larger positive first difference indicates a higher NTC for the upcoming hurricane season, while a smaller or more negative first difference indicates a lower NTC for the upcoming hurricane season.)

Similarly, one can compute the "usual" current trend values of the 10-yma values for the other parameters and estimate their expected levels of activity for the 2010 hurricane season. Such an analysis suggests that the 10-yma value of NH for 2005 will be about 7.9 ± 0.1, thereby yielding the estimate for 2010 of $NH = 14 \pm 2$ (57% chance), $NH \leq 16$ (72% chance), and $NH \geq 12$ (85% chance). For NMH, its 10-yma value for 2005 is expected to be about 3.8 ± 0.1, thereby yielding the estimate for 2010 of $NMH = 7 \pm 2$ (65% chance), $NMH \leq 9$ (81% chance), and $NMH \geq 5$ (83% chance). For NUSLFH, its 10-yma value for 2005 is expected to be about 2.1 ± 0.1, thereby yielding the estimate for 2010 of $NUSLFH = 4 \pm 2$ (78% chance), $NUSLFH \leq 6$ (91% chance), and $NUSLFH \geq 2$ (87% chance).

2.3 Armagh Observatory (Northern Ireland) Surface-Air Temperature and Correlations Against It Based on 10-yma Values

Figure 3a displays the yearly means of surface-air temperature (in °C) at Armagh Observatory in Northern Ireland (<AT>) for the interval 1950–2009, plotted as the thin-jagged line, and its 10-yma values, plotted as the thick-smoothed line. Figure 3b shows the variation of the first difference in the 10-yma values of <AT>. For the 60-yr interval 1950–2009, <AT> has averaged 9.47 °C, spanning a range of 8.35 to 10.59 °C and has an $sd = 0.52$ °C. Ten-year moving average values of <AT> are found to decrease between the mid-1950s and about 1982, then to increase thereafter, somewhat loosely reminiscent of the behaviors of NTC, NH, NMH, and NUSLFH plotted in figure 1. Since 1995, all yearly values of <AT> have exceeded its long-term mean except for the year 1996, and the yearly value for 2007 is the highest surface-air mean temperature ever recorded at Armagh Observatory since the beginning of its calibrated continuous record in 1844. (Temperature measurements actually extend from 1796 at Armagh Observatory but have been calibrated only since 1844. [23–25])

First differences of the 10-yma values of <AT> are broadly distributed, with 40 of 54 years (74%) having a "usual" first difference of ± 0.05 °C. Presuming such behavior to continue, one expects the 10-yma value for <AT> in 2005 to be about 10.1 ± 0.05 °C, thereby, yielding an expected yearly surface-air temperature at Armagh Observatory in 2010 to be about $\langle AT \rangle = 10.33 \pm 1$ °C, with any value exceeding 10.59 °C being a new record high temperature at Armagh Observatory.

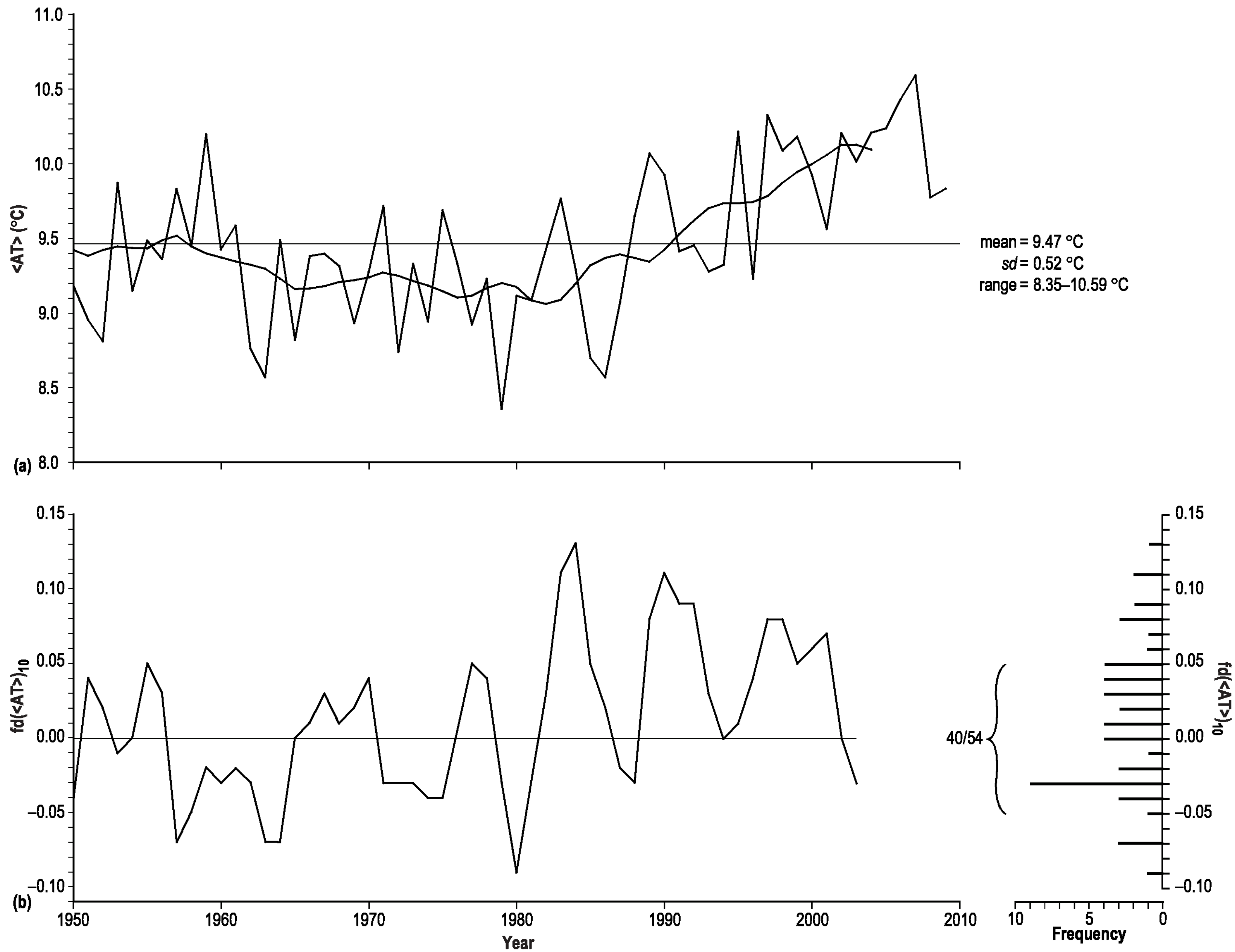

Figure 3. Armagh observations for the interval 1950–2009: (a) Yearly mean <AT> and (b) first differences of the 10-yma values of <AT>.

Figure 4 depicts the scatter plots and inferred regressions of the 10-yma values of (a) NTC, (b) NH, (c) NMH, and (d) NUSLFH against <AT> for the present more active interval 1995–2004 (y_1) and the overall interval 1950–2004 (y_2). All inferred regressions show that, during either the present more active interval or the overall interval, a direct correlation between the parametric values and <AT> is hinted at, one that suggests increased frequencies as temperature increases. However, a radical departure of the inferred regression using only the more recent values (y_1) in comparison to the inferred regression using all available values (y_2) is apparent (i.e., the inferred regression for the more recent values has a much steeper slope than the inferred regression using all available values). This behavior is found to be true for all correlations. It is interesting that the branch of values above the regressions and to the left (denoted y_3), in particular for NMH, represents values for the first more active interval (1950–1965), while the flat horizontal branch (averaging about 1.8) that connects the two more active branches represents the values for the less active interval (which has considerable overlap with the second more active interval beginning about 1985). The inferred slopes for the two more active interval regressions are numerically similar, 3.2 for the first more active interval and 2.9 for the second more active interval. The primary difference between the two more active interval regressions is that the present one has shifted about 0.5 °C warmer with respect to the earlier more active interval regression. Such behavior suggests that the Earth's chaotic climate system demonstrates hysteresis on decadal time scales.

Table 1 summarizes separately the inferred regression equations for NTC, NH, NMH, and NUSLFH against <AT> based on 10-yma values for both the present more active interval 1995–2004 and the overall interval 1950–2004. All regressions are inferred to be statistically important (at a >99.9% confidence level (*cl*)). For the present more active interval, the inferred regression for NTC against <AT> has a coefficient of correlation (r) = 0.988 and a coefficient of determination (r^2) = 0.977, meaning that nearly 98% of the variance in the 10-yma values of NTC (since 1995) can be explained simply by the variation of the 10-yma values of <AT> alone. Instead, for the larger overall interval, the inferred regression for NTC against <AT> has a slightly smaller r and r^2, inferring that only about 79% of the variance in NTC can be explained by the variation in <AT> alone. Similar findings are found for the other parameters, with the present more active interval having inferred regressions of larger r and r^2 as compared to inferred regressions for the overall interval.

Presuming the 10-yma value of <AT> for 2005 to be 10.1 ± 0.05 °C from the "usual" behavior of its first difference in 10-yma values (i.e., a first difference of ± 0.05 °C having occurred about 74% of the time, as discussed above), one infers the 10-yma value of NTC for 2005 to be about 15.06 ± 0.5, based on the fit for the present more active interval 1995–2004, which further suggests a yearly frequency of NTC = 14 ± 10 for 2010. Instead, based on the overall interval 1950–2004, one expects the 10-yma of NTC for 2005 to be only about 13.86 ± 0.25, which is unrealistic since such a value implies a negative yearly frequency for NTC in 2010. Based on the overall interval fit, to have an average yearly frequency (NTC = 11) for 2010, the 10-yma value of NTC for 2005 must equal 14.9, which in turn means that the 10-yma value of <AT> for 2005 would need to be about 10.12 °C (based on the fit of <AT> against NTC). However, such a value suggests that the yearly mean surface-air temperature at Armagh Observatory for 2010 would be about 10.73 °C or 0.14 °C warmer than its previous record high temperature of 10.59 °C in 2007 and 0.9 °C warmer than the yearly mean surface-air temperature of 9.83 °C in 2009.

