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On the Current Trend of Tropical Cyclone Activity and the Lengthening of the Tropical Cyclone Season in the North Atlantic Basin

Robert M. Wilson
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July 2013

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LIST OF ACRONYMS AND ABBREVIATIONS

10-yma	10-year moving average
AMM	Atlantic Meridional Mode
AMO	Atlantic Multidecadal Oscillation
ASAT	Armagh surface-air temperature
DOY	day of year
ENSO	El Niño Southern Oscillation
FSD	first storm day
GLOTI	Global Land-Ocean Temperature Index
LL	long-lived
LN	La Niña
LOS	length of season
LSD	last storm day
MCA	maximum covariance analysis
NAO	North Atlantic Oscillation
NHC	National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration
NSD	number of storm days
NTC	number of tropical cyclones
ONI	Oceanic Niño Index
SL	short-lived

LIST OF ACRONYMS AND ABBREVIATIONS (Continued)

SST	sea-surface temperature
TC	tropical cyclone
THC	thermohaline circulation
TP	Technical Publication

NOMENCLATURE

a	*y*-intercept
b	slope
cl	confidence level
fd	first difference
n	year
P	probability
r	coefficient of correlation
r^2	coefficient of determination
sd	standard deviation
se	standard error of estimate
t	statistic for independent samples; measure of the strength of the inferred correlation
y	dependent variable in regression equation

TECHNICAL PUBLICATION

ON THE CURRENT TREND OF TROPICAL CYCLONE ACTIVITY AND THE LENGTHENING OF THE TROPICAL CYCLONE SEASON IN THE NORTH ATLANTIC BASIN

1. INTRODUCTION

For the interval 1945–2010, the National Hurricane Center's (NHC) 'best tracks' archival database reveals that some 715 tropical cyclones (TCs) formed in the North Atlantic basin (available online at <http://www.nhc.noaa.gov>), thus yielding a mean seasonal or yearly frequency of about 11 TCs per year.[1] The fewest number of TCs occurred in 1983, measuring only 4, while the largest number of TCs occurred in 2005, measuring 28. The mean frequency of TC activity is observed to have substantially increased in the mid 1990s from about 9.6 TCs per year during the earlier interval 1945–1994 to about 14.8 TCs per year during the latter interval 1995–2010, an increase of about 54%, with the difference in the means being statistically very important at confidence level (*cl*) >99.9% based on the *t*-statistic for independent samples.[2]

By definition, a TC is described as a warm core, nonfrontal, synoptic scale system that forms over tropical or subtropical waters, having an organized deep convection and closed wind circulation about a well defined center (<http://www.nhc.noaa.gov>). When the winds about the center attain a 1-min sustained peak wind speed of 34 kt (63 km hr^{-1}), the TC is named; it becomes a hurricane when its 1-min sustained peak wind speed attains 64 kt (118.6 km hr^{-1}), and it becomes a major or intense hurricane when its 1-min sustained peak wind speed reaches 96 kt (177.9 km hr^{-1}). Although TC occurrences in the North Atlantic basin have been documented historically going back hundreds of years from ship logs and landfalls, the record of greatest reliability dates only from the 1960s, owing to the routine use of weather satellites, with minor tweaking occurring after about 2002 due to the addition of new tools and data sources.[3–5]

Conventionally, the official hurricane season extends from June 1–November 30 during each calendar year, with the interval August 1–October 31 accounting for the bulk of TC activity.[6] For the interval 1945–2010, Wilson found that nearly 97% of the TCs had their onsets during the conventional hurricane season, with 78% having their onsets during the subinterval of August 1–October 31.[1] Of the 715 known TCs occurring during the inclusive interval 1945–2010, only 22 events were found to have had their onsets outside the conventional hurricane season, with two of the events being quite odd—the February 1952 and January 1978 unnamed TCs, both of tropical storm strength only and both having their onsets several months prior to the bulk of the yearly TC activity. Hence, these two events appear to be statistical outliers and are treated as such in this Technical Publication (TP) (i.e., they have been excluded).

Previously, Kossin investigated the length of the hurricane season in the North Atlantic on the basis of the NHC archival database for the interval 1851–2007.[7] Using the method of quantile regression,[8] he investigated changes within the distribution of TC formation dates in the North Atlantic basin, finding a consistent signal that was suggestive of a lengthening of the hurricane season that correlated with warming sea-surface temperature (SST).

Several studies, however, have been reported regarding the apparent trend in the yearly frequency of TC activity in the North Atlantic basin, especially for the years prior to 2005. In particular, these studies suggest that the number of TCs in the North Atlantic basin, especially during the interval prior to the National Oceanic Atmospheric Administration (NOAA) weather satellite era (1960–present), might be severely underestimated, thereby potentially impacting any determination of an apparent trend in the yearly number of TCs and/or in the length of the yearly season. For example, Chang and Guo, on the basis of a comparison of TC tracks from 1976 to 2005 through ship observations from 1900 to 1965, found that TC activity may have been underestimated by up to 2.1 TCs per year during the interval 1904–1913, with this number decreasing to about 1 TC per year or less during the 1920s and later decades.[9] Additionally, Landsea showed that a significant difference exists when one compares seasonal TC tracks for the years 1933 and 2005, the two busiest years of TC activity on record, further stating that with the inclusion of 3.2 more TCs per year during the interval 1900–1965 and one more TC per year during the interval 1966–2002, the trend in TC activity, while continuing to have a somewhat quasicyclic appearance (i.e., consisting of both active and quiet intervals of decadal length believed to be related to the Atlantic Multidecadal Oscillation (AMO)[10]), becomes statistically unimportant.[5]

Other results related to the possible trending in TC activity include those of Vecchi and Knutson, Landsea et al., and Villarini et al.[11–15] In their 2008 study, Vecchi and Knutson noted that the evidence for a significant increase in TC activity in the North Atlantic basin is 'mixed,' and in their 2011 study, they noted that their results do not support the hypothesis that the warming of the tropical North Atlantic basin due to anthropogenic greenhouse gas emissions is the causative agent for the apparent increase in the North Atlantic basin TC frequency.[11,12] Landsea et al. noted that, while the frequency of short-lived TCs (i.e., those having number of storm days (NSD) $\leq$ 2 days) has dramatically increased from less than one per year in the late 19th to early 20th centuries to about five per year since about 2000, medium-to-long-lived TCs (i.e., those having NSD $>$ 2 days) have increased little, if at all, suggesting that the trend in TC activity may be artificially induced, owing to recent improvements in the quality and quantity of observations along with enhanced interpretation techniques.[13] Lastly, Villarini et al. found no support for the hypothesis that the overall record of short-lived TCs contains a detectable climate signal and suggested instead that TC activity studies should focus only on medium-to-long-lived TCs.[14,15]

In this TP, the trend in North Atlantic basin TC activity, especially as related to the determination of the length of season (LOS) and its possible association with warming surface-air and sea-surface temperature, is revisited. In particular, examined are: (1) the trend in TC activity for the yearly intervals 1945–1965, 1966–1994, and 1995–2012 for TCs having duration NSD $\geq$ 0.25 day, $<$2 days, $\geq$2 days, $\geq$4 days, and $\geq$8 days; (2) the latitudinal and longitudinal genesis locations of the short-lived TC (defined herein as those TCs having duration NSD $<$ 2 days) for the three yearly intervals; (3) the first storm day (FSD), last storm day (LSD), and LOS based on TCs having duration

NSD ≥ 0.25 day and NSD ≥ 2 days; (4) the relationship between FSD, LSD, and LOS for TCs having duration NSD ≥ 0.25 day and NSD ≥ 2 days; (5) the surface-air and sea-surface temperature, wind, and North Atlantic Oscillation (NAO) during the interval 1945–2012; (6) the relationship of FSD, LSD, and LOS against surface-air and sea-surface temperature, wind, and the NAO; (7) the relationship of TC activity against surface-air and sea-surface temperature, wind, and the NAO; and (8) the relationship of TC activity against FSD and LOS. This TP represents an update to an earlier study by Wilson concerning the length of the yearly hurricane season.[16]

