NASA/TP—2012–217470

Estimating the Length of the North Atlantic Basin Hurricane Season

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October 2012

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LIST OF ACRONYMS AND ABBREVIATIONS

10-yma	10-year moving average
AMM	Atlantic Meridional Mode
AMO	Atlantic Multidecadal Oscillation
AT	Armagh Observatory surface air temperature
DOY	day of year
ENSO	El Niño Southern Oscillation
ENY	El Niño year
FSD	first storm day
HURDAT	hurricane data
LNY	La Niña year
LOS	length of season
LSD	last storm day
NENM	number of El Niño months
NLNM	number of La Niña months
NY	neutral year
ONI	Oceanic Niño Index
PWS	peak wind speed
SST	sea surface temperature

NOMENCLATURE

cl	confidence level
n+	number of annual values above mean
n–	number of annual values below mean
n + *r*	number of annual value positive runs
P	probability
r	coefficient of correlation
r^2	coefficient of determination
sd	standard deviation
se	standard error of estimate
x	independent variable
y	dependent variable
z	normal deviate of sample

TECHNICAL PUBLICATION

ESTIMATING THE LENGTH OF THE NORTH ATLANTIC BASIN HURRICANE SEASON

1. INTRODUCTION

Conventionally, the North Atlantic basin hurricane season spans the 183-day period from June 1 to November 30. Of the 67 yr spanning 1945–2011, an interval considered to be the most reliable based on the near continuous use of reconnaissance aircraft and especially Earth-orbiting satellite imaging (since the 1960s),[1–3] only 22 yr had yearly (or seasonal) first or last storm days outside this interval[4] where the first storm day (FSD) and the last storm day (LSD) of a season refer, respectively, to the first and last days of a yearly hurricane season when tropical cyclones had a 1-min sustained peak wind speed (PWS) of at least 34 kt. The yearly length of season (LOS) is defined as the elapsed time in days between FSD and LSD for that year.

For the interval 1945–2011, some 734 tropical cyclones formed in the North Atlantic basin, including 416 storms that became hurricanes (i.e., those having PWS ≥64 kt), of which 183 storms became major or intense hurricanes (i.e., those having PWS ≥96 kt). Of the 734 tropical cyclones, 712 (or about 97%) originated during the nominal hurricane season of June 1–November 30 with the bulk (78%) originating in the months of August (27%), September (34%), and October (17%). Of the remaining 22 storms, all but two originated during the months of April (2), May (10), and December (8), months immediately adjacent to the nominal hurricane season.[4] The two tropical cyclones that formed outside the inclusive interval of April 1–December 31 include one each tropical cyclone of tropical storm strength only (i.e., 34≤ PWS ≤63 kt) that formed in the months of January and February, respectively. For the interval 1945–2011, no tropical cyclone is known to have formed in the North Atlantic basin during the month of March. Because the January 1978 and February 1952 tropical storms were not closely preceded nor followed by additional tropical cyclones, they are considered statistical outliers and have been excluded in this study.

Previously, Kossin[5] examined the interval 1851–2007 'best track' hurricane record (i.e., the HURDAT, available online at <www.nhc.noaa.gov/pastall.shtml>) and suggested that the hurricane season is increasing in length due to the occurrences of both earlier and later seasonal storms, attributing the increased lengthening to warming sea surface temperature (SST). His analysis was based on the use of quantile regression.[6,7]

In this analysis, the 'best track' hurricane record for 1945–2011 is used to ascertain the exact day of year (DOY) for each year's FSD and LSD, thereby allowing for determination of each year's LOS. Ten-year moving averages (10-yma) are then determined for each parameter. Next, based on the annual values, the scatter plot of LOS versus FSD is determined, one that reveals a preferential inverse correlation between the parameters and that is statistically important at the 0.1% level of significance (or >99.9% confidence level, or *cl*). From the reported FSD for the year 2012 (i.e., May 19, 2012 or DOY = 140), the LOS and LSD for the current hurricane season are estimated based on the inferred regression. Lastly, the trend of LOS is compared to trends of various markers of surface-air temperature, SST, and the El Niño Southern Oscillation (ENSO) to ascertain the degree of similarity between the parameters.