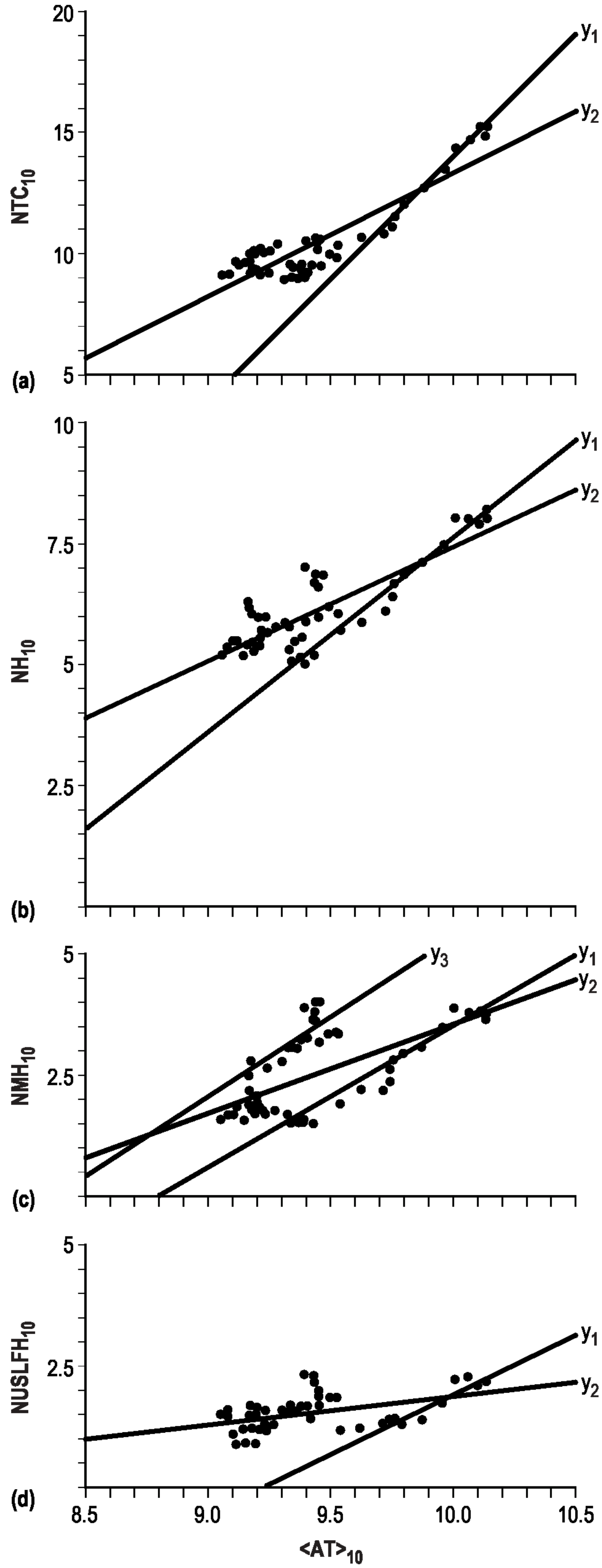

Figure 4. Scatter plots of the 10-yma values of (a) NTC, (b) NH, (c) NMH, and (d) NUSLFH against 10-yma values of <AT>.

Table 1. Correlations of NTC, NH, NMH, and NUSLFH versus <AT> using 10-yma values for the intervals 1995–2004 and 1950–2004.

1995–2004				1950–2004			
Regression Equation	r	r^2	se	Regression Equation	r	r^2	se
NTC = –87.54 + 10.158<AT>	0.988	0.977	0.16	NTC = –37.57 + 5.092<AT>	0.891	0.794	0.81
NH = –32.51 + 4.017<AT>	0.967	0.935	0.24	NH = –16.41 + 2.388<AT>	0.827	0.684	0.47
NMH = –25.41 + 2.895<AT>	0.937	0.878	0.17	NMH = –14.57 + 1.817<AT>	0.621	0.386	0.69
NUSLFH = –22.82 + 2.476<AT>	0.927	0.859	0.16	NUSLFH = –4.12 + 0.605<AT>	0.491	0.241	0.31

Similarly, presuming the 10-yma value of <AT> for 2005 to be 10.1 ± 0.05 °C, the 10-yma value of NH for 2005 is found to be about 8.06 ± 0.2, using the present more active interval fit, and about 7.71 ± 0.12, using the overall interval fit; the 10-yma value of NMH for 2005 using the two fits is found to be about 3.83 ± 0.14 and 3.78 ± 0.09, respectively; and the 10-yma value of NUSLFH for 2005 using the two fits is found to be about 2.19 ± 0.12 and 1.99 ± 0.03, respectively. Based on these projected 10-yma parametric values, one expects yearly values for 2010 using the two fits to be about NH $= 17 \pm 4$ or 10 ± 3, respectively; NMH $= 8 \pm 2$ or 7 ± 1, respectively; and NUSLFH $= 6 \pm 2$ or 2 ± 2, respectively. Obviously, a higher mean surface-air temperature in 2010 at the Armagh Observatory would suggest a greater yearly frequency of tropical cyclone formation in the North Atlantic basin, while a lower mean surface-air temperature would suggest a lower yearly frequency of tropical cyclone formation (for all categories of tropical cyclones).

2.4 Comparison of Armagh Observatory (Northern Ireland) Surface-Air Temperatures and Mauna Loa Carbon Dioxide Atmospheric Concentration Measurements Based on 10-yma Values

Recently, it was shown that surface-air temperature, as measured at the Armagh Observatory, Northern Ireland, is strongly related to the atmospheric concentration of carbon dioxide (CO_2,) as measured at Mauna Loa, Hawaii, particularly since about 1982.[20] Armagh Observatory lies about 1 km northeast of the center of the ancient city of Armagh, Northern Ireland, being located at latitude 54°21'12" N and longitude 6°38'54" W and situated about 64 m above sea level at the top of a small hill in an estate of natural woodland and parkland that measures about 7 ha. Continuous calibrated daily measurements of the minimum and maximum temperature have been made there since 1844. On the other hand, the Mauna Loa Observatory is located in a barren lava field of an active volcano located at latitude 19°32' N and longitude 155°35 W at an elevation of 3,397 m above sea level. The Mauna Loa measurements represent the longest continuous record of atmospheric CO_2 concentration measurements available for study,[26] having begun in 1958.

Figure 5 shows the yearly variation of the 10-yma of the Mauna Loa CO_2 ($MLCO_2$) atmospheric concentration (in ppmv) for the data-available interval 1963–2004. The 41-yr record of 10-yma values of $MLCO_2$ plainly shows that the atmospheric concentration of CO_2, as measured at Mauna Loa, has increased continuously with the passage of time from about 319 ppmv in 1963 to nearly 378 ppmv in 2004, an increase of slightly more than 18%. Furthermore, the rate of growth in the 10-yma values of $MLCO_2$ is found to exceed that of a simple linear increase, being more reflective of an exponential rise. Hence, higher concentrations appear more likely to occur sooner rather than later, especially if the rise in CO_2 atmospheric concentration continues unabated.

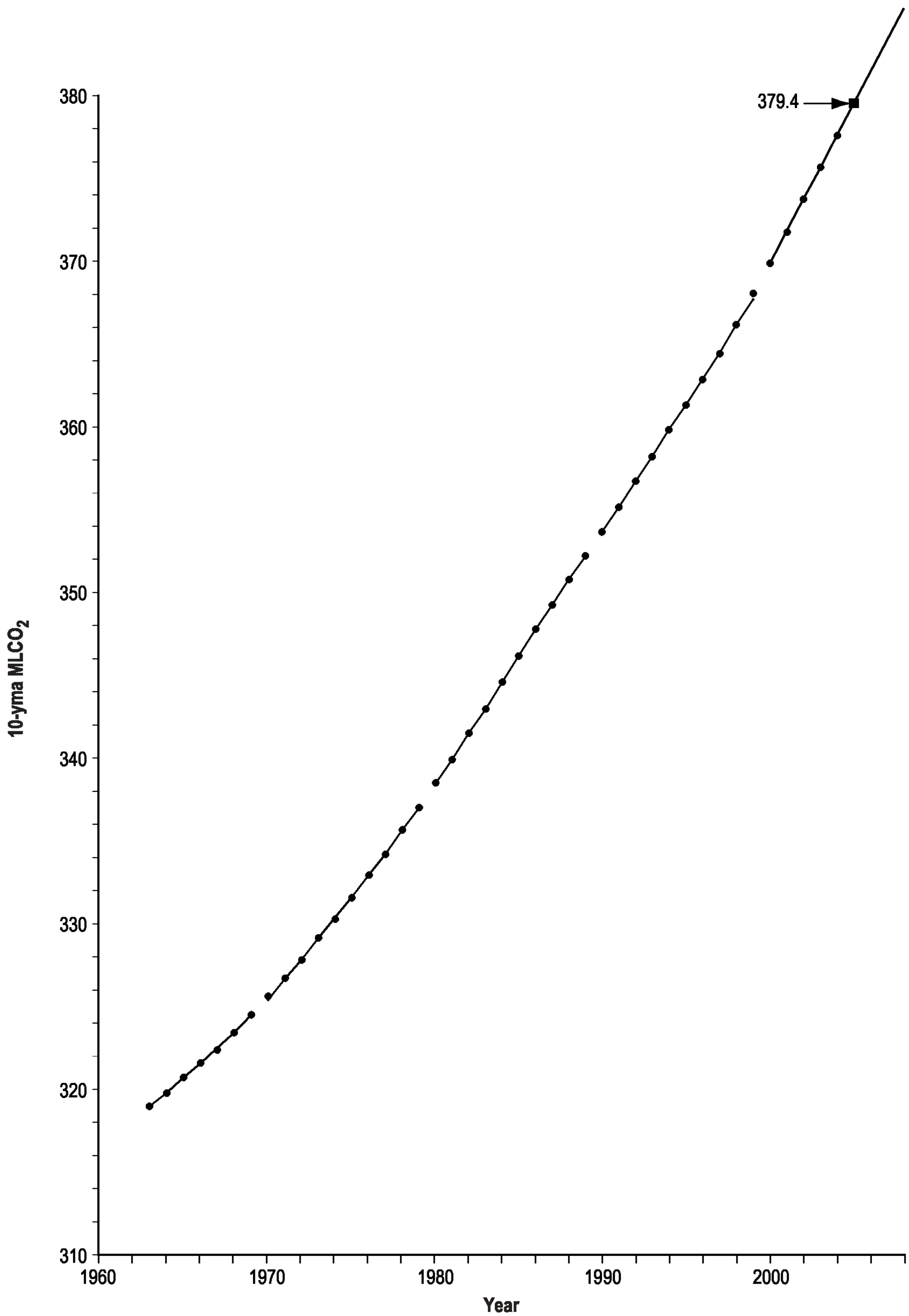

Figure 5. 10-yma values of $MLCO_2$.

In figure 5, individual linear fits are shown as the straight lines for each decadal set of observations (1960–1969, 1970–1979, etc.). The 10-yma values of $MLCO_2$ within each decadal set are found to essentially lie along these individual decadal linear fits. Extension of the most recent linear fit (2000–2004) to 2005 (the filled square) suggests that the 10-yma value of the $MLCO_2$ concentration will be about 379.4 ppmv.

Figure 6 displays the scatter plot of 10-yma values of <AT> against 10-yma values of $MLCO_2$. The individual dots represent specific years, which are observed to move progressively from the lower left to the upper right with the passage of time. For convenience, calendar years are identified at 5-year intervals to guide the reader.

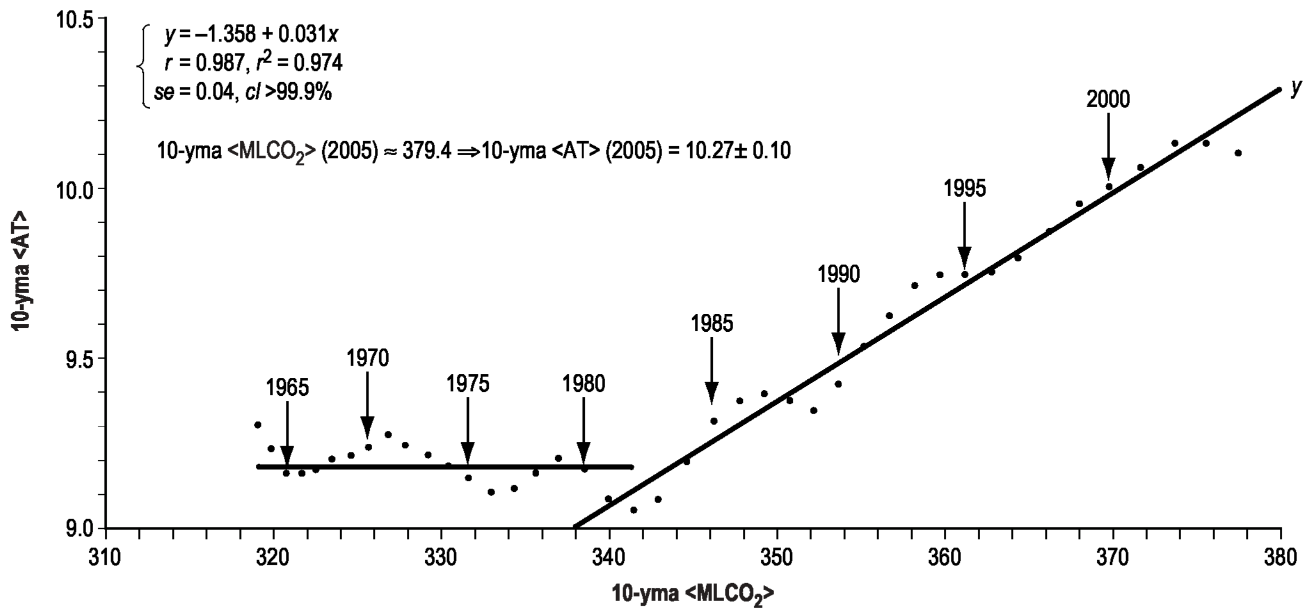

Figure 6. Scatter plot of 10-yma values of <AT> against 10-yma values of $MLCO_2$.