2. RESULTS

2.1 Trend in Tropical Cyclone Activity in the North Atlantic Basin, 1945–2012

Figure 1 displays the observed annual (thin line) and 10-year moving average (10-yma) (thick line, used here to illustrate trend) number of tropical cyclones (NTC) having duration NSD (a) ≥0.25 day, (b) <2 days, (c) ≥2 days, (d) ≥4 days, and (e) ≥8 days for the interval 1945–2012. Also identified is the beginning (in 1960) of the NOAA weather satellite era and the start (in 1966) of complete data coverage in the NHC archival database (i.e., the year when minimum air pressure determinations at 0.25-day intervals appear on a continuous basis; it is to be noted that the format for the archival database was changed at the end of the 2012 hurricane season to allow for additional ancillary data, in particular, size determinations based on the 34-, 50-, and 64-kt wind fields). Statistically speaking, on the basis of the *t*-statistic for independent samples, there is no statistically significant difference in the means between that for 1945–1965 and 1966–1994 for TCs having durations NSD ≥ 0.25 day, NSD < 2 days, NSD ≥ 2 days, NSD ≥ 4 days, or NSD ≥ 8 days; i.e., no matter which TC-duration grouping is examined, the two intervals 1945–1965 and 1966–1994 have similar statistical properties and could be combined into a single statistical population (i.e., a single interval 1945–1994). However, highly statistically important differences are noted between the means for both 1945–1965 and 1966–1994 when they are compared individually against the means for 1995–2012 for all TC-duration groupings. Hence, the observed increase in TC activity from 1995 onwards is inferred to be inherently different as compared to that which was seen during the earlier intervals 1945–1965 or 1966–1994.

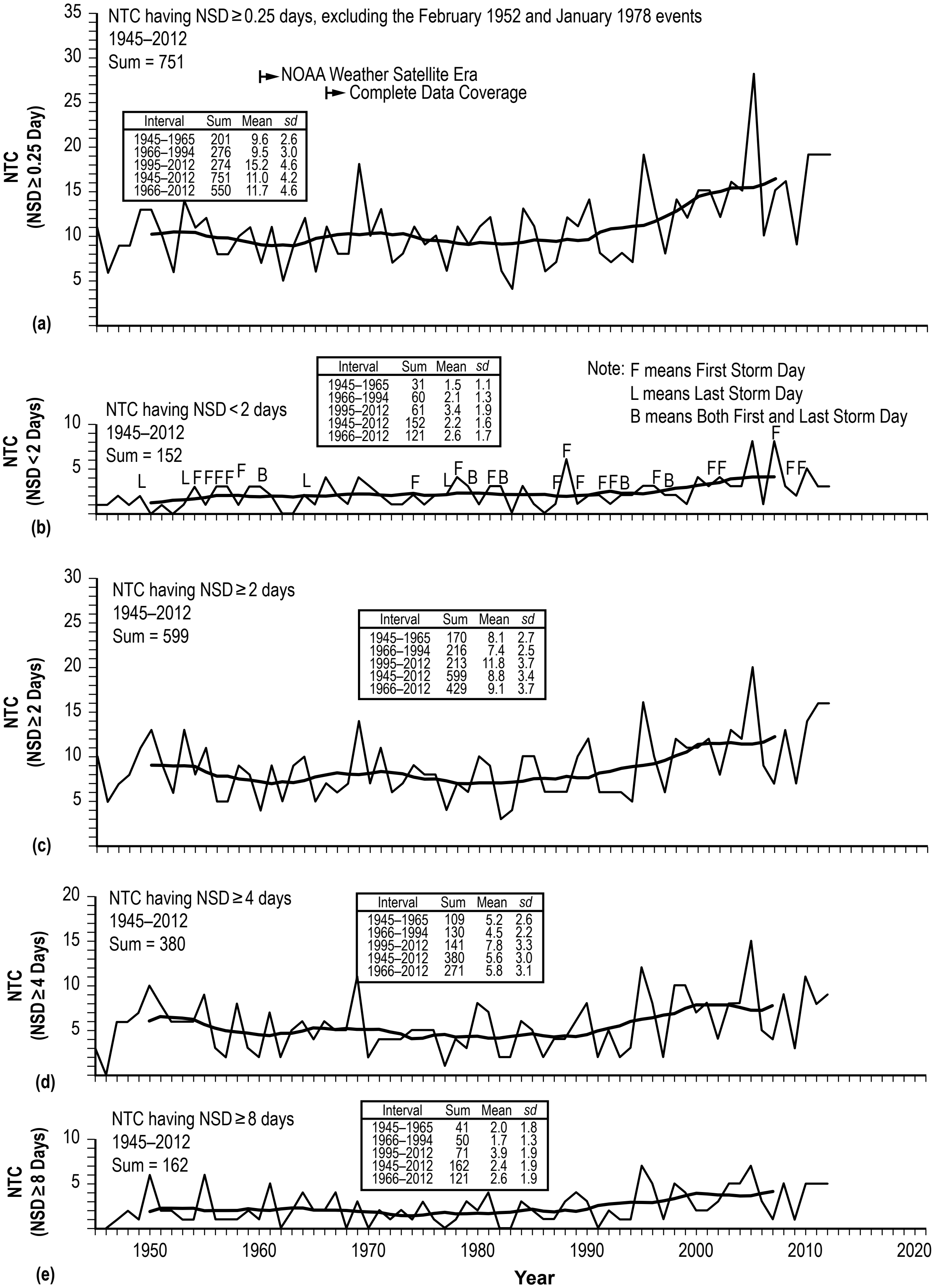

Figure 1. Yearly variation of NTC having duration NSD (a) ≥0.25 day, (b) <2 days, (c) ≥2 days, (d) ≥4 days, and (e) ≥8 days for the interval 1945–2012.

For the current ongoing active interval 1995–2012, on average, there have been 15.2 TCs per year, having an *sd* of 4.6 events per year. Of these, on average, there have been about 3.4 short-lived events (NSD < 2 days) per year and 11.8 medium-to-longer duration events (NSD ≥ 2 days) per year. Concerning the longer duration events, on average, there have been about 7.8 events per year having NSD ≥ 4 days and 3.9 events per year having NSD ≥ 8 days.

In figure 1(b), the letters F, L, and B are employed to identify those years when the first (F), last (L), or both (B) first and last storm days of the season were associated with short-lived TCs. Thus, for the interval 1945–1965, 5 of the 21 years had their FSD associated with short-lived events, 3 years had their LSD associated with short-lived events, and 1 year had both its FSD and LSD associated with short-lived events. For the interval 1966–1994, 8 of the 29 years had their FSD associated with short-lived events, 1 year had its LSD associated with a short-lived event, and 3 years had both their FSD and LSD associated with short-lived events. For the current ongoing active interval 1995–2012, 6 of the 18 years have their FSD associated with short-lived events, and 1 year has both its FSD and LSD associated with short-lived events. Interestingly, the ratios of the combined number of FSD and LSD years to the respective interval lengths are strikingly similar for all intervals (0.429, 0.414, and 0.389, respectively), implying that about 40% of the time, the FSD and/or LSD for the yearly hurricane season is determined by a short-lived event (i.e., a TC having duration NSD < 2 days).

Recall from Landsea that the NTC prior to the year 2003 might be substantially underestimated (i.e., some TC may have occurred, but were unreported).[5] Following his suggestion, one could increase the number of TCs before 1966 by three per year and increase the number of TCs for the inclusive interval 1966–2002 by one per year. Doing so adds 100 TCs to the total NTC for the interval 1945–2012. Presumably, most of these unreported TCs largely would be short-lived events. Figure 2 shows the result of adjusting the observed record following this recipe, making all the increase as short-lived events. Clearly, the overall appearance now looks decidedly more quasicyclic than before (as remarked by Landsea), having a peak in the 1950s and another larger peak occurring now, with a lull of activity separating the two, thus suggestive that the record of TC activity in the North Atlantic basin during the overall interval 1945–2012 might be better interpreted as consisting of both active (1945–1965 and 1995–2012) and quiet (1966–1994) intervals of TC activity, each lasting about 20–30 years or more in length.[17]

From figure 2, one sees that the adjusted rate of overall TC activity (NTC(NSD ≥ 0.25 day)) has increased for all time intervals, from 9.6 per year on average to 12.6 per year for the interval 1945–1965 (an increase of 31%), from 9.5 per year to 10.5 per year for the interval 1966–1994 (an increase of 10.5%), and from 15.2 per year to 15.7 per year in the current ongoing interval 1995–2012 (an increase of 3%). For short-lived events (NTC(NSD < 2 days)), the increase is far more dramatic, from 1.5 to 4.5 per year (an increase of 200%), from 2.1 to 3.1 per year (an increase of 47.6%), and from 3.4 to 3.8 per year (an increase of 11.8%), respectively.