2. RESULTS

Figure 1 displays the variation of the DOY for FSD (fig. 1(a)) and LSD (fig. 1(b)) during the interval 1945–2011, ignoring the two previously described outlier tropical storms. The thin jagged line represents the annual values and the thick smoothed line represents the 10-yma values. During the 67-yr interval, the DOY for FSD is found to average about 180.5 (corresponding to about July 1), having a standard deviation (*sd*) of about 33 days and range of 110 to 242, and the DOY for LSD is found to average about 310 (corresponding to about November 6), having *sd* of about 23 days and range of 263 to 371. (Recall that eight tropical cyclones formed in the month of December with two ending in the following calendar year, including one hurricane spanning December 30, 1954–January 5, 1955 and one tropical storm spanning December 30, 2005–January 6, 2006. Hence, the LSD for 1954 is 370, and the LSD for 2005 is 371, as indicated in fig. 1(b)).

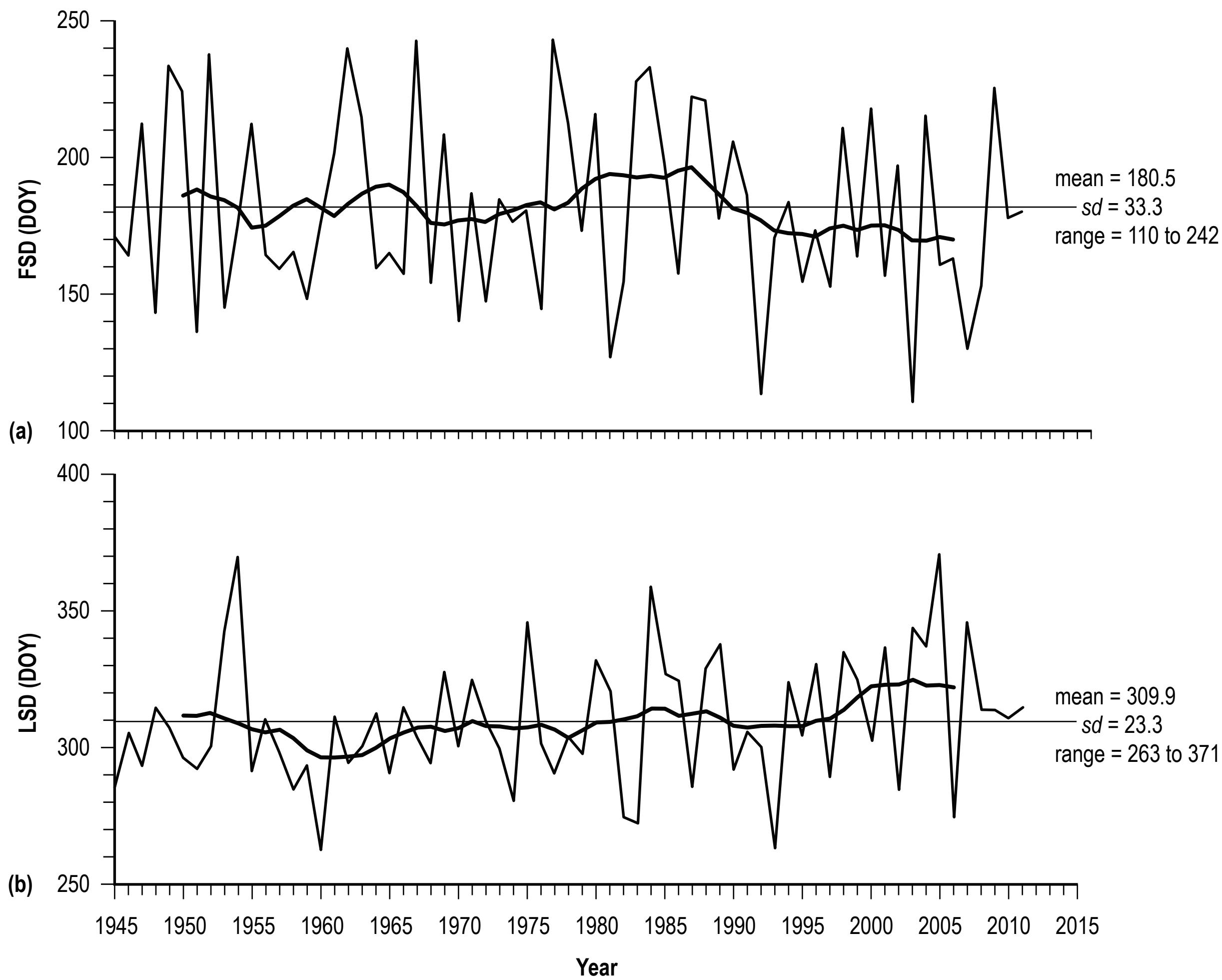

Figure 1. The annual and 10-yma values of (a) FSD and (b) LSD for the interval 1945–2011. Excludes FSD33 in 1952 and FSD19 in 1978, both short-lived tropical storms and considered statistical outlier events in this study.