Prior to about 1982, 10-yma values of <AT> do not appear to correlate strongly with 10-yma values of $MLCO_2$, as indicated by the horizontal straight line through the individual yearly values (1963–1982). However, from about 1982 onwards (an interval of 24 years), a very strong correlation is inferred to exist between 10-yma values of <AT> and $MLCO_2$, one having $r = 0.987$, indicating that more than 97% of the variance in the 10-yma values of <AT> can be explained by the variation of the 10-yma values of $MLCO_2$. The variation about the inferred linear regression line, while having a standard error of estimate (se) = 0.04 °C, appears to range (i.e., maximal extremes) by about ±0.1 °C, indicating a spread of about ±2.5 se. Using the estimated value of 379.4 ppmv for the 10-yma value of $MLCO_2$ for 2005 (from figure 5), one infers that the 10-yma value of <AT> should be about 10.27 ± 0.1 °C for 2005, which, if true, indicates that the first difference for the 10-yma value of <AT> for 2005 will be about 0.17 ± 0.1 °C, a value outside and high of the "usual" first difference expected range (± 0.05 °C). Recall from figure 3b that 9 of 54 years (17%) have had first differences in the 10-yma values of <AT> ≥ 0.07 °C, with no year, as yet, having a first difference that exceeded 0.13 °C. However, the indication from the <AT>–$MLCO_2$ relationship (fig. 6) is that the first difference in 10-yma values of <AT> will be ≥ 0.07 °C and possibly as high as 0.27 °C, implying that the 10-yma value of <AT> for 2005 should be ≥ 10.17 °C, a new record high at Armagh Observatory, if true.

However, a 10-yma value of <AT> for 2005 ≥ 10.17 °C presents a difficult quandary in that it would suggest a yearly temperature <AT> ≥ 11.73 °C at Armagh Observatory in 2010, a value well above the record high temperature of 10.59 °C in 2007. Furthermore, such a value would indicate a year-to-year change in yearly temperature from 2009 to 2010 ≥ 1.9 °C. Large year-to-year temperature excursions ≥ 1.5 °C in absolute value occasionally have been seen at Armagh Observatory, but never has there been one as large or larger than 1.9 °C. For example, the yearly temperature at Armagh dropped 1.54 °C between 1815 and 1816, very probably due to the eruption of Tambora in April 1815.[27] Also, the yearly temperature dropped 1.54 °C between 1878 and 1879, possibly related to the eruption of Cotopaxi in June 1877,[26] and an unexplained drop of 1.7 °C occurred between 1921 and 1922. In contrast, an unexplained rise of 1.56 °C occurred between 1892 and 1893, unexplained in that there is no apparent ENSO event[28] or cataclysmic volcanic eruption[26] occurring around these dates. Therefore, while large year-to-year fluctuations in temperature at Armagh Observatory have occurred, they have occurred only rarely, with none having been seen since 1921–1922 and none being larger than 1.7 °C.

Should a large-year-to-year temperature rise ≥ 1.9 °C actually occur between 2009 and 2010, one would expect yearly parametric frequencies possibly far greater in 2010 than has ever been seen before. As noted above, a rise of 1.9 °C to 11.73 °C in 2010 yields a 10-yma of 10.17 °C in 2005 for <AT>. Using this value in the inferred regressions given in table 1, one can deduce 10-yma values for the parameters for 2005, which in turn can provide estimates for the yearly frequencies for 2010. For NTC, such an analysis yields 10-yma values from y_1 and y_2 for 2005 of 15.77 and 14.22, respectively, suggesting a yearly frequency for 2010 of NTC = 28 and 0 (actually, –3, which is unrealistic), respectively; for NH, one obtains 10-yma values for 2005 of 8.34 and 7.88, respectively, suggesting a yearly frequency for 2010 of NH = 23 and 14, respectively; for NMH, one obtains 10-yma values for 2005 of 4.03 and 3.91, respectively, suggesting a yearly frequency for 2010 of NMH = 12 and 9, respectively; and for NUSLFH, one obtains values for 2005 of 2.36 and 2.03, respectively, suggesting a yearly frequency for 2010 of NUSLFH = 9 and 3, respectively. Since there is no known reason not to use the inferred regressions for the now occurring more active interval (y_1), one which plainly suggests that the Earth's climate system has undergone recent change and that tropical cyclone formation in the North Atlantic basin is now responding directly to the effects of enhanced warming more strongly than in previous years, it is surmised that increased activity during the 2010 hurricane season should be expected with, perhaps, as many as 28 NTC, 23 NH, 12 NMH, and 9 NUSLFH possibly being seen (these estimates are considered upper limits). Such expected frequencies, should they truly occur, represent record to near record yearly frequencies for the North Atlantic basin. However, if the current ongoing EN event, which had its onset in June 2009, persists through 2010, a sharp reduction in the expected yearly parametric frequencies for 2010 might occur.[29–32]

2.5 El Niño Southern Oscillation Cycle Effects

Today, the Oceanic Niño Index (ONI) is often used to determine the state of the ENSO cycle. The ONI represents the 3-month running mean (also called the 2-mma) of the ERSST.v3b sea surface temperature (SST) anomalies in the Niño 3.4 region (5° N–5° S and 120–170° W) relative to the 1971–2000 base period.[33] An EN is said to be occurring when the $\text{ONI} \geq 0.5$ °C for five or more consecutive months. When $0.5\ °\text{C} \leq \text{ONI} < 1\ °\text{C}$, the EN is described as being of "weak" (W) strength; when $1\ °\text{C} \leq \text{ONI} < 1.5\ °\text{C}$, the EN is described as being of "moderate" (M) strength; and when $\text{ONI} \geq 1.5\ °\text{C}$, the EN is described as being of "strong" (S) strength. The current ongoing EN is now classified as an S event, having had an apparent ONI maximum value of 1.8 °C in December 2009 (ONI slightly decreased to 1.7 °C in January 2010). Similarly, an LN is said to be occurring when the $\text{ONI} \leq -0.5$ °C for five or more consecutive months. When $-1\ °\text{C} \leq \text{ONI} < -0.5\ °\text{C}$, the LN is described as being of W strength; when $-1.5\ °\text{C} \leq \text{ONI} < -1\ °\text{C}$, the LN is described as being of M strength; and when $\text{ONI} < -1.5\ °\text{C}$, the LN is described as being of S strength. All other times, when the ONI fails to meet the definition of EN or LN, the ENSO cycle is said to reflect ENSO-neutral conditions.

On the basis of ONI, there have been 31 ENSO extreme events for the interval 1950–2009, including 18 EN and 13 LN events. For convenience, these 31 events are identified in table 2, giving their start, peak, and end dates; duration in months (from start to end); max ONI; mean ONI over the duration of the event (<<ONI>>); event type; event strength; and the sums of NTC, NH, NMH, and NUSLFH that formed during the event (between event start and end). Averages of the specific parameters appear at the bottom but they exclude the first LN event, which had an onset prior to January 1950, and the last EN event, which remains an ongoing event. Hence, of the 18 EN events, 5 have been W events, 4 have been M events, and 9 have been S events. For the 17 EN events with complete coverage, the average duration is 10.1 months; the average max ONI is 1.4 °C; the average <<ONI>> is 0.97 °C; and the average NTC, NH, NMH, and NUSLFH during an EN event is 8, 4.4, 1.5, and 1, respectively.

The EN event of longest duration (19 months) occurred August 1986–February 1988, having multiple peaks in February 1987 (1.3 °C), August 1987 (1.6 °C), and September 1987 (1.6 °C). The EN event of largest anomaly (max $\text{ONI} = 2.5$ °C) occurred May 1997–May 1998, and this event also had the largest <<ONI>> (1.74 °C). The W EN event of June 2004–February 2005 had the largest sums of NTC (15), NH (9), NMH (6), and NUSLFH (6). Weak EN events average about 6 months in duration, having a range of 5 to 9 months, and average about 9, 6, 2.4, and 0.4 for NTC, NH, NMH, and NUSLFH, respectively, during their operative lives. Moderate EN events average about 8 months in duration, having a range of 6 to 11 months, and average about 5.8, 3.8, 1, and 0.3 for NTC, NH, NMH, and NUSLFH, respectively, during their operative lives. Strong EN events average about 13.6 months in duration, having a range of 11 to 19 months, and average about 8.5, 3.6, 1.3, and 1 for NTC, NH, NMH, and NUSLFH, respectively, during their operative lives. Plainly, as the strength of the EN anomalous event increases, there is a tendency for its duration to increase in length and tropical cyclone activity to be suppressed, this is particularly true for NH, NMH, and NUSLFH.

Table 2. Listing of EN and LN events based on ONI (ERSST.v3b).

EN and LN Events								Sums			
Start	Peak	End	Dur (mo)	max ONI	<<ONI>>	Event Type	Strength	NTC	NH	NMH	NUSLFH
B01-1950	01-1950(?)	03-1951	>15	–1.7(?)	–	LN	S	13	11	8	3
08-1951	10-1951	12-1951	5	0.8	0.7	EN	W	9	7	4	0
04-1954	11-1955a	01-1957	34	–2	–0.98	LN	S	31	21	10	9
04-1957	01-1958	06-1958	15	1.7	0.99	EN	S	9	3	2	1
09-1962	11-1962*	01-1963	5	–0.7	–0.62	LN	W	3	2	1	0
07-1963	11-1963*	01-1964	7	1	0.86	EN	M	9	7	2	1
04-1964	10-1964*	01-1965	10	–1.2	–0.93	LN	M	12	6	6	4
06-1965	11-1965	04-1966	11	1.6	1.12	EN	S	6	4	1	1
12-1967	02-1968	04-1968	5	–0.9	–0.72	LN	W	0	0	0	0
11-1968	01-1969*	06-1969	8	1	0.79	EN	M	0	0	0	0
09-1969	11-1969	01-1970	5	0.8	0.66	EN	W	12	8	2	1
07-1970	01-1971*b	01-1972	19	–1.3	–0.91	LN	M	22	10	3	4
05-1972	12-1972	03-1973	11	2.1	1.32	EN	S	7	3	0	1
05-1973	12-1973c	05-1976	37	–2.1	–1.11	LN	S	29	14	6	2
09-1976	11-1976	02-1977	6	0.8	0.63	EN	W	3	2	0	0
09-1977	11-1977a	01-1978	5	0.7	0.64	EN	W	6	4	0	1
05-1982	12-1982*	06-1983	14	2.3	1.39	EN	S	6	2	1	0
10-1984	12-1984	09-1985	12	–1.1	–0.71	LN	M	11	8	2	4
08-1986	08-1987*d	02-1988	19	1.6	1.11	EN	S	11	6	1	2
05-1988	11-1988*	05-1989	13	–1.9	–1.29	LN	S	12	6	3	1
05-1991	01-1992e	07-1992	15	1.8	1.13	EN	S	9	4	2	1
05-1994	12-1994	03-1995	11	1.3	0.83	EN	M	7	3	0	0
09-1995	11-1995f	03-1996	7	–0.7	–0.63	LN	W	7	5	3	1
05-1997	11-1997*	05-1998	13	2.5	1.74	EN	S	8	3	1	1
07-1998	12-1999*	06-2000	24	–1.6	–1.03	LN	S	26	18	8	6
10-2000	12-2000	02-2001	5	–0.7	–0.58	LN	W	4	1	0	0
05-2002	11-2002	03-2003	11	1.5	1.03	EN	S	12	4	2	1
06-2004	09-2004	02-2005	9	0.9	0.72	EN	W	15	9	6	6
08-2006	11-2006*	01-2007	6	1.1	0.83	EN	M	7	5	2	0
09-2007	01-2008*	05-2008	9	–1.4	–1.04	LN	M	13	6	2	1
06-2009	12-2009	–	>8	1.8	–	EN	S	(9)	(3)	(2)	(0)
Averages: EN			10.1#	1.4#	0.97#			8#	4.4#	1.5#	1#
LN			15@	–1.3@	–0.88@			14.2@	8.1@	3.7@	2.7@