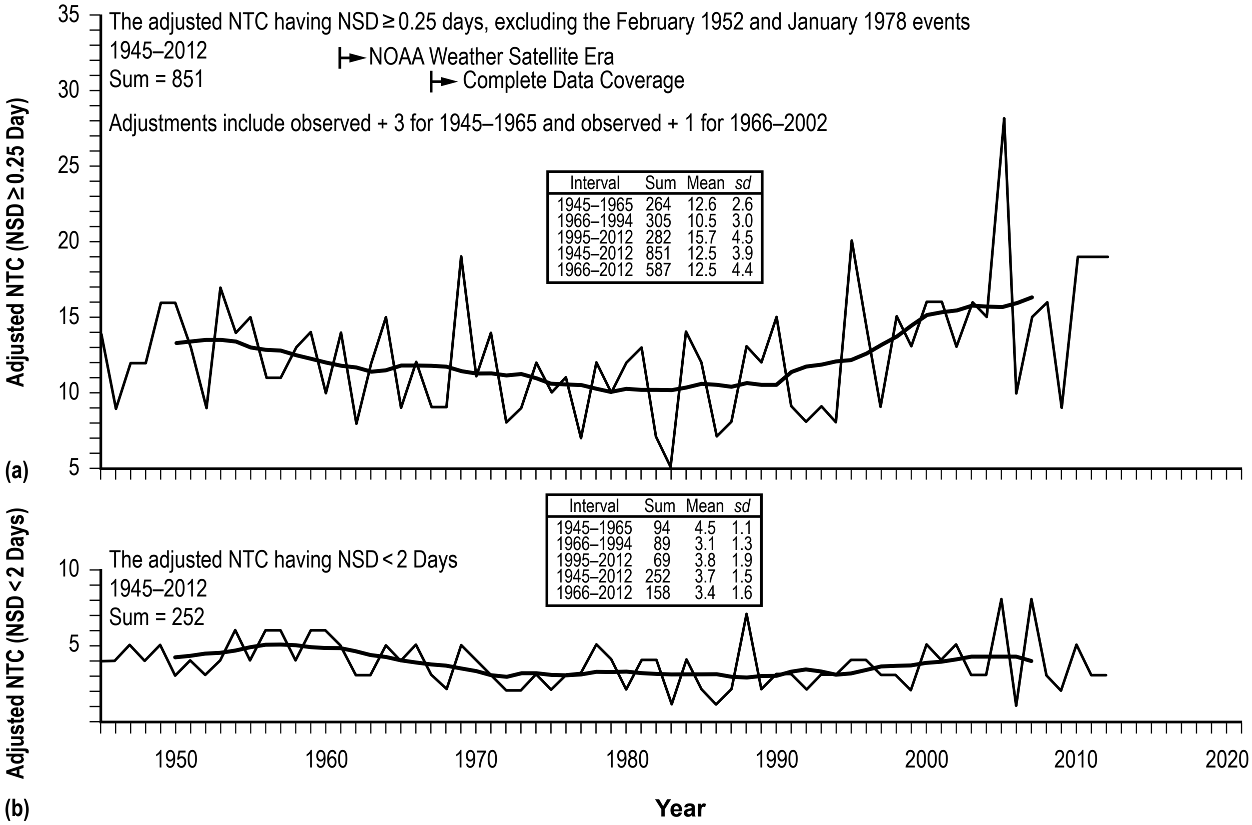

Figure 2. Yearly variation of the adjusted NTC having duration NSD (a) ≥0.25 day and (b) <2 days for the interval 1945–2012.

Comparing the interval means for overall TC activity, one finds the difference in means between the first and second intervals is now statistically important ($t = 2.58$, $cl > 98\%$), whereas it was not prior to adjustment ($t = 0.12$, $cl < 90\%$). Likewise, the difference in means between the first and third interval, which was highly statistically important prior to adjustment ($t = 4.77$, $cl > 99.9\%$), is now only of slightly less statistical importance ($t = 2.68$, $cl > 98\%$). The difference in means between the second and third intervals, which had been highly statistically important prior to adjustment ($t = 5.15$, $cl > 99.9\%$), remains highly statistically important ($t = 4.76$, $cl > 99.9\%$).

Comparing the interval means for short-lived events, one finds the difference in means between the first and second intervals, which was only of marginal statistical importance prior to adjustment ($t = 1.72$, $cl > 90\%$), is now highly statistically important ($t = 4$, $cl > 99.9\%$). The differences in means between the first and third intervals and between the second and third intervals, both of which had been statistically important ($t = 3.89$, $cl > 99.9\%$ and $t = 2.79$, $cl > 98\%$, respectively), are now no longer statistically important ($t = 1.43$, $cl < 90\%$ and $t = 1.5$, $cl < 90\%$, respectively).

Hence, even after adjusting the yearly seasonal frequencies upwards for the years prior to 2003 to account for possible underestimation, the current ongoing active interval for overall TC activity remains substantially more active than was seen for the earlier intervals, including the previous peak of activity in the 1950s. From this, one infers that the recent upward trend in TC activity appears real and cannot be explained simply as being due to an underestimation of events caused by either a lack of observations in earlier years and/or recent changes in the tools and techniques used to analyze TC activity in the current era. Troubling, however, is the adjustment of the short-lived NTC (i.e., those having duration NSD < 2 days) during the first interval, which has a mean that increased by 200% to a value of 4.5 events per year, a value that exceeds not only the mean for the current ongoing short-lived event activity of 3.8 events per year, but exceeds the overall mean for short-lived events. Instead of attributing the entire increase (100 events) to only short-lived events, it might be better to attribute at least a small portion (perhaps as many as 15–20 events) to medium-to-longer duration events (i.e., those having duration NSD ≥ 2 days). But exactly how one would apportion the increase over the time interval is conjectural. So, for the remainder of this TP, the analysis and results will be based only on the observed record of known TC activity and not on the adjusted record of TC activity.

2.2 Latitudinal and Longitudinal Genesis Locations of Short-Lived Tropical Cyclones

Figure 3 displays the latitudinal and longitudinal genesis locations for short-lived TCs during the intervals (a) 1945–1965, (b) 1966–1994, and (c) 1995–2012. During the earliest interval 1945–1965, there were 31 known short-lived events. None of the short-lived TCs had its genesis location east of 50° W. On average, these 31 events became TCs at 23.3 ± 5.3° N. and 82.4 ± 12.6° W. (i.e., the mean ± 1 *sd* intervals). For the interval 1966–1994, there were 60 known short-lived events, with only three of the short-lived events having their genesis location east of 50° W. On average, these 60 events became TCs at 26.4 ± 7.7° N. and 72.2 ± 19.5° W. For the current ongoing interval 1995–2012, there have been 61 short-lived events, with 10 events having their genesis location east of 50° W. On average, these 61 events became TCs at 24.8 ± 7.2° N. and 73.7 ± 20.7° W. Statistically speaking, while there is no statistically important difference in the means of the latitudinal or longitudinal genesis locations for the three temporal intervals, visually, the region of genesis formation for short-lived events appears to have expanded over time, especially when comparing the intervals of 1945–1965 and 1966–1994 with that of the current ongoing interval 1995–2012. Such behavior is consistent with either a lack of observations in the open North Atlantic basin (i.e., primarily for the earliest interval 1945–1965) or possibly to an eastward shift in the genesis region for TC formation over time.