Based on the movement of the 10-yma values (used to indicate trend), since about 1987, FSD has decreased from about DOY 195 to about DOY 170 (in 1996), a decrease of about 13%, varying between DOY = 169–174 after 1996 and between DOY = 175–190 prior to 1987. The 10-yma values of FSD have remained below the long-term mean (DOY = 180.5) since about 1990.

Since the early 1960s, LSD has slowly increased from about DOY 297 (in 1960) to about DOY 325 (in 2003), an increase of about 9%. The 10-yma values of LSD have been relatively flat (about DOY = 322–325) between 2000 and 2006, the last available 10-yma value of LSD, and above the long-term mean (DOY = 310) since about 1997.

Together, these movements in the trends of FSD and LSD suggest that LOS will display a preferential upward movement, indicative of a lengthening of the hurricane season. Indeed, as shown in figure 2, based on the movement of its 10-yma values, LOS has increased from about 113 days (in 1979) to about 157 days (in 2003), an increase of about 39%. In terms of annual values, LOS is found to average about 130 days, having *sd* of about 42 days and range of 47 to 235 days. Runs-testing[8] indicates that the annual values of LOS vary nonrandomly at the 5% level of significance (or cl>95%) based on the observed 33 annual LOS values above the mean (n+), the 34 values below the mean (n–), and the 22 positive runs ($n+r$), which together yields the normal deviate of the sample $z = 2.31$, a value suggestive of nonrandom variation. The current interval of higher than average 10-yma values of LOS began in 1992 and continues through 2006, now measuring about 154 days. During the interval 1992–2011, annual values of LOS exceeded the long-term mean in 13 of 20 yr and fell below the long-term mean in 7 of 20 yr, averaging about 148 ± 43 days (i.e., the ±1 *sd* interval).