Note: B means before.
? means uncertain.
* means the month shown and the following month.
a means the month shown and the two following months.
b means multiple peaks: –0.9 in September and November 1970, –1.3 in January and February 1971, and –1 in November 1971.
c means multiple peaks: –2.1 in December 1973, –1.1 in April 1974, –0.9 in November 1974, and –1.7 in November and December 1975.
d means multiple peaks: 1.3 in February 1987 and 1.6 in August and September 1987.
e means multiple peaks: 1 in July 1991 and 1.8 in January 1992.
f means the month shown and the following 3 months.
means excludes 06–2009 event.
@ means excludes B01–1950 event.

In contrast, of the 13 LN events, 4 have been W events, 4 have been M events, and 5 have been S events. For the 12 LN events with complete coverage, the average duration is 15 months; the average max ONI is –1.3 °C; the average <<ONI>> is –0.88 °C; and the average NTC, NH, NMH, and NUSLFH during an LN event is 14.2, 8.1, 3.7, and 2.7, respectively. The LN event of longest duration (37 months) occurred May 1973–May 1976, having multiple peaks in December 1973 (–2.1 °C), April 1974 (–1.1 °C), November 1974 (–0.9 °C), November 1975 (–1.7 °C), and December 1975 (–1.7 °C). The LN event of largest anomaly (max ONI = –2.1 °C) occurred May 1973–May 1976. The LN event of largest <<ONI>> (–1.29 °C) occurred May 1988–May 1989. The LN event of largest NTC (31), NH (21), NMH (10), and NUSLFH (9) occurred April 1954–January 1957. Weak LN events average about 5.5 months in duration, having a range of 5 to 7 months, and average about 3.5, 2, 1, and 0.3 for NTC, NH, NMH, and NUSLFH, respectively, during their operative lives. Moderate LN events average about 12.5 months in duration, having a range of 9 to 19 months, and average about 14.5, 7.5, 3.3, and 3.3 for NTC, NH, NMH, and NUSLFH, respectively, during their operative lives. Strong LN events average about 27 months in duration, having a range of 13 to 37 months, and average about 24.5, 14.8, 6.8, and 4.5 for NTC, NH, NMH, and NUSLFH, respectively, during their operative lives. Plainly, as the strength of the LN anomalous event increases, there is a tendency for its duration to increase in length and tropical cyclone activity to be enhanced.

Table 3 shows the frequency distribution (by calendar month) of the onset, peak, and end dates for EN and LN events. Both EN and LN events have always had their onsets after the month of March, with June being the most prominent month of onset for an EN event (there is no prominent onset month for an LN event). Fourteen of the 17 EN events with complete coverage had their primary peak in November–January, and 10 of the 12 LN events with complete coverage had their primary peak also in November–January. Hence, 24 of the 29 ENSO extreme events (82.8%) had their peak temperature anomalous excursion, as determined by the ONI, in November–January. For both EN and LN events, the end of the event tends to occur during January–June, just before the

Table 3. Frequency distribution of onset, peak, and end dates for EN and LN events.

	Onset		Peak		End	
Month	EN	LN	EN	LN	EN	LN
01			3	2	4	4
02				1	3	1
03					3	2
04	1	2			1	1
05	6	2			1	3
06	3				3	1
07	1	2			1	
08	3		1			
09	3	3	1			1
10		2	1	1		
11	1		8	4		
12		1	3	4	1	

official start of the hurricane season. This is true for 15 of 17 EN events (88.2%) and 11 of 12 LN events (91.7%), respectively.

Figure 7 shows the temporal variation of the annual mean ONI (<ONI>) values (fig. 7a) and the first difference of the 10-yma annual mean ONI values (fig. 7b), plotted similarly to that of figure 3. <ONI> is merely the 12-month average of the monthly ONI values. While yearly values of <ONI> are found to vary randomly about the value of <ONI> = 0 °C, the behavior of the 10-yma values of <ONI> (the thick smoothed line) suggests that <ONI> values tended to be negative prior to about 1980 and positive thereafter. Presently (in 2004, the last available 10-yma of <ONI>), the 10-yma value of <ONI> = 0.03, and the current trend of the 10-yma values of <ONI> appears, at least to the eye, to possibly be tracking downward, which, if true, suggests that it might soon become negative in value. From the "usual" first difference, one finds that 33 of 49 years (67%) have had a first difference in the 10-yma value of <ONI> = ±0.05 °C. Hence, one expects the 10-yma value of <ONI> for 2005 to be about 0.03 ± 0.05 °C if the "usual" first difference occurs again for 2004. Such a value implies a yearly value of <ONI> for 2010 of –2.2 ± 1 °C (or ≤–1.2 °C).

Negative values of yearly <ONI> are indicative of ENSO-neutral to LN-like conditions in the ENSO cycle, while positive values of yearly <ONI> are indicative of ENSO-neutral to EN-like conditions in the ENSO cycle. Because the yearly <ONI> value for 2010 is expected to be negative (≤–1.2 °C) from the "usual" behavior of the first difference in the 10-yma values of <ONI>, one infers that the present ongoing EN that began in mid-2009 might soon end and be replaced by an LN event of M-to-S strength sometime during the 2010 hurricane season. If true (remember, the reliability of the prediction is dependent solely upon whether the first difference in the 10-yma of <ONI> will, indeed, be ± 0.05 °C), then the activity level in the North Atlantic basin during the 2010 hurricane season should be expected to be higher than average.

The reader should note that there is only a 15% chance that the first difference in the 10-yma value of <ONI> for 2004 will be of value 0.06 °C or warmer, and it has exceeded 0.09 °C only once. For the 2010 value of <ONI> to be ≥0 °C, the 10-yma value of <ONI> for 2005 would have to measure 0.14 °C or warmer, meaning that the first difference in the 10-yma value of <ONI> for 2004 would have to be 0.11 °C or higher, something that has happened only once (0.15 °C in 1960.)

Table 4 gives the number of EN months (NENM), the number of LN months (NLNM), and the number of ENSO-neutral months (NNM) separately for negative and positive <ONI> yearly values for the interval 1950–2009 (720 months). Negative and positive <ONI> values are observed to have occurred equally, 360 months each. Of the 360 months when <ONI> was negative in value, 178 were classified NLNM, 167 were classified NNM and only 15 were classified NENM. Thus, when the yearly <ONI> value is negative, there is only about a 4% chance that the year contained any EN-related months, a 46% chance that it contained ENSO-neutral-related months, and a 49% chance that it contained LN-related months. When the yearly <ONI> value is positive, there is only about a 5% chance that the year contained any LN-related months, a 50% chance that it contained ENSO-neutral-related months, and a 45% chance that it contained EN-related months. For the interval 1950–2009, NENM has occurred about 25% of the time, NLNM has occurred about 27% of the time, and NNM has occurred about 48% of the time.

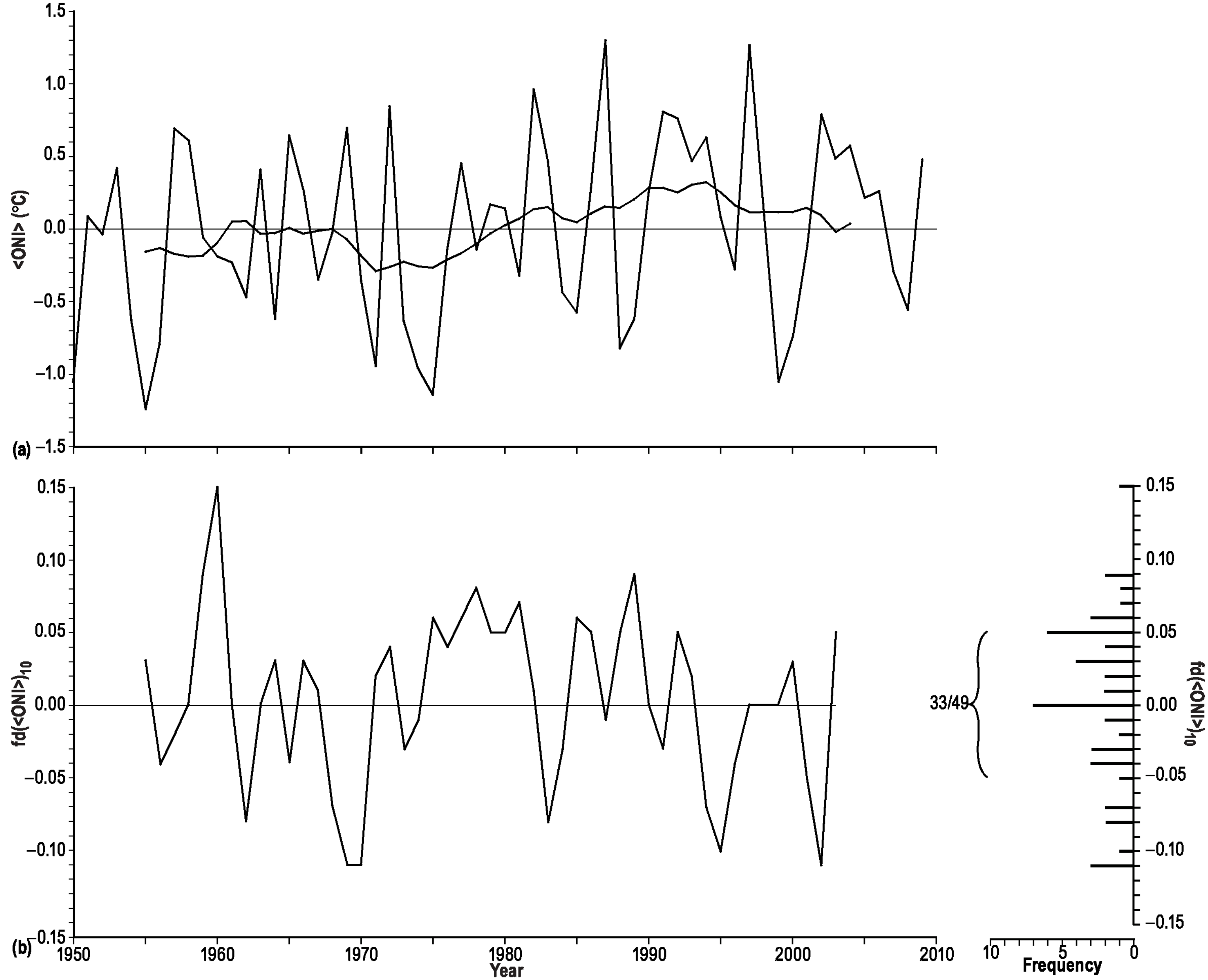

Figure 7. Observations of ONI: (a) Yearly mean <ONI> and (b) first differences of the 10-yma values of <ONI>.