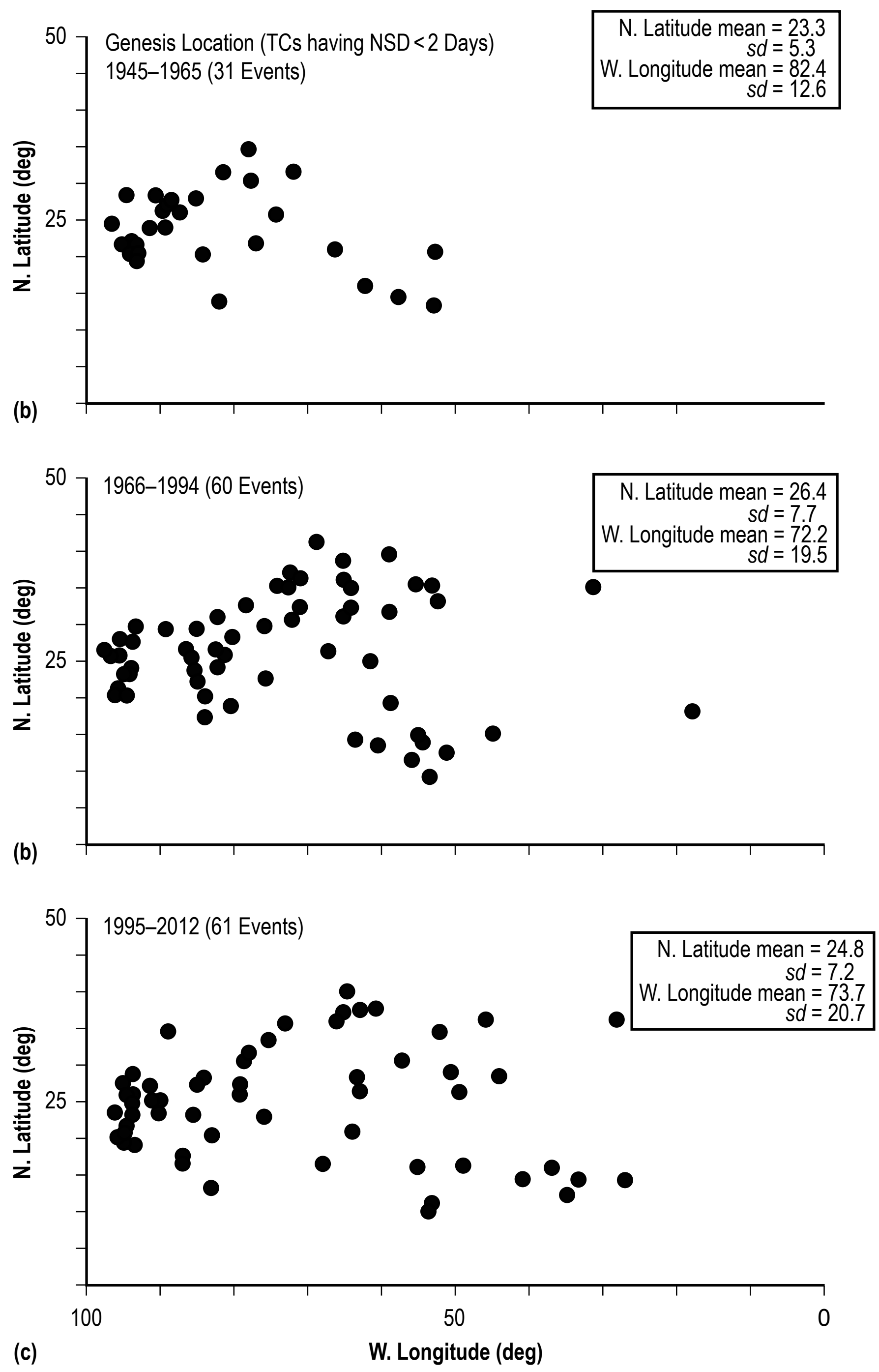

Figure 3. Genesis latitudinal and longitudinal location of TCs having duration NSD < 2 days for the intervals (a) 1945–1965, (b) 1966–1994, and (c) 1995–2012.

2.3 FSD, LSD, and LOS for TCs Having Duration NSD ≥ 0.25 Day and NSD ≥ 2 Days

Figure 4 depicts the yearly (thin line) and 10-yma (thick line) variation of the duration (i.e., NSD) of the TC associated with the (a) FSD and (b) LSD during the interval 1945–2012. Clearly, the FSD has been associated with TCs having duration from 0.75 day (1978) to 19.25 days (2000), while the LSD has been associated with TCs having duration from 1 day (1977) to 11.75 days (1984). Visually, it appears that the duration of TCs associated with the FSD possibly has been decreasing over time, while the duration of TCs associated with the LSD possibly has been increasing over time. Statistically speaking, however, the only statistically important difference between the means for the time intervals is the one between 1945–1965 (mean duration = 4.4 days) and 1966–1994 (mean duration = 2.89 days) for FSD ($t = 2.05$, $cl > 95\%$), inferring that the earlier epoch possibly missed some TCs that were associated with short-lived events that also could have been FSD events had they been reported.

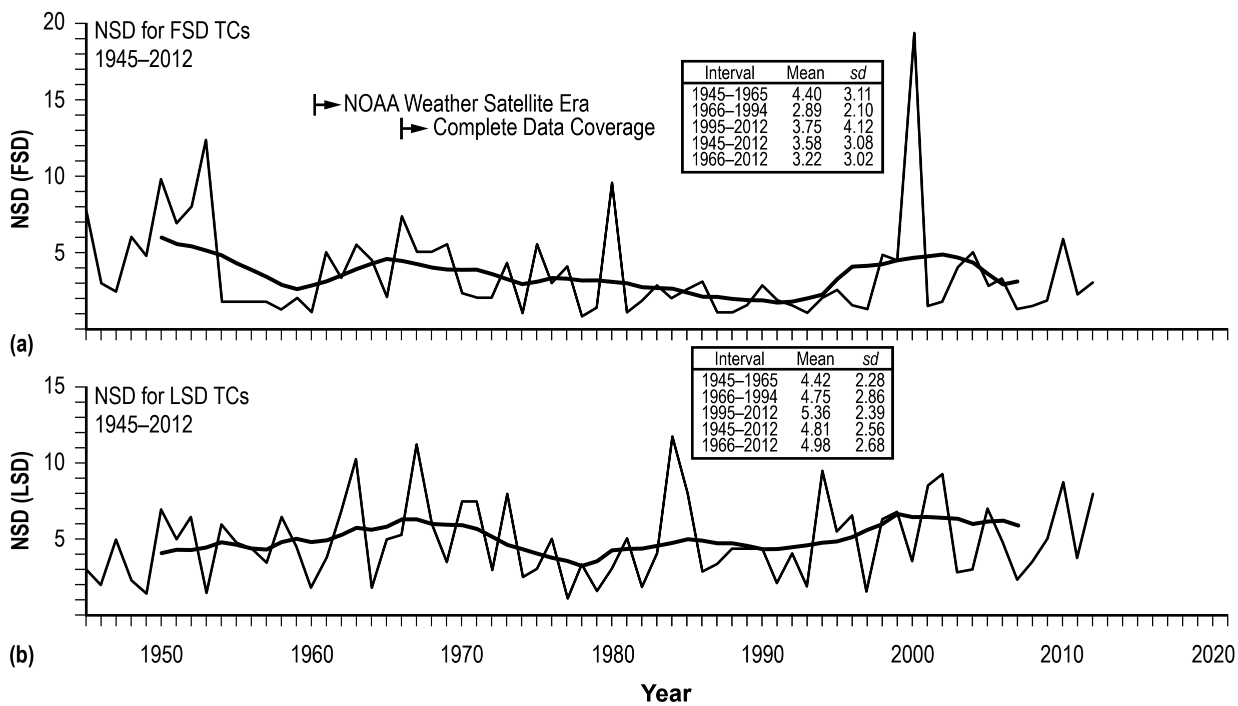

Figure 4. Yearly variation of the duration NSD of the TCs associated with (a) FSD and (b) LSD for the interval 1945–2012.