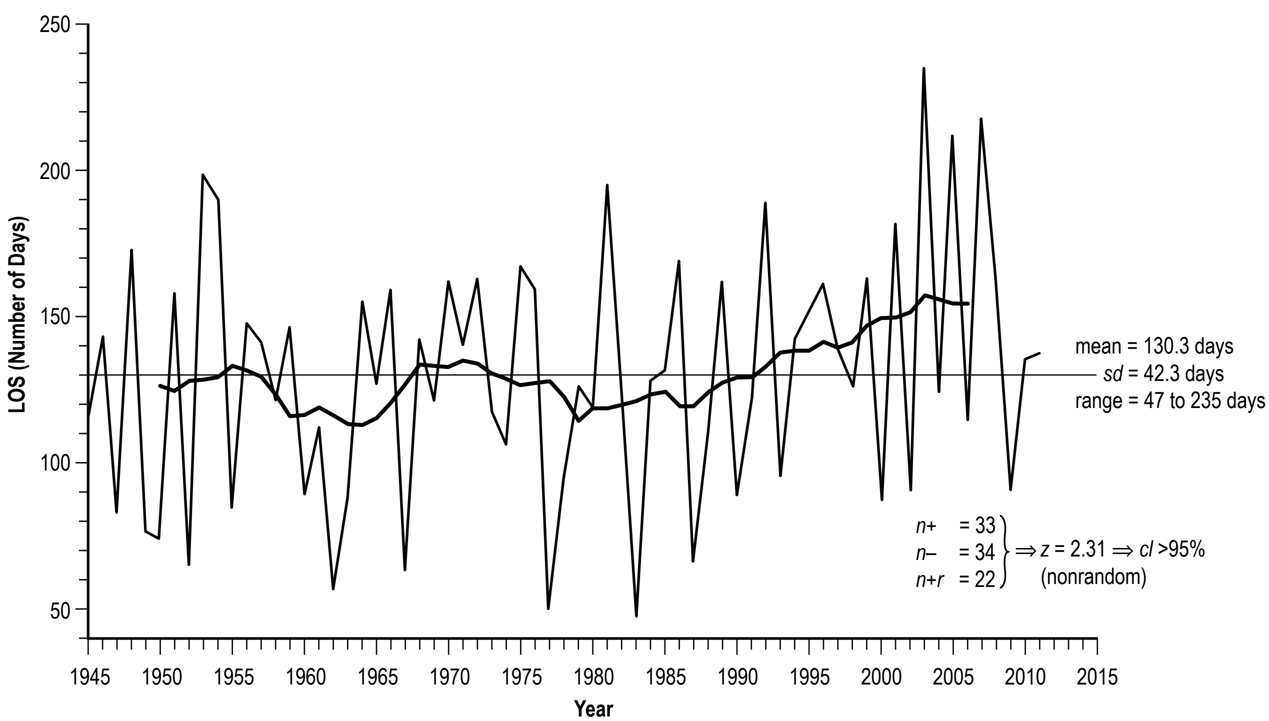

Figure 2. The annual and 10-yma values of LOS for the interval 1945–2011.

When one plots the annual values of LOS against FSD, one infers a highly statistically important preferential inverse correlation between the two parameters. Figure 3 displays the scatter plot of LOS versus FSD for the interval 1945–2011. The diagonal line is the inferred regression line, indicating an inverse correlation between the two parameters, with delayed FSD indicative of shorter LOS and early FSD indicative of longer LOS. Hypothesis testing[9] of the slope indicates that the inferred regression is statistically important at the 0.1% level of significance (or $cl > 99.9\%$). Given in the scatter plot is the regression equation, having a coefficient of correlation $r = -0.84$, a coefficient of determination $r^2 = 0.7$ (meaning that the inferred regression, based on FSD, can explain about 70% of the variance in LOS), and a standard error of estimate $se = 23$ days. Also given in the figure is the observed 2×2 contingency table, which is determined from the median values of FSD and LOS (the thin vertical and horizontal lines in the scatter plot), and the result of Fisher's exact test for 2×2 contingency tables,[10] which indicates a probability (P) of only 0.002% of obtaining the observed table, or one more suggestive of a departure from independence (chance). Hence, a very strong preferential association is found to exist between the two parameters, such that when FSD is less than (greater than) DOY = 175, LOS is expected to be greater than (less than) 128 days. Because FSD for the year 2012 has been reported[11] as May 19, 2012 (or DOY = 140), one strongly suspects that LOS for the year 2012 will be ≥128 days from the 2×2 contingency table and likely equal to about 173 ± 23 days (i.e., the ±1 *se* prediction interval) from the inferred regression. Hence, one surmises that there is about a 68% probability that the LSD for the year 2012 will occur about November 8 ± 23 days, with only about a 5% chance that it will end either before about September 23, 2012 or after about December 24, 2012.