Table 4. Comparison of <ONI> and NLNM, NNM, and NENM.

ENSO Category	Negative <ONI>	Positive <ONI>	Totals
NLNM	178	17	195
NNM	167	180	347
NENM	15	163	178
Total	360	360	720

Table 5 gives the distribution of NLNM/yr, NNM/yr, and NENM/yr for specific ranges of <ONI> yearly values. The table is comprised of three sections, with table 5a giving the results for NLNM/yr, table 5b giving the results for NNM/yr, and table 5c giving the results for NENM/yr. As an example, there have been 4 years when <ONI> measured in the range –1.49 to –1 °C, with all 4 years being associated with LN events and all having NLNM = 12 during those years. When <ONI> measures –1.49 to –0.5 °C, one finds LN-related months to have occurred about 81% of the time, ENSO-neutral-related months to have occurred about 16% of the time, and EN-related months to have occurred only about 3% of the time. Hence, when <ONI> is –0.5 °C or cooler, one can confidently say that the hurricane season probably is LN-related, since 13 of 15 years had 8 or more LN-related months during the year and 15 of 15 years had 5 or more LN-related months during the year.

Similarly, when <ONI> measures 0.5 °C or warmer, one finds EN-related months to have occurred about 68% of the time, ENSO-neutral-related months to have occurred about 30% of the time, and LN-related months to have occurred only about 2% of the time. Hence, when <ONI> is 0.5 °C or warmer, one expects the hurricane season to be EN-related, since 13 of 13 years had 6 or more EN-related months during the year when <ONI> was 0.5 °C or warmer.

The difficulty in determining whether a particular hurricane season might be LN-related or EN-related and, thus, possibly affecting the expected activity levels for the hurricane season occurs when <ONI> = –0.49 to 0.49 °C. Thirty-two of 60 years have had <ONI> within this range. Of the 32 years (384 months), LN-related months were observed about 12% of the time (6 or fewer months of the year), ENSO-neutral-related months were observed about 71% of the time, and EN-related months were observed about 17% of the time (7 or fewer months of the year). Hence, when <ONI> falls within the range of –0.49 to 0.49 °C, it is highly likely that the year will be classified as ENSO-neutral; however, there remains about a one in eight chance that an LN event might overlap the hurricane season and about a one in six chance that an EN event might overlap the hurricane season.

2.6 The Relationship Between the Annual Mean Oceanic Niño Index and the Annual Mean Surface-Air Temperature at Armagh Observatory

Figure 8 displays the scatter plot of <ONI> against <AT> using 10-yma values for the interval 1955–2004. The thin vertical and horizontal lines represent the median values for the 10-yma values of <AT> and <ONI>, respectively. The diagonal line running from lower left to upper right represents the inferred regression based on linear regression analysis. Ten-year moving average values of <ONI> are observed to range between –0.29 °C (in 1971) and 0.32 °C (in 1994), while 10-yma values of <AT> are observed to range between 9.05 °C (in 1982) and 10.13 °C (in 2002 and 2003).

Table 5. Distribution of (a) NLNM/yr, (b) NNM/yr, and (c) NENM/yr versus <ONI> yearly value.

a. NLNM/yr versus <ONI> yearly value

	<ONI> Yearly Value						
NLNM/yr	–1.49 to –1	–0.99 to –0.5	–0.49 to 0	0 to 0.49	0.5 to 0.99	1 to 1.49	Total
0	0	0	6	13	8	2	29
1	0	0	1	1	3	0	5
2	0	0	1	0	0	0	1
3	0	0	2	1	0	0	3
4	0	0	3	1	0	0	4
5	0	2	1	0	0	0	3
6	0	0	1	1	0	0	2
7	0	0	0	0	0	0	0
8	0	2	0	0	0	0	2
9	0	4	0	0	0	0	4
10	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0
12	4	3	0	0	0	0	7
Total	4	11	15	17	11	2	60

b. NNM/yr versus <ONI> yearly value

	<ONI> Yearly Value						
NLNM/yr	–1.49 to –1	–0.99 to –0.5	–0.49 to 0	0 to 0.49	0.5 to 0.99	1 to 1.49	Total
0	4	3	0	0	0	1	8
1	0	1	0	1	0	0	2
2	0	2	0	0	2	0	4
3	0	3	1	0	1	0	5
4	0	0	0	1	5	1	7
5	0	0	1	3	2	0	6
6	0	0	1	2	1	0	4
7	0	2	1	2	0	0	5
8	0	0	1	1	0	0	2
9	0	0	2	1	0	0	3
10	0	0	1	1	0	0	2
11	0	0	2	0	0	0	2
12	0	0	5	5	0	0	10
Total	4	11	15	17	11	2	60

c. NENM/yr versus <ONI> yearly value

	<ONI> Yearly Value						
NLNM/yr	–1.49 to –1	–0.99 to –0.5	–0.49 to 0	0 to 0.49	0.5 to 0.99	1 to 1.49	Total
0	4	8	10	5	0	0	27
1	0	1	3	0	0	0	4
2	0	1	1	1	0	0	3
3	0	1	0	2	0	0	3
4	0	0	1	1	0	0	2
5	0	0	0	4	0	0	4
6	0	0	0	3	1	0	4
7	0	0	0	1	3	0	4
8	0	0	0	0	5	1	6
9	0	0	0	0	1	0	1
10	0	0	0	0	1	0	1
11	0	0	0	0	0	0	0
12	0	0	0	0	0	1	1
Total	4	11	15	17	11	2	60

The results of Fisher's exact test for 2×2 contingency tables appears at the bottom,[34] yielding the probability (*P*) of obtaining the observed result, or one more suggestive of a departure from independence (chance), to be 0.2%. Similarly, one infers that the regression is statistically significant at *cl* >99.9%. Hence, given an expected value for the 10-yma of <AT> for 2005, one can estimate the expected 10-yma value of <ONI> for 2005, which can then be used to estimate the yearly value of <ONI> for 2010 for a determination of the likelihood that 2010 will be either LN-related, ENSO-neutral-related, or EN-related.

From the "usual" behavior of the first difference of the 10-yma values of <AT>, as has previously been shown, one expects a 10-yma value of <AT> for 2005 to be about 10.1 ± 0.05 °C (fig. 3). However, from the expected value of the 10-yma of $MLCO_2$ for 2005 (379.4 ppmv in figure 5), one expects the 10-yma value of <AT> for 2005 to be about 10.27 ± 0.1°C (fig. 6). Averaging the two estimates yields the "best guess" 10-yma value of <AT> to be about 10.19 ± 0.08 °C for 2005.

Presuming that the 10-yma value of <AT> for 2005 will, indeed, be 10.19 °C, from the linear regression (fig. 8) one infers the 10-yma value of <ONI> to be about 0.18 °C for 2005, which implies that the first difference of the 10-yma value of <ONI> would be 0.15 °C for 2005, well outside and high of its "usual" first difference value (± 0.05 °C) and tying the record set in 1960. A 10-yma value of <ONI> equal to 0.18 °C means that the <ONI> yearly value for 2010 would be 0.8 °C, which further suggests that the 2009 EN event very likely would continue into the 2010 hurricane season, in contrast to that presented earlier, which had presumed a downward trend in the 10-yma values of <ONI>.

Another reason for possibly accepting <ONI> as being positive in value for 2010 is that the 2009 EN is now known to be classified as an S event. Recall that S EN events average about 14 months in length and have persisted as long as 19 months in length (range 11 to 9 months), as shown in table 2 for the 1986 EN event. Because the 2009 EN has, thus far, persisted only 8 months, through January 2010, it likely will continue for several more months. A fit of EN duration versus max ONI, not shown, suggests that the 2009 EN, having a max ONI of 1.8 °C (in December 2009), should have a duration (± 1 *se*) measuring about 12 ± 3 months. Hence, the 2009 EN should end sometime between March and September 2010. However, if it turns out to be a multiyear event, it could persist through 2010 and not end until early 2011. Previously, there have been five multiyear EN events (where a multiyear EN event is one having a duration longer than 12 months), including EN events in 1957, 1982, 1986, 1991, and 1997. The 2009 EN event ranks as the fourth strongest EN event since 1950, tied with the 1991 EN event in terms of max ONI.

The behavior of the 10-yma of <AT> certainly suggests a far different scenario for <ONI> in 2010 than the one based on the "usual" behavior of the first difference of the 10-yma value of <ONI>. Recall that the "usual" behavior of the 10-yma of <ONI> suggests that the 2009 EN event should end in early 2010 (before June) and be replaced by an M-to-S LN event in the latter portion of 2010. Also, from table 4 it was shown that a positive value of <ONI> tends to be indicative of a year that is classified ENSO-neutral-related or EN-related, while a negative value of <ONI> tends to be indicative of a year that is classified ENSO-neutral-related or LN-related. Obviously, the first several months of 2010 should prove instructive for determining whether the 2010 hurricane season might