Figure 5 shows the yearly variation of (a) FSD, (b) LSD, and (c) LOS for the interval 1945–2012 based on the observed TC record. Recall that FSD marks the first day of the TC yearly season when the 1-min sustained peak wind speed measured ≥34 kt (63 km hr^{-1}), and LSD marks the last day of the TC yearly season when the 1-min sustained peak wind speed measured ≥34 kt (63 km hr^{-1}), with LOS being the inclusive difference between the yearly FSD and LSD dates (also, the TC is not classified as 'extratropical'). Concerning FSD and LSD, there appear to be no statistically important differences when comparing the means for FSD and LSD for the intervals 1945–1965 and 1966–1994. During these intervals, on average, FSD occurs on or about day of year (DOY)

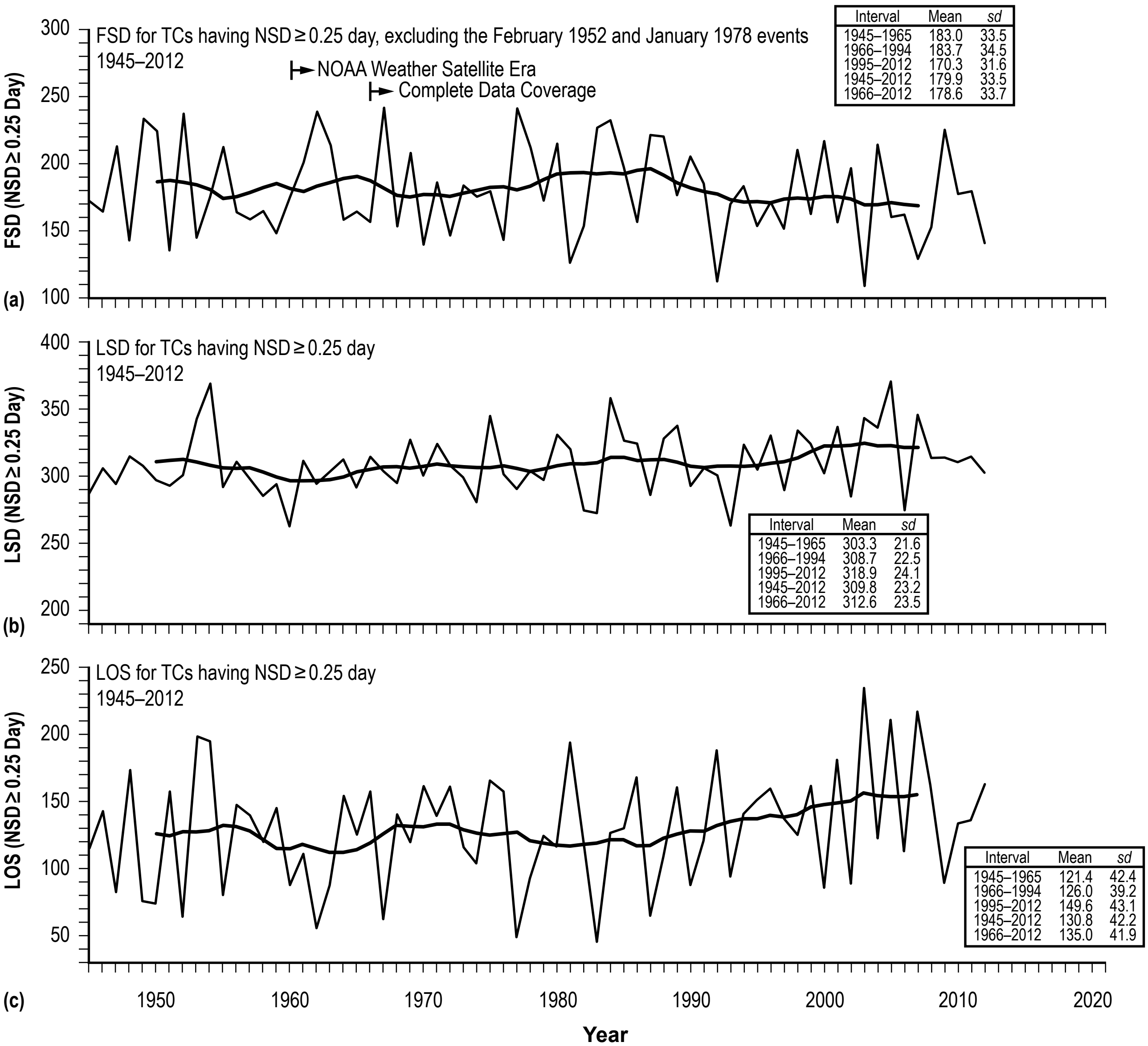

Figure 5. Yearly variation of (a) FSD, (b) LSD, and (c) LOS for TCs having duration NSD ≥ 0.25 day for the interval 1945–2012.

183 (i.e., about July 2), and LSD occurs on or about DOY 303–309 (i.e., about November 1–7), thus suggesting LOS to be about 121–126 days. However, for FSD, LSD, and LOS in the current ongoing interval 1995–2012, respectively, they measure DOY = 170 (i.e., about June 19), DOY = 319 (i.e., about November 15), and about 150 days in length. Based on 10-yma values, FSD has decreased over time from DOY 195.5 (in 1987) to 167.5 (in 2007), indicating that FSD now occurs, on average, about 28 days sooner than it did in 1987, while LSD has increased over time from 296.6 (in 1960) to 324.8 (in 2003), indicating that LSD now occurs, on average, about 28 days later than it did in 1960. Together, the changes in FSD and LSD have caused the LOS to increase over time from about 118 days (in 1987), on average, to nearly 156 days (in 2007). Hence, LOS is now considerably longer as compared to what it was about 20 years ago. On the basis of the *t*-statistic for independent samples, the difference in the means between the current ongoing interval 1995–2012 and the interval

1945–1965 is statistically important ($t=2.05$, $cl>95\%$); however, the difference is only of marginal statistical importance when comparing the current ongoing interval with that of the immediately preceding interval 1966–1994 ($t=1.93$, $cl>90\%$).

Figure 6 is similar to figure 5, but now is based on the exclusion of the short-lived events (i.e., it computes FSD, LSD, and LOS using the observed TC having duration NSD ≥ 2 days). While the difference in means is not statistically important for FSD or LSD when comparing the current ongoing interval with either of the preceding intervals, the difference is inferred to be statistically important for LOS when comparing the current ongoing interval with the interval 1966–1994 ($t=2.39$, $cl=98\%$). Hence, LOS during the current ongoing interval has indeed lengthened, especially since the 1980s.