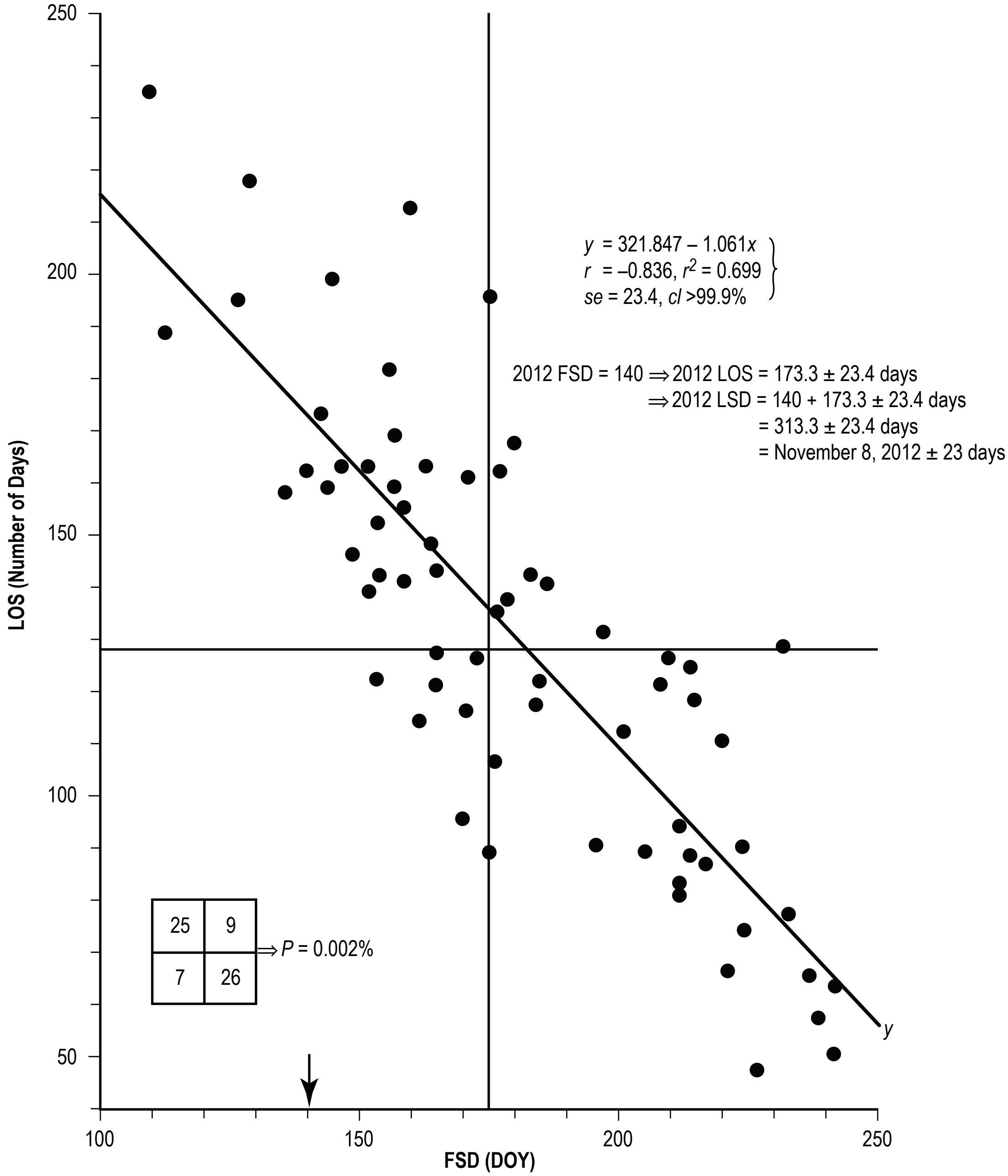

Figure 3. The scatter plot of annual values of LOS versus FSD.

As previously noted, the cause of the lengthening of LOS is believed to be warming of the SST. Figure 4 displays the annual and 10-yma values of the Armagh Observatory (Northern Ireland) surface-air temperature (<AT>, fig. 4(a)) and the SST anomaly indices associated with the Atlantic Multidecadal Oscillation (<AMO>, fig. 4(b)), the Atlantic Meridional Mode (<AMM>, fig. 4(c)), and the Oceanic Niño Index (<ONI>, fig. 4(d)). Also included in figure 4 are histograms (fig. 4(e)) that delineate the number of El Niño months (NENM) and the number of La Niña months (NLNM) during each of the years spanning 1950–2011, based on monthly values of the ONI. (The symbols < > about AT, AMO, AMM, and ONI simply indicate that the values are annual averages of the monthly parametric values).