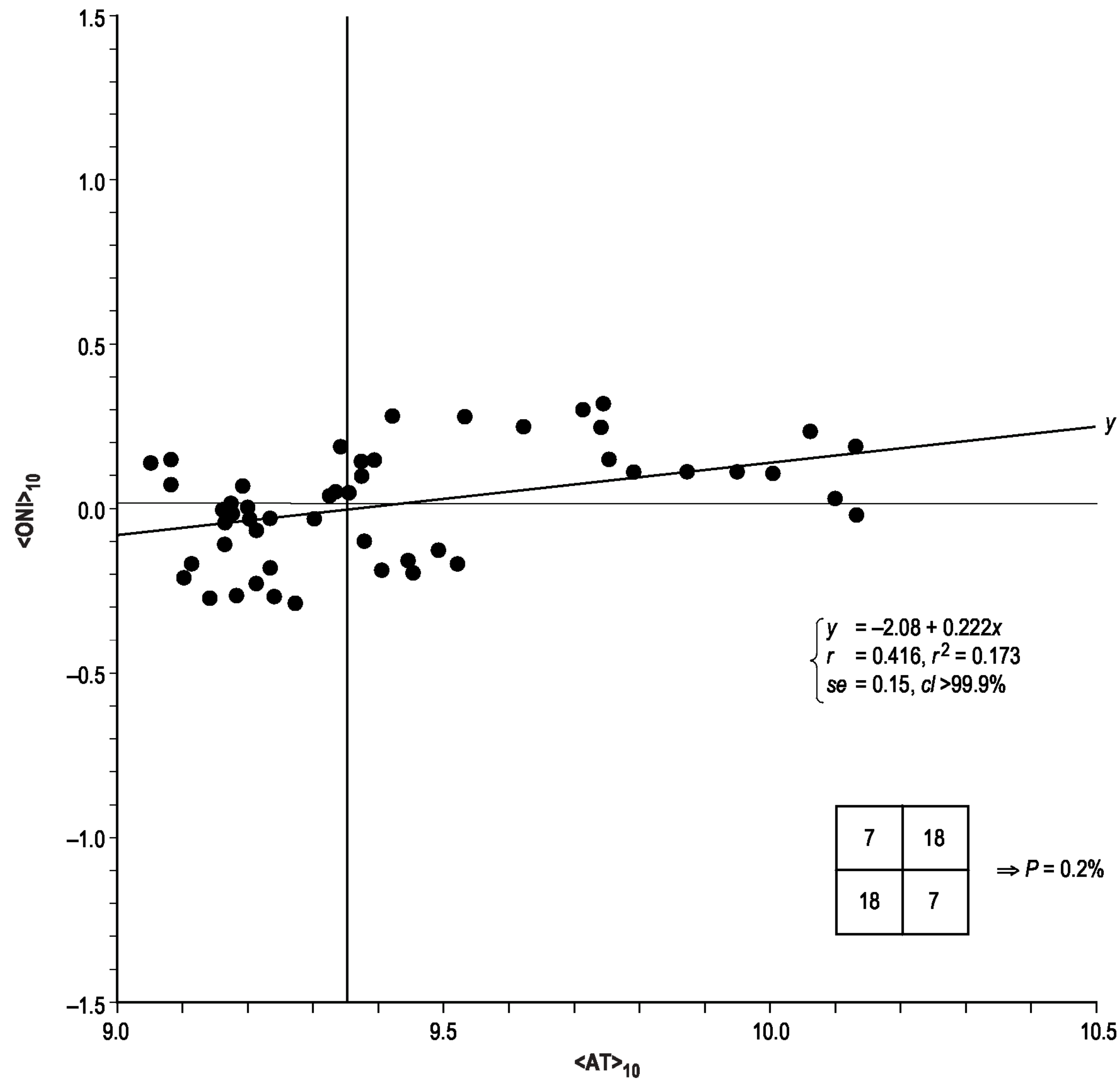

Figure 8. Scatter plot of 10-yma values of <ONI> against 10-yma values of <AT>.

be expected to be ENSO-neutral or associated with an ENSO extreme event (either a continuing EN event or the occurrence of an LN event).

2.7 Predicting Yearly <ONI> From the January–May Average and Prediction of Warmest and Coolest Monthly ONI Value

Figure 9 compares the <ONI> yearly value against the average ONI value for the 5-month interval January–May. The average ONI value for January–May appears to provide a fairly strong indication as to whether the year as a whole would be expected to be either of positive or negative value. When the average <ONI> value for January–May is positive, the <ONI> yearly value also is expected to be positive in value, as indicated by the inferred regression line (*y*) and the distribution of positive values, which has been true for 22 of 30 years. Likewise, when the January–May average is

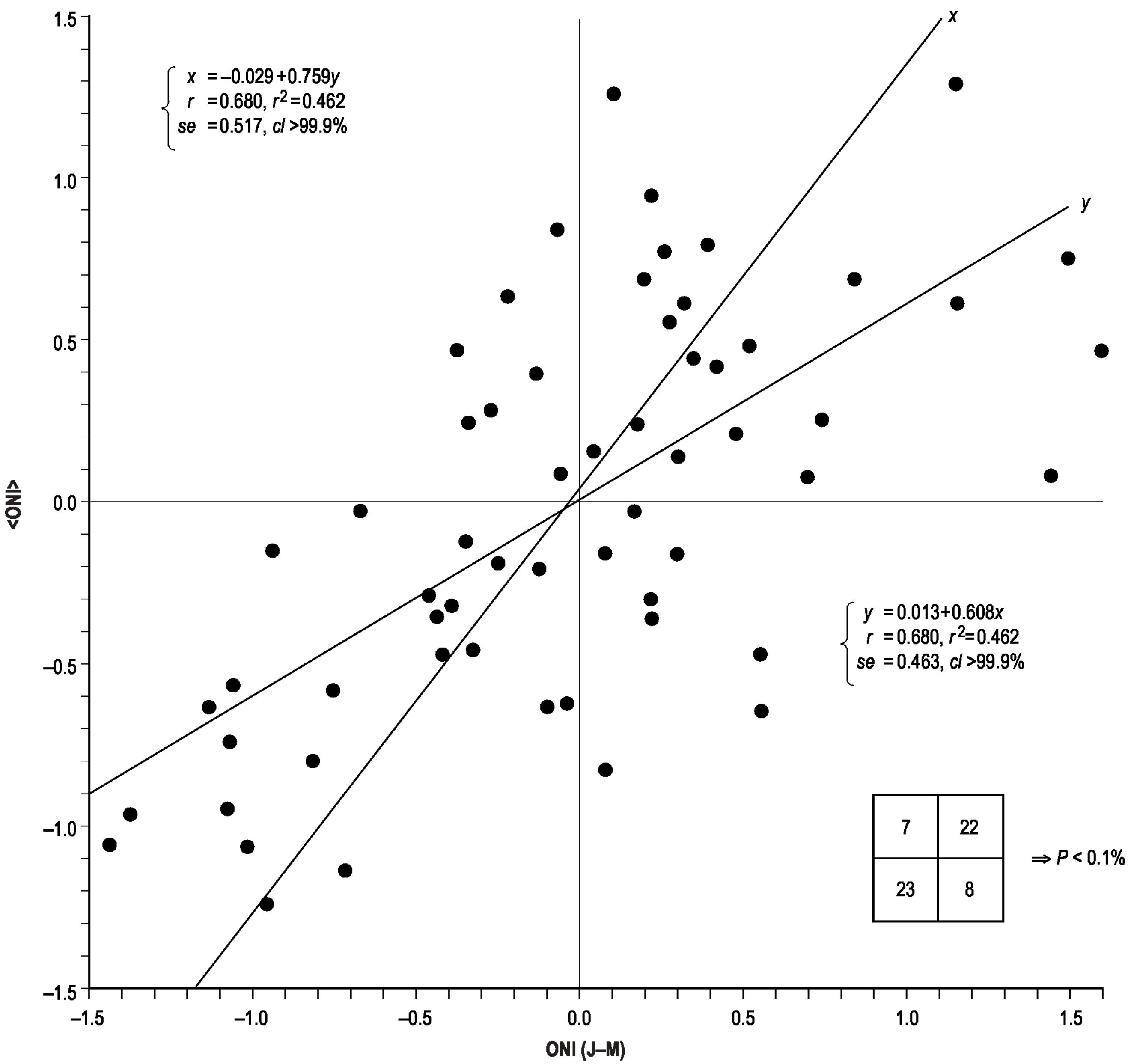

Figure 9. Scatter plot of <ONI> against the January–May average value of ONI.

negative, the <ONI> yearly value also is expected to be negative, as indicated by the inferred regression and the distribution of negative values, which has been true for 23 of 30 years. Furthermore, when the January–May value is ≥0.5 °C, 9 of 11 times this previously has indicated that the <ONI> yearly value was, indeed, positive, and 4 of 11 times it indicated that it too was ≥0.5 °C; whereas, when the January–May value is ≤–0.5 °C, 13 of 13 times this previously has indicated that the <ONI> yearly value was negative and 11 of 13 times it also indicated an <ONI> yearly value ≤–0.5 °C. (In figure 9, the inferred regression line marked *x* plots the ONI 5-month averages against the <ONI> yearly value, so that, given an expected <ONI> yearly value, one might gauge the expected ONI average for the first 5 months of the year.)

From above, based on the expected value of the 10-yma of <AT> for 2005 (10.19 °C) and the inferred relationship between 10-yma values of <ONI> and <AT>, one expects the <ONI> yearly value for 2010 to be about 0.8 °C. If true, then the first 5-month average of ONI for 2010 should be about 0.58 ± 0.52 °C (± 1 *se*), indicating that the 2009 EN event probably is slowly decreasing in strength towards ENSO-neutral conditions later in the year. The preferential relationship shown in figure 9 has failed in 15 of 60 years, so there remains a 1 in 4 chance that it might also fail in 2010, as well. The NOAA Climate Prediction Center continues to predict the persistence of the 2009 EN, at least, through the spring of 2010.[35]

Figure 10 compares (a) the warmest monthly ONI and (b) the coolest monthly ONI with the <ONI> yearly value. Accepting 0.8 °C as the 2010 <ONI> yearly value, one infers that the warmest monthly ONI should be about 1.6 ± 0.5 °C (± 1 *se*) and the coolest monthly ONI should be about 0 ± 0.4 °C (± 1 *se*) for 2010. (In January 2010, the ONI monthly value measured 1.7 °C.)

2.8 Predicting the 2005 10-yma Values for NTC, NH, NMH, and NUSLFH From the Expected 10-yma Values of <AT> and <ONI> and the Yearly Frequencies for 2010

Table 6 gives the observed and predicted 10-yma parametric values for the interval 1995–2004, using a single-variate fit based on the 10-yma value of <AT> and a bivariate fit based on 10-yma values of both <AT> and <ONI>. For comparison, the mean and *sd* values of the parameters for the interval 1995–2004 are also given. The use of the bivariate fits does not appear to substantially improve the predictions as compared to using the single-variate fit based on <AT> alone.

Table 7 provides the 2005 10-yma value predictions for NTC, NH, NMH, and NUSLFH based on the mean statistical behavior (1995–2004), the single-variate fit (using <AT> alone), and the bivariate fit (using both <AT> and <ONI>, where the latter fits use the "usual" expected values and the "best guess" values). For all parameters, values higher than their statistical means are indicated. For NTC, the 2005 10-yma value is estimated to be about 15.5 ± 0.5; for NH, the 2005 10-yma value is estimated to be about 8.2 ± 0.3; for NMH, the 2005 10-yma value is estimated to be about 4 ± 0.2; and for NUSLFH, the 2005 10-yma value is estimated to be about 2.4 ± 0.2. From these 10-yma values, one can estimate the 2010 parametric yearly values. For NTC, NH, NMH, and NUSLFH, the 2010 expected frequencies are 26 ± 10, 20 ± 6, 11 ± 4, and 10 ± 4, respectively. Therefore, the techniques as employed here suggest that the 2010 North Atlantic basin hurricane season will be an above average season in terms of activity, having NTC ≥ 16, NH ≥ 14, NMH ≥ 7, and NUSLFH ≥ 6.

2.9 Comparison With Colorado State University and Tropical Storm Risk Estimates

The early CSU team estimate calls for the 2010 North Atlantic basin hurricane season to be somewhat more active than the long-term statistical means,[1] this estimate being more typical of the current active phase (since 1995). In particular, the CSU team estimates 11–16 tropical cyclones, 6–8 hurricanes, and 3–5 major hurricanes during the 2010 hurricane season. They also estimate the likelihood of a U.S. land-falling hurricane to be above average during the 2010 hurricane season.