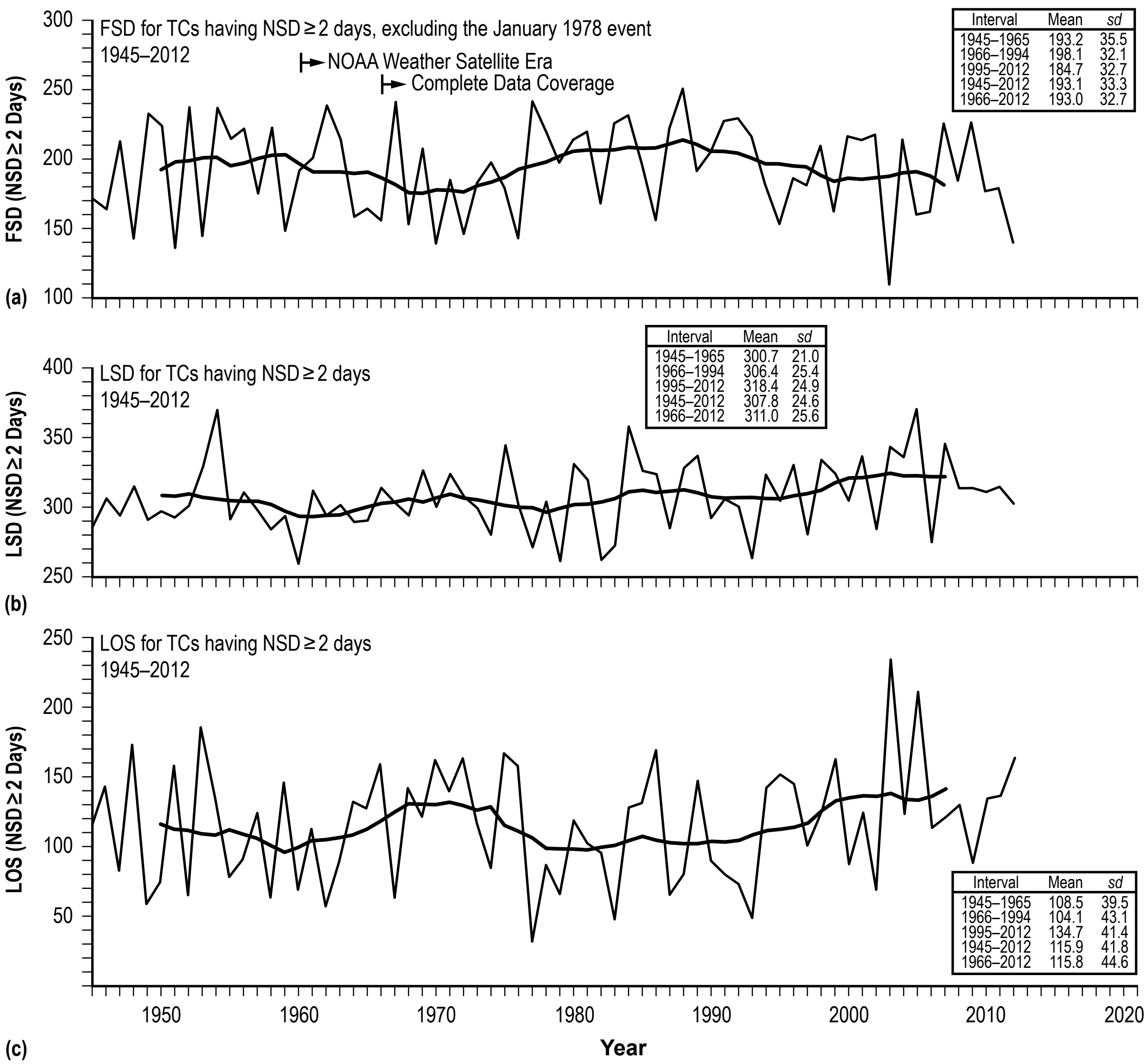

Figure 6. Yearly variation of (a) FSD, (b) LSD, and (c) LOS for TCs having duration NSD ≥ 2 days for the interval 1945–2012.

Figure 7 depicts the latitudinal and longitudinal genesis locations of the TCs associated with FSD for (a) 1945–1965, (b) 1966–1994, and (c) 1995–2012 and with LSD for (d) 1945–1965, (e) 1966–1994, and (f) 1995–2012. Based on the *t*-statistic for independent samples, none of the differences in the means of the genesis latitudinal or longitudinal locations for FSD are statistically important. Hence, the genesis latitudinal and longitudinal locations of the TC associated with FSD are essentially the same. Similarly, based on Fisher's exact test for 2×2 contingency tables[18] (determined by the median values of the latitude and longitude for the TCs associated with FSD for each time interval, the thin vertical and horizontal lines drawn in the figure) and the use of hypothesis testing, the probability of obtaining the observed results, or one more suggestive of a departure from independence (chance), is consistent with the genesis location of the TC associated with FSD being randomly distributed, even though, visually, it appears that the TCs associated with the FSD seem to form farther eastward as time progresses.

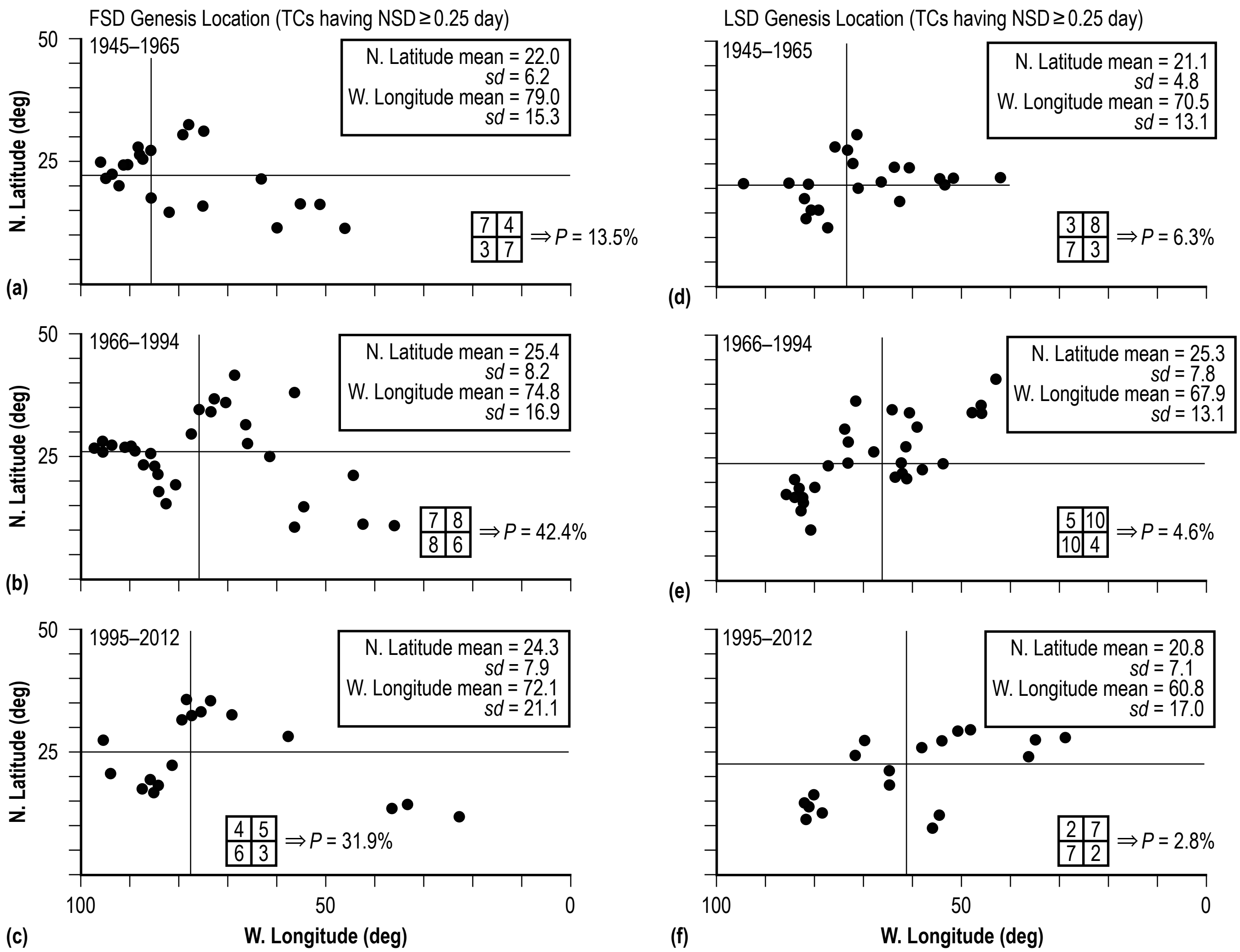

Figure 7. FSD ((a)–(c)) and LSD ((d)–(f)) genesis latitudinal and longitudinal locations of TCs having duration NSD ≥ 0.25 day for the intervals 1945–1965, 1966–1994, and 1995–2012, respectively.

However, a noticeably different result is apparent for the TC associated with LSD. Namely, based on the *t*-statistic for independent samples, the difference in the means of the genesis latitudinal locations for TCs associated with LSD is statistically important when comparing the interval 1945–1965 against the following interval 1966–1994 ($t = 2.18$, $cl > 95\%$), but not so when comparing against the current ongoing interval 1995–2012 ($t = 0.16$, $cl < 90\%$). This suggests that the genesis latitudinal location of TCs associated with LSD shifted northward during the interval 1966–1994 as compared to the interval 1945–1965, but has now returned to a lower mean latitude during the current ongoing interval 1995–2012. Likewise, the difference in the means of the genesis longitudinal locations for TCs associated with LSD is statistically important ($t = 2.01$, $cl > 95\%$) when comparing the intervals 1945–1965 and 1995–2012. Hence, the genesis longitudinal locations of TCs associated with LSD also appear to have shifted eastward over time (or it could mean that TC activity during the earlier interval is incomplete due to a lack of observations of TCs having a genesis longitude farther eastward). On the basis of Fisher's exact test for 2×2 contingency tables and hypothesis testing, the probability of obtaining the observed results, or ones more suggestive of independence, is consistent with the genesis latitudinal and longitudinal location of the TC associated with the LSD being driven by real changes in the physical environment over time.[19–22] For example, the probability (P) for obtaining the observed table, or one more suggestive of a departure from independence, is 6.3% for the interval 1945–1965, while being 4.6% for the interval 1966–1994 and only 2.8% for the current ongoing interval 1995–2012.