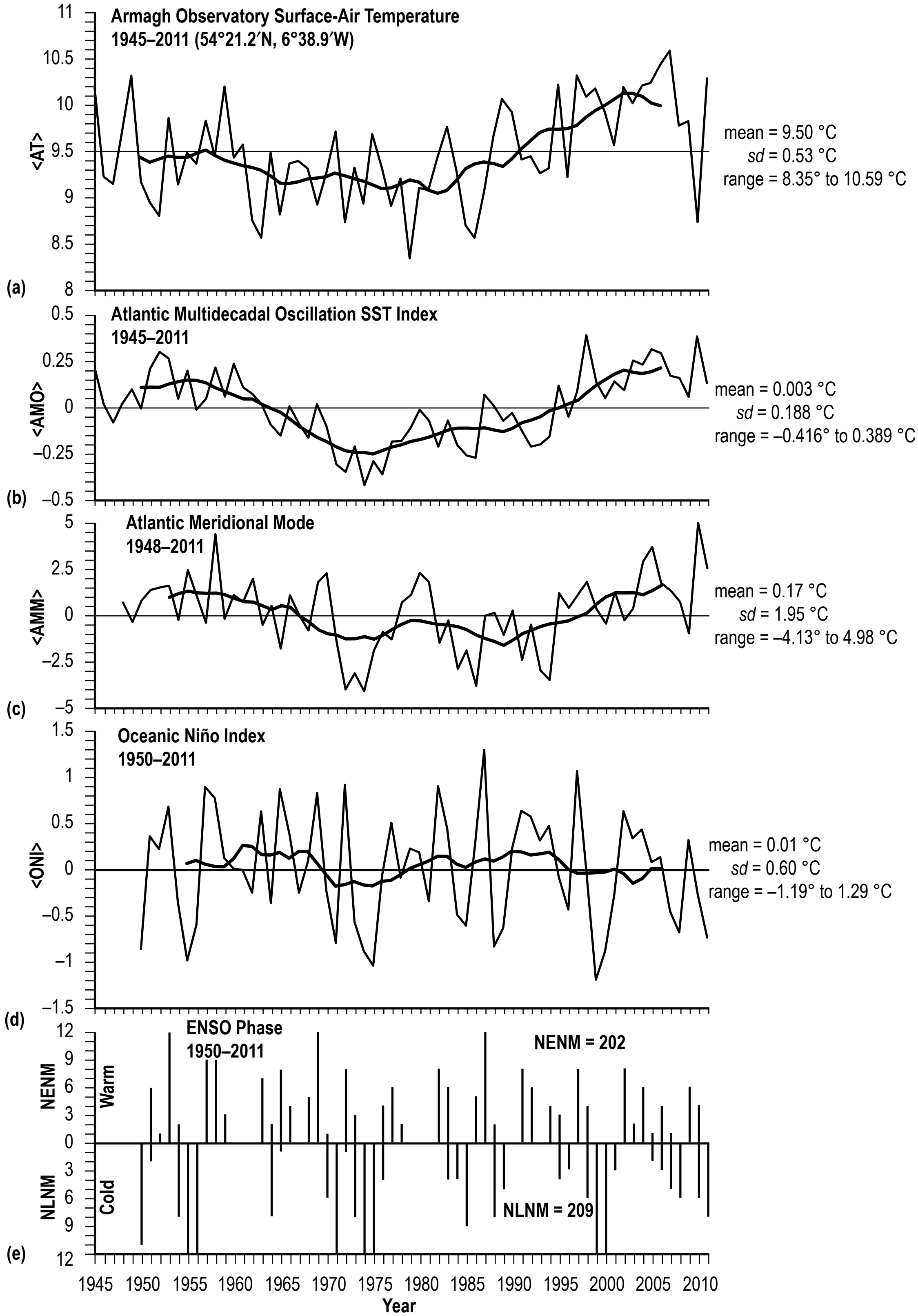

Figure 4. The annual and 10-yma values of (a) <AT>, (b) <AMO>, (c) <AMM>, and (d) <ONI> for the interval 1945–2011, and (e) the NENM and NLNM during the interval 1950–2011.

The Armagh Observatory surface-air temperature record is one of the longest available for study, being continuous from 1844 to the present.[12–15] The observatory lies about 1 km northeast of the ancient city of Armagh in Northern Ireland at 54°21.2′ N. latitude and 6°38.9′ W. longitude. Measurements of temperature are determined daily using minimum and maximum thermometers. The AMO is defined as a fluctuation in the detrended SST in the North Atlantic Ocean, north of the equator (i.e., 0°–70° N. latitude).[16–22] The AMM is part of a broader class of meridional modes that is characterized by an anomalous meridional SST gradient across the mean latitude of the intertropical convergence zone.[23–26] The ONI is a measure of the SST anomaly in the Niño 3.4 region (5° N.–5° S. latitude, 120°–170° W. longitude) based on 3-mo running means of the National Oceanic and Atmospheric Administration's Extended Reconstructed SST, version 3b;[27] hence, it serves as a useful indicator for monitoring the phase of the ENSO (i.e., the occurrences of warm El Niño and cold La Niña events). Monthly values of AT, AMO, AMM, and ONI are readily available online.

A comparison of the 10-yma values of LOS with <AT>, <AMO>, and <AMM> bears strong resemblance, at least for the past two decades, with all parameters tracking upward with time. Figure 5 depicts the comparison of 10-yma values of LOS versus <AT> (fig. 5(a)), <AMO> (fig. 5(b)), <AMM> (fig. 5(c)), and <ONI> (fig. 5(d)). Prior to the late 1980s, the association between LOS and the surface-air and SST anomaly parameters appears rather weak; however, since about 1989, the 10-yma values appear more tightly coupled, suggesting that the LOS, perhaps, is now being driven by warmer temperature in the North Atlantic basin, as previously suggested by Kossin.[5] While the associations of LOS against <AT>, <AMO>, and <AMM> are strongly positive ($r \geq 0.97$), the association of LOS against <ONI> is negative ($r = -0.83$). Hence, since at least about 1989, more negative (positive) <ONI>, indicative of cooling (warming) in the Niño 3.4 region, apparently is related to warming (cooling) and longer (shorter) LOS in the North Atlantic basin. (The arrows plotted in fig. 5 identify the last available 10-yma values: the year 2006. Also, the 1989–2006 values are plotted as filled squares, while those prior to 1989 are plotted as filled circles).