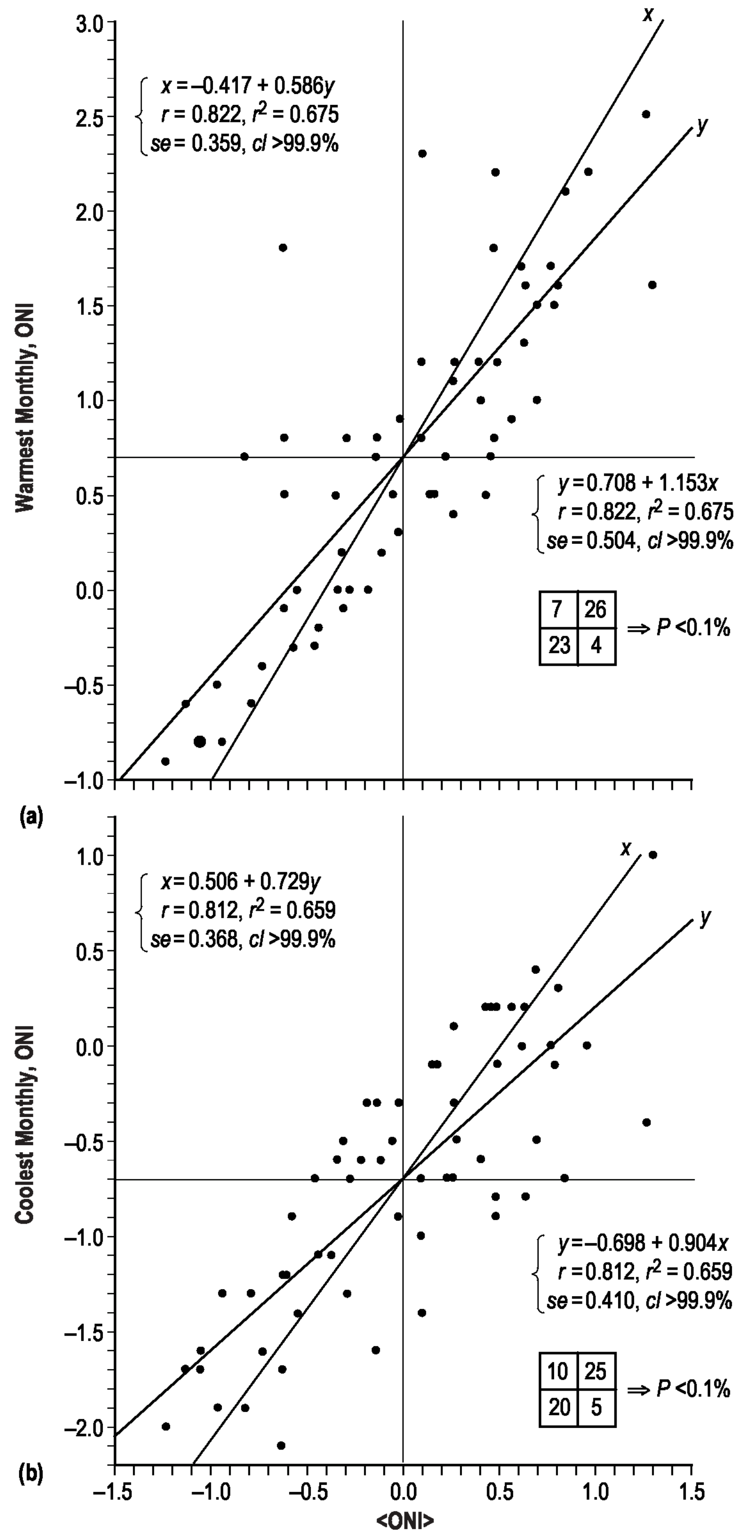

Figure 10. Scatter plot of (a) the warmest and (b) the coolest monthly ONI value against the yearly mean <ONI>.

Table 6. Observed and predicted 10-yma parametric values for 1995–2004.

	Observed*				Predicted (<AT>)**				Predicted (<AT>, <ONI>)***			
Year	NTC	NH	NMH	NUSLFH	NTC	NH	NMH	NUSLFH	NTC	NH	NMH	NUSLFH
1995	11.1	6.4	2.6	1.4	11.4	6.6	2.8	1.3	11.3	6.6	2.8	1.4
1996	11.5	6.7	2.8	1.4	11.5	6.7	2.8	1.3	11.6	6.7	2.8	1.3
1997	12.1	6.9	3	1.3	11.9	6.8	2.9	1.4	12	6.8	2.9	1.3
1998	12.7	7.1	3.1	1.4	12.7	7.1	3.2	1.6	12.8	7.2	3.2	1.6
1999	13.5	7.5	3.5	1.7	13.5	7.5	3.4	1.8	13.5	7.5	3.4	1.8
2000	14.4	8	3.9	2.2	14	7.7	3.5	1.9	14	7.7	3.5	2
2001	14.7	8	3.8	2.3	14.6	7.9	3.7	2.1	14.5	7.9	3.7	2.2
2002	14.9	8	3.7	2.2	15.4	8.2	3.9	2.3	15.3	8.2	3.9	2.3
2003	15.3	8.2	3.8	2.2	15.4	8.2	3.9	2.3	15.5	8.2	3.9	2.1
2004	15.3	7.9	3.8	2.1	15.1	8.1	3.8	2.2	15.1	8.1	3.8	2.1

* NTC: mean = 13.55, *sd* = 1.599
NH: mean = 7.47, *sd* = 0.646
NMH: mean = 3.4, *sd* = 0.481
NUSLFH: mean = 1.82, *sd* = 0.416

** Single variate fits: NTC = –87.541 + 10.158<AT>, *r* = 0.988, *se* = 0.207
NH = –32.51 + 4.017<AT>, *r* = 0.967, *se* = 0.238
NMH = –25.411 + 2.895<AT>, *r* = 0.937, *se* = 0.177
NUSLFH = –22.818 + 2.476<AT>, *r* = 0.927, *se* = 0.143

*** Bivariate fits: NTC = –80.297 + 9.452<AT> – 2.027<ONI>, *r* = 0.99, *se* = 0.255
NH = –30.631 + 3.834<AT> – 0.513<ONI>, *r* = 0.962, *se* = 0.2
NMH = –24.95 + 2.85<AT> – 0.118<ONI>, *r* = 0.94, *se* = 0.186
NUSLFH = –29.327 + 3.109<AT> + 1.913<ONI>, *r* = 0.954, *se* = 0.142

Table 7. Predictions of 10-yma parametric values for 2005 based on the interval 1995–2004.

FIT	NTC	NH	NMH	NUSLFH
Mean (±*sd*):	13.5±1.6	7.5±0.7	3.4±0.5	1.8±0.4
Single Variate:("usual" behavior <AT> = 10.1±0.05)	15.1±0.5	8.1±0.2	3.8±0.2	2.2±0.1
Single Variate:("best guess" <AT> = 10.19±0.08)	16 ±0.8	8.4±0.3	4.1±0.2	2.4±0.2
Bivariate:("usual" behaviors <AT> = 10.1±0.05, <ONI> = 0.03±0.05)	15.1±0.4	8.1±0.1	3.8±0.2	2.1±0.3
Bivariate:("best guess" <AT> = 10.19±0.08, <ONI> = 0.18±0.15)	15.7±0.4	8.3±0.3	4.1±0.2	2.7±0.5

Similarly, the TSR team estimate calls for the 2010 North Atlantic basin hurricane season to also be more active than the long-term statistical mean.[2] In particular, the TSR team projects an increase of 35% above average in numbers of tropical cyclones and U.S. land-falling hurricanes for the 2010 season, with a 62% likelihood that the 2010 season will be in the upper one-third of active years. The TSR team predicts about 13.9±4.9 tropical storms, 7.4±3.1 hurricanes, and 3.4±1.8 major hurricanes.

As previously noted, the techniques employed in this study indicate increased activity in the North Atlantic basin during the 2010 hurricane season, in agreement with the early forecasts of the CSU and TSR teams. It is anticipated that the 2010 season will have seasonal frequencies for all categories of tropical cyclones above their statistical means, both long-term means and means for the current more active interval (which began in 1995). This is attributed primarily to an expected rise in surface-air temperature at the Armagh Observatory due to the continued increase of the atmospheric concentration of CO_2. For the 2010 North Atlantic basin hurricane season, one expects NTC = 14.5 ± 4.7, NH = 7.8 ± 3.2, NMH = 3.7 ± 1.8, and NUSLFH = 2 ± 2, based on the means (± 1*sd*) for the current more active interval (1995–2009); NTC = 19 ± 2, NH = 14 ± 2, NMH = 7 ± 2, and NUSLFH = 4 ± 2, based on the "usual" behavior of the first differences; and NTC ≥ 16, NH ≥ 14, NMH ≥ 7, and NUSLFH ≥ 6, based on the expected average ranges from the preferential single-variate and bivariate fits. Until additional information becomes available, it seems highly likely that the 2010 North Atlantic basin hurricane season will be considerably more active, especially in comparison to that experienced in the 2009 hurricane season. However, should the 2009 EN event persist through 2010 and have an additional peak in late 2010 or early 2011, a reduction in the seasonal estimates might be required.

2.10 Predicting the Next El Niño Southern Oscillation Extreme Event Occurrence

Recently, it was shown that there exists a statistically significant association between the recurrence period (RP) and duration of EN events of M-to-S strength,[19] where the RP is determined from the start date of the event of known duration. Figure 11 displays the scatter plot of RP versus duration. In figure 11, filled circles identify W events, filled squares identify M events, and filled triangles identify S events. The inferred regression (y) is determined using only EN events of M-to-S strength and has $r = 0.681$, $se = 14$ months, and $cl > 98\%$. Thus, given the duration of an M-to-S EN event, one can crudely estimate the likelihood of the occurrence of the next EN event.

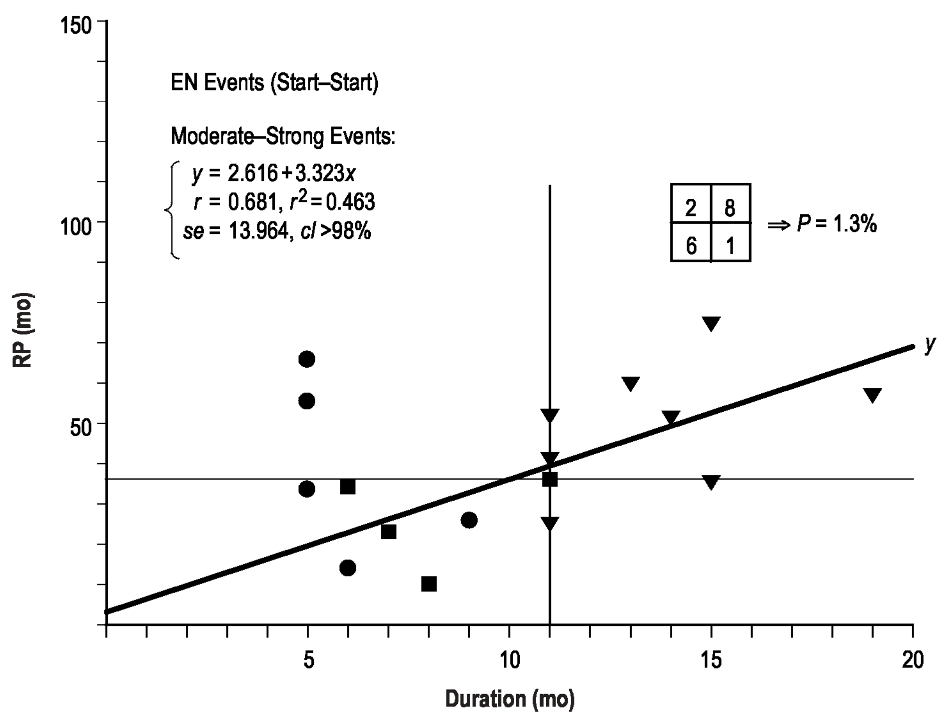

Figure 11. Scatter plot of RP against duration for EN events.

Similarly, based on the Fisher's exact test for 2×2 contingency tables, the observed distribution, or one more suggestive of a departure from independence, is computed to be only $P = 1.3\%$ for EN events. Six of 9 W and M EN events are observed to be located in the lower left quadrant (duration < 11 months and RP < 36 months), while 7 of 8 S EN events populate the upper right quadrant (duration ≥ 11 months and RP ≥ 36 months). Because the 2009 EN event is of S strength, statistically speaking, one expects its duration to be ≥ 11 months and to have an associated RP ≥ 36 months, indicating that one should not expect another EN event until June 2012 or later.