2.4 Relationship Between FSD, LSD, and LOS for TCs Having Duration NSD ≥ 0.25 Day and NSD ≥ 2 Days

Figure 8 displays scatter plots of (a) LSD and (b) LOS versus FSD for TCs having duration NSD ≥ 0.25 day during interval 1945–2012 (i.e., the overall interval) and scatter plots of (c) LSD and (d) LOS versus FSD for TCs having duration NSD ≥ 0.25 day during the interval 1966–2012 (i.e., the most reliable satellite era interval). One finds that, while LSD does not correlate well with FSD for either time interval, for both time intervals, LOS is found to correlate strongly with FSD ($cl > 99.9\%$). Hence, from figures 8(b) and (d), given the observed occurrence of the FSD at the start of a hurricane season, one can approximate the LOS for the yearly hurricane season. For the current 2013 North Atlantic basin hurricane season, FSD occurred on June 5, 2013 (DOY = 156); hence, from figure 8(b), one estimates that the current 2013 hurricane season will have LOS = 156 ± 23 days (i.e., the ±1 standard error of estimate (*se*) prediction interval), inferring that it should end about DOY = 312 ± 23, or about November 8 (±23 days), with only a 16% chance of ending either after December 1 or before October 16. Using figure 8(d), one finds LOS = 158 ± 24 days. Based on the observed 2×2 tabular distribution, one certainly expects LOS for the current 2013 hurricane season to be ≥130 days, based on the observed FSD = 156.

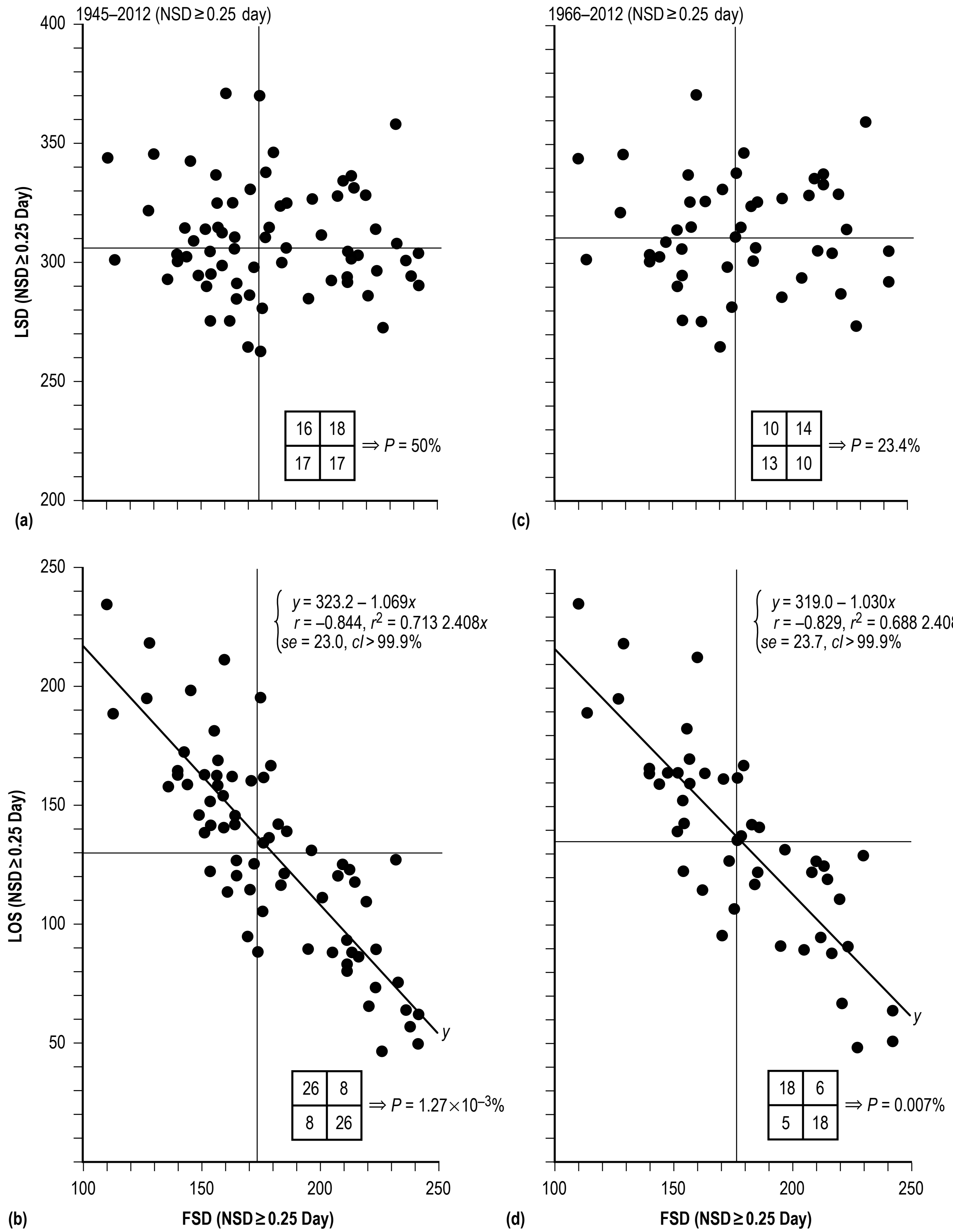

Figure 8. Scatter diagrams of LSD ((a) and (c)) and LOS ((b) and (d)) versus FSD for the intervals 1945–2012 and 1966–2012, respectively, using TCs having duration NSD ≥ 0.25 day.

Figure 9 replots the scatter diagrams, but this time using only medium-to-longer-lived events (NSD ≥ 2 days). Again, while there is no inferred preferential correlation between LSD and FSD for either time interval, a strong correlation is inferred to exist between LOS and FSD. Therefore, continuing the previous example, given FSD = 156, one expects the LOS for the 2013 hurricane season based on medium-to-long-lived TCs to be either about 153 ± 25 days (based on fig. 9(b)) or 158 ± 26 days (based on fig. 9(d)). Based on the 2×2 tabular distributions, one would expect the season's LOS to be ≥120 days.

The construction of figures 8 and 9 presumes that the two parameters, FSD and LOS, are randomly distributed and are not influenced by quasiperiodic climate factors like the phase of the El Niño Southern Oscillation (ENSO) phenomenon. Figure 10 plots the residual (in *sd* units) based on the inferred regressions given in figures 8(b) and (d) and figures 9(b) and (d), where the residual is defined as the observed value minus the predicted value divided by the *sd* for the appropriate regression. Figures 10(e) and (f) plot the January–June and July–December averages of the monthly Oceanic Niño Index (ONI). The ONI monthly values serve as a convenient means for gauging the phase of the ENSO and marking the occurrences of anomalous SST events. When the 2-month moving average (also called 3-month running mean) of the monthly ONI is ≥0.5 °C for at least five consecutive months, an El Niño (warm) event is said to be occurring, while when ONI is ≤–0.5 °C for at least five consecutive months, a La Niña (LN) (cold) event is said to be occurring, where ONI values are determined using the extended reconstructed SST, version 3b SST anomalies,[23] in the Niño 3.4 region, a region located in the Pacific Ocean at latitude ±5° north or south of the equator and at longitude ±25° either side of 145° W., and centered on 30-year base periods that are updated every 5 years. Intervals not meeting these threshold conditions are considered neutral ENSO periods. Monthly ONI values are available online at <http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml>.