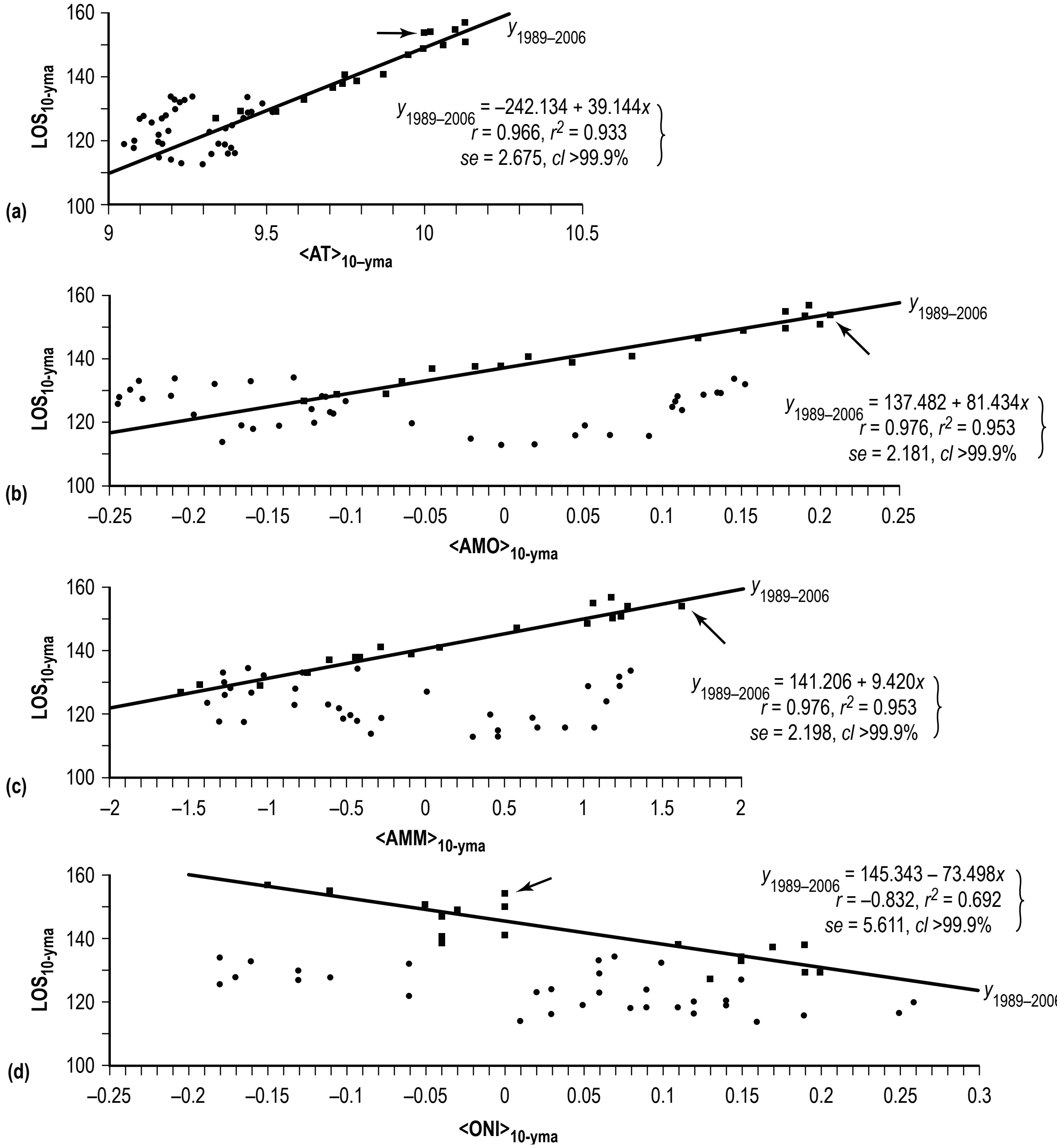

Figure 5. Scatter plots of LOS versus (a) <AT>, (b) <AMO>, (c) <AMM>, and (d) <ONI>.