While there appears to be a loose statistical association between RP and duration for EN events, no such statistically important relationship is found for LN events. Figure 12 shows the scatter plot of RP against the duration for LN events, plotted similarly to that of figure 11. Obviously, RP for LN events is independent of the duration and strength of the preceding LN event.

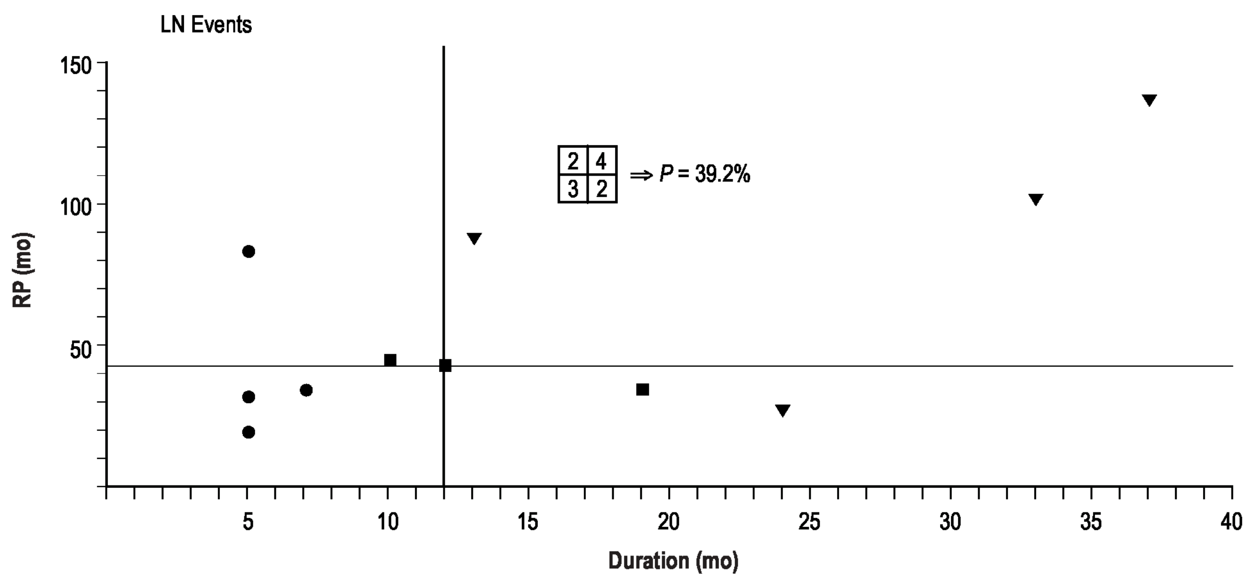

Figure 12. Scatter plot of RP against duration for LN events.

3. SUMMARY

This present work marks a continuation of studies of the Earth's climate system as related to the prediction of hurricane activity for the North Atlantic basin. The record of hurricane activity is considered reliable only since about 1950, owing to the routine use of aircraft reconnaissance and continuous satellite viewing (since the 1960s).[36] On average, about 11 tropical cyclones have formed in the North Atlantic basin during the hurricane season since 1950, spanning a range of 4 to 28, with the fewest occurring in 1983 and the most in 2005; on average, about 6 hurricanes have formed in the North Atlantic basin during the hurricane season, spanning a range of 2 to 15, with the fewest occurring in 1982 and the most in 2005; and, on average, about 2–3 major hurricanes have formed in the North Atlantic basin, spanning a range of 0 to 8, with no major hurricanes having occurred in 1968, 1972, 1986, and 1994 and the most occurring, thus far, only in 1950. The years of lowest frequency have always been associated with the occurrences of EN events, while the highest frequencies have always been associated with years having no occurrences of EN events.

Concerning land-falling hurricanes that strike the U.S. Gulf coast and eastern seaboard, on average, this has occurred about 1–2 times per year, spanning a range of 0 to 6. The fewest number have occurred 12 times (including years 1951, 1962, 1973, 1978, 1981, 1982, 1990, 2000, 2001, 2006, and 2009) with nearly half of these years being associated with EN events, and the most have occurred only 3 times (including years 1985, 2004, and 2005).

On the basis of the 10-yma behavior of the frequency of major hurricanes, it is apparent that the activity level in the North Atlantic basin varies on decadal timescales, with greater activity having been seen prior to 1966 and again after 1994 and lesser activity of about three decades length separating the two more active states. For the first more active interval (prior to 1966), the averages (± 1 *sd*) of NTC, NH, NMH, and NUSLFH are found to be about 9.6 ± 2.6, 6.3 ± 2.3, 3.6 ± 2.2, and 1.8 ± 1.2, respectively, and for the second more active interval (1995–present) to be about 14.5 ± 4.7, 7.8 ± 3.2, 3.7 ± 1.8, and 2 ± 2, respectively. Statistical testing reveals that, while there is no statistically important difference in the means for the two more active intervals for NH, NMH, and NUSLFH, the difference in means is statistically important for NTC. Also, compared to the less active interval, which has respective averages of about 9.6 ± 3, 5.4 ± 2.1, 1.6 ± 1.1, and 1.3 ± 1.3, the present more active interval has parametric means that are all significantly different, except for NUSLFH. Hence, there has been a significant increase in the frequency of tropical cyclone formation in the North Atlantic basin, one that manifests itself for all categories of tropical cyclones with the exception of U.S. land-falling hurricanes (when the comparison is between the current more active interval and the preceding less active interval).

First differences in the 10-yma values of the parameters are useful in that they provide reasonable estimates for the expected frequencies of tropical cyclones for an upcoming season, estimates based on the "usual" statistical behavior of their distributions (current trends). For the 2010 North Atlantic basin hurricane season, the "usual" behavior of their first differences in 10-yma values suggests NTC, NH, NMH, and NUSLFH to be about 19 ± 2 (50% chance), 14 ± 2 (57% chance), 7 ± 2

(65% chance), and 4 ± 2 (78% chance), respectively. The chances of exceeding the lower estimates are 83% (≥ 17), 85% (≥ 12), 83% (≥ 5), and 87% (≥ 2), respectively.

The 10-yma seasonal frequency of tropical cyclone formation in the North Atlantic basin is found to strongly associate with the 10-yma of surface-air temperature as recorded at the Armagh Observatory in Northern Ireland, particularly during the current more active interval.[15–18] Statistically important regressions, having $r \geq 0.93$, are inferred to exist between the 10-yma values of NTC, NH, NMH, and NUSLFH and 10-yma values of <AT> for the interval 1995–2004. Based on the "usual" behavior of the first differences of the 10-yma values of <AT>, one expects the 2005 10-yma value for <AT> to be about 10.1 ± 0.05 °C (74% chance), which suggests 10-yma values for 2005 of NTC = 15.06 ± 0.5, NH = 8.06 ± 0.2, NMH = 3.83 ± 0.14, and NUSLFH = 2.19 ± 0.12. Such values imply 2010 frequencies to be 14 ± 10, 17 ± 4, 8 ± 2, and 6 ± 2, respectively. Also, a 2005 10-yma of <AT> = 10.1 °C implies that the 2010 <AT> yearly temperature would measure 10.73 °C, which, if true, represents a new record high temperature at Armagh, one that exceeds the previous record high of 10.59 °C in 2007.

Now, the 10-yma value of <AT> is known to track the 10-yma of the CO_2 atmospheric concentration as measured at the Mauna Loa Observatory in Hawaii fairly closely ($r = 0.987$),[20] particularly since about 1982. Carbon dioxide appears to be increasing exponentially from about 319 ppmv in 1963 to 378 ppmv in 2004, based on 10-yma $MLCO_2$ values. Projecting forward 1 year suggests that the 10-yma value of $MLCO_2$ will measure about 379.4 ppmv in 2005, which further suggests that the 10-yma value of <AT> will measure about 10.27 ± 0.1 °C in 2005. However, such a value presents a difficult quandary in that it implies an <AT> yearly temperature ≥11.73 °C in 2010, a value more than 4 *sd* higher than the 1950–2009 average. Presuming the 10-yma of <AT> = 10.17 °C (the lower limit) in 2005, one expects NTC = 28, NH = 23, NMH = 12, and NUSLFH = 9 in the 2010 hurricane season, all record highs or near-record highs.

Instead, using a "best guess" for the 10-yma of <AT> (= 10.19 °C), achieved by averaging the "usual" first difference current trend value (10.1 °C) and the expected value from the <AT>-$MLCO_2$ inferred relationship (10.27 °C), one obtains NTC = 26 ± 10, NH = 20 ± 6, NMH = 11 ± 4, and NUSLFH = 10 ± 4 for the 2010 hurricane season. From these inferred ranges, one determines NTC ≥ 16, NH ≥ 14, NMH ≥ 7, and NUSLFH ≥ 6 for the 2010 hurricane season. In comparison to the CSU and TSR forecasts, the estimates presented here are above their upper limits, with all forecasts suggesting the 2010 hurricane season to be more active than the 2009 season and more akin to the averages of the current more active interval that began in 1995.

Whether or not the 2009 EN will be of sufficient duration to inhibit the expected frequencies of tropical cyclone formation that have been forecast for the 2010 season is an unknown. It is known that the 2009 EN event is an S event (max ONI = 1.8 °C in December 2009), and S events are known to persist about 14 months on average (range 11 to 19 months). Through January 2010, the 2009 EN event has persisted 8 months (onset in June 2009). It is anticipated that it will slowly weaken in strength, perhaps ending sometime between March and September 2010 (usually an EN event ends in the first half of a year). If the current EN event ends before the 2010 hurricane season, then one expects the 2010 hurricane season to be ENSO-neutral to LN like and the expected frequencies to be more akin to the current averages and observed ranges (NTC = 8–28, NH = 3–15, NMH = 1–7, and

NUSLFH = 0–6). On the other hand, if the 2009 EN event should persist into the 2010 hurricane season, then one would expect to see a sharp reduction in the frequencies for the 2010 hurricane season. About one-third of the EN events since 1950 have been multiyear EN events. These include the 1957, 1982, 1986, 1991, and 1997 EN events. So, it is possible that the 2009 EN event could also be a multiyear event, although it certainly is not expected based on the "usual" first difference value of the 10-yma of <ONI>, which strongly suggests the quick demise of the 2009 EN event in early 2010, being replaced by an M-to-S LN event during the latter portion of the year. On the basis of the RP-duration preferential association for M-to-S EN events, one does not expect another EN event to have an onset until June 2012 or later, suggesting that the next two seasons will be ENSO-neutral to LN like and be more indicative of increased activity.

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14. ABSTRACT
Estimates are presented for the tropical cyclone activity expected for the 2010 North Atlantic basin hurricane season. It is anticipated that the 2010 season will be more active than the 2009 season, reflecting increased frequencies more akin to that of the current more active phase that has been in vogue since 1995. Averages (± 1 *sd*) during the current more active phase are 14.5 ± 4.7, 7.8 ± 3.2, 3.7 ± 1.8, and 2 ± 2, respectively, for the number of tropical cyclones (NTC), the number of hurricanes (NH), the number of major hurricanes (NMH), and the number of United States (U.S.) land-falling hurricanes (NUSLFH). Based on the "usual" behavior of the 10-yma parametric first differences, one expects NTC $= 19 \pm 2$, NH $= 14 \pm 2$, NMH $= 7 \pm 2$, and NUSLFH $= 4 \pm 2$ for the 2010 hurricane season; however, based on the "best guess" 10-yma values of surface-air temperature at the Armagh Observatory (Northern Ireland) and the Oceanic Niño Index, one expects NTC ≥ 16, NH ≥ 14, NMH ≥ 7, and NUSLFH ≥ 6.

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