Returning to figure 4(e), one finds that in the 62-yr interval 1950–2011, there have been 202 NENM and 209 NLNM, inferring 333 ENSO neutral months (i.e., months when the ONI was neither representative of El Niño nor La Niña). For convenience, one can call a year an El Niño year (ENY) when it has NENM ≥ 6 and call a year a La Niña year (LNY) when it has NLNM ≥ 6. Doing so, one finds that there are 18 yr classified as ENY and 18 yr classified as LNY during the 62-yr interval, inferring 26 ENSO neutral years (NY). On average, the DOY of FSD for an ENY, LNY, and NY, respectively, is about 182 ± 38, 184 ± 25, and 177 ± 36. Plainly, the differences in the DOY of FSD for ENY, LNY, and NY are not statistically important; hence, using the DOY of FSD, one cannot differentiate the kind of year 2012 will be (i.e., an ENY, LNY, or NY). Similarly for LOS, although the average LNY appears, on average, to be about 15 days longer than the average ENY, the difference does not appear to be statistically important. However, the difference in the DOY of LSD between ENY and LNY does appear to be statistically important (at $cl > 95\%$); on average, the DOY of LSD is about 300 ± 20 for an ENY and about 316 ± 21 for an LNY, while for NY, on average, the DOY of LSD is about 313 ± 27. Thus, one tends to favor the year 2012 to be a non-ENY, especially if the DOY for LSD > 320 (i.e., after about November 15, 2012). Presently, although an El Niño is anticipated to start either later this year or sometime next year,[4,28,29] by definition as employed in this study, for the year 2012 to be classified as an ENY, its onset must have occurred by July 2012, something that did not happen. Hence, the year 2012 must be considered non-ENY.

3. CONCLUSION

This study confirms the results of Kossin[5] that the length of the hurricane season has increased and that warmer temperatures appear to be the driving force behind the lengthening. The lengthening results because both early season and late season storms have more frequently been reported recently. On average, the FSD of a year occurs about DOY = 180.5 (about July 1), having sd = 33 and range = 110–242, and the LSD about DOY = 310 (about November 6), having sd = 23 and range =263–371. Thus, on average, the mean length of season is about 130 days, having sd = 42 days and range = 47–235 days. While true, the length of season is found to be highly dependent upon when the FSD occurs, with the scatter plot of annual values being statistically important at the 0.1% level of significance, having r = –0.84 and se = 23 days. Because FSD for 2012 occurred on DOY = 140 (May 19), one infers that the 2012 hurricane season likely will have a length of about 173 ± 23 days, ending about DOY = 313 ± 23 (November 8 ± 23 days), with only about a 5% chance of ending either before September 23, 2012 or after December 24, 2012. Presently, some 14 tropical cyclones have formed in the months of May–September 2012, with at least 2 mo remaining in the nominal hurricane season. (The reader should note that this study used the full HURDAT record for the interval 1945–2011. As such, the possibility exists that weaker, shorter duration tropical cyclones forming farther from land in the open Atlantic could easily have been missed, thereby leading to an underestimate of LOS, especially for the interval prior to the routine use of satellites, which began about the mid-1960s.[30–34] While true, it must be emphasized that the observed increase in LOS has been shown to begin about 1979, subsequent to the routine use of Earth-orbiting satellite imagery. Hence, the inferred increase appears real and is highly statistically important. A more detailed study of LOS is planned, one incorporating the duration, strength, and geographic region of the tropical cyclones).

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14. ABSTRACT

For the interval 1945–2011, the length of the hurricane season in the North Atlantic basin averages about 130 ± 42 days (the ±1 standard deviation interval), having a range of 47 to 235 days. Runs-testing reveals that the annual length of season varies nonrandomly at the 5% level of significance. In particular, its trend, as described using 10-yr moving averages, generally has been upward since about 1979, increasing from about 113 to 157 days (in 2003). Based on annual values, one finds a highly statistically important inverse correlation at the 0.1% level of significance between the length of season and the occurrence of the first storm day of the season. For the 2012 hurricane season, based on the reported first storm day of May 19, 2012 (i.e., DOY = 140), the inferred preferential regression predicts that the length of the current season likely will be about 173 ± 23 days, suggesting that it will end about November 8 ± 23 days, with only about a 5% chance that it will end either before about September 23, 2012 or after about December 24, 2012.

15. SUBJECT TERMS

first storm day, last storm day, length of season, the 2012 hurricane season

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(Include area code)*
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