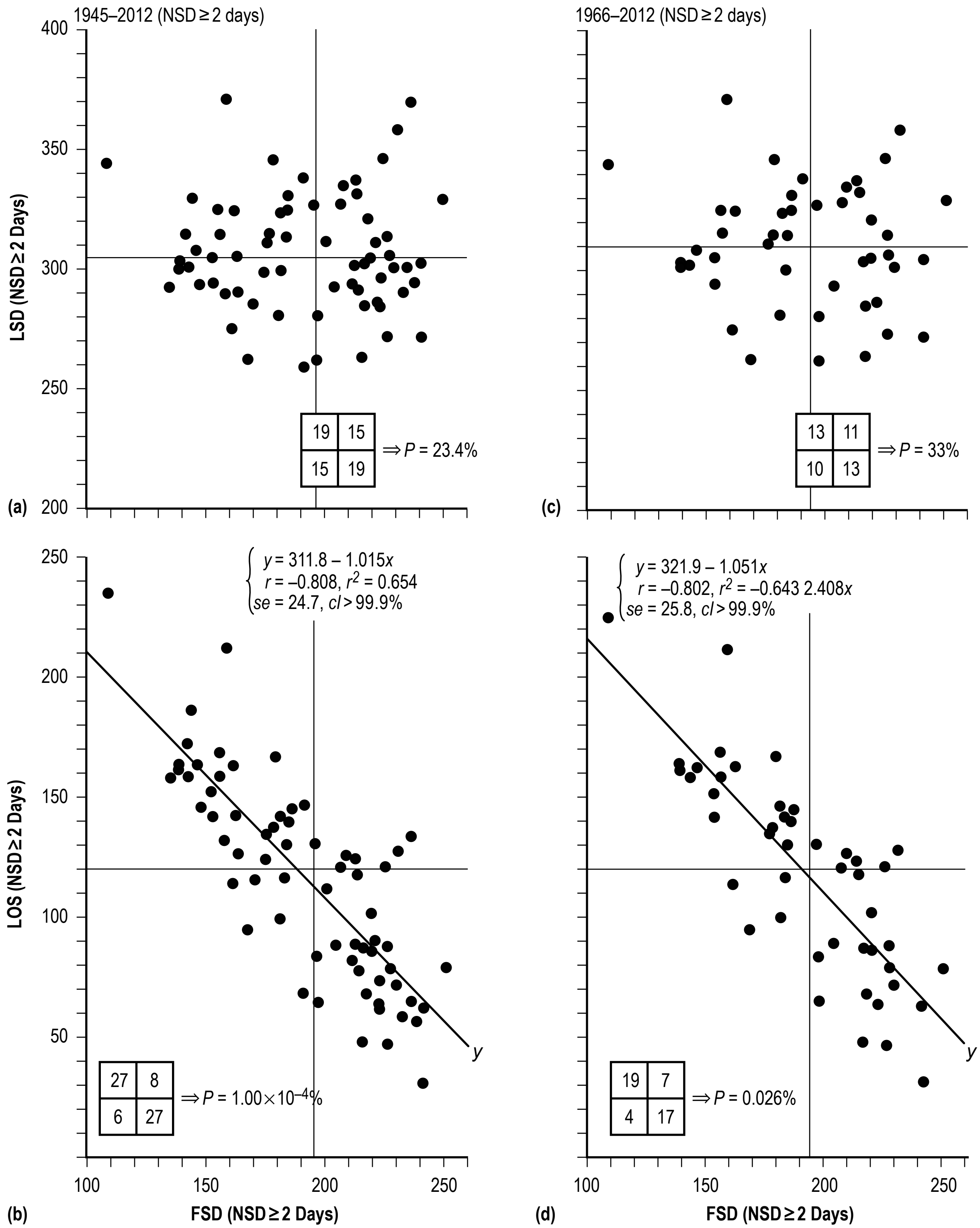

Figure 9. Scatter diagrams of LSD ((a) and (c)) and LOS ((b) and (d)) versus FSD for the intervals 1945–2012 and 1966–2012, respectively, using TCs having duration NSD ≥ 2 days.

Inspection of figure 10 reveals that the residuals essentially mimic each other and, based on runs-testing,[2] they are consistent with random behavior. As an example, examination of figure 10(a) shows that 48 of the 68 years have residuals that fall within the ±1 *sd* prediction interval, a proportion similar to that expected using the normal curve. Of the 20 years having a larger residual, 12 were outside-high (i.e., the observed LOS is longer than expected) and 8 were outside-low (i.e., the observed LOS is shorter than expected). The 12 longer than expected LOS years include 1953, 1954, 1975, 1980, 1984, 1989, 1998, 2001, 2003–2005, and 2007, and the 8 shorter than expected LOS years include 1945, 1958, 1960, 1974, 1982, 1983, 1993, and 2006. Excluding the year 1945 when the ENSO phase is not available based on the published record of ONI monthly values, only the years 1953 and 1998 appear to be associated with anomalously warm January–June averages of ONI, and only the years 1953 and 1982 appear to be associated with anomalously warm July–December averages of ONI. Likewise, only the year 1989 appears to be associated with anomalously cold January–June averages of ONI, and only the years 1974 and 1983 appear to be associated with anomalously cold July–December averages of ONI. Thus, there appears to be no clear association between longer than expected or shorter than expected residuals and the phase of the ENSO. Indeed, runs-testing of the January–June and July–December ONI averages suggests that the ONI averages are randomly distributed as well.

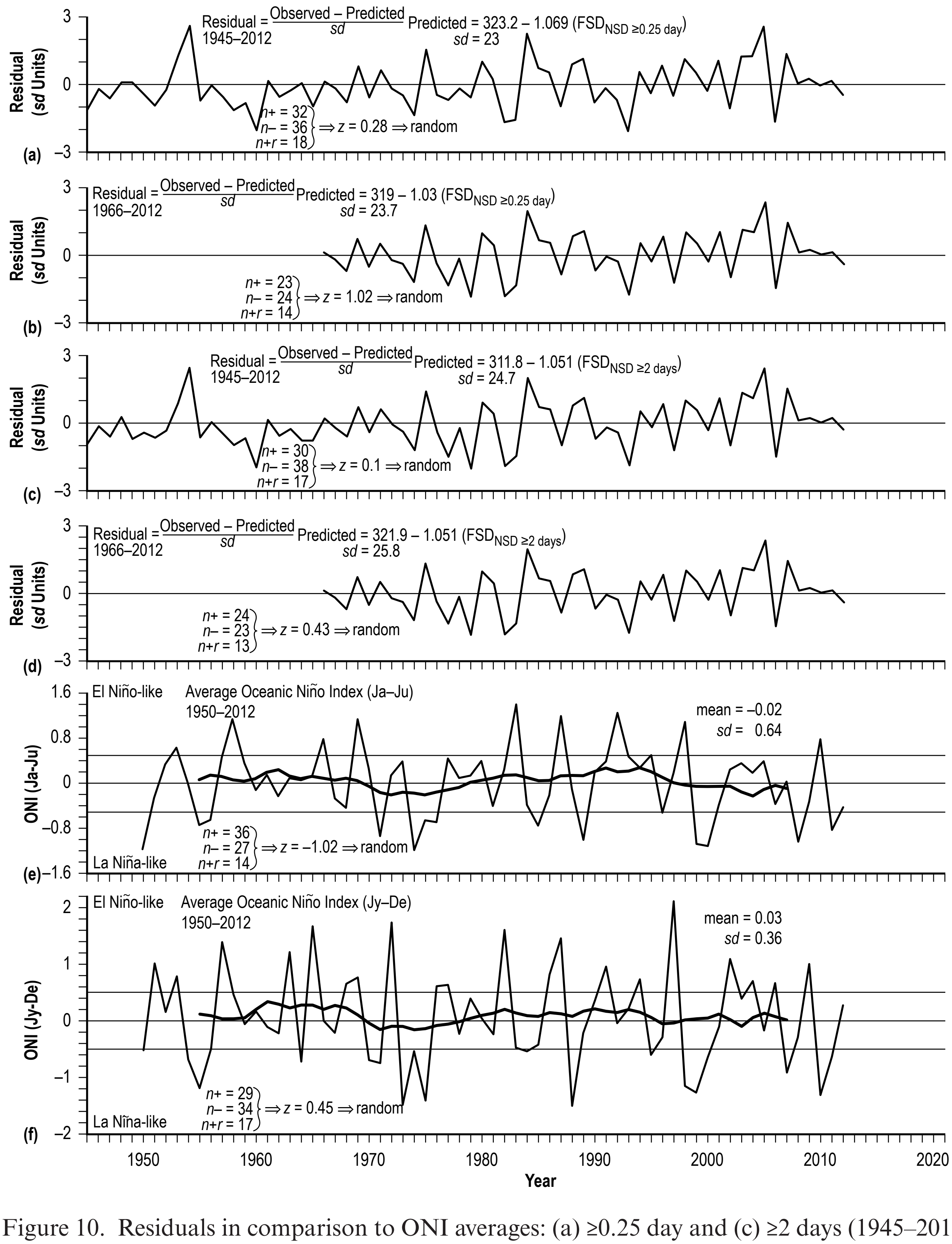

Figure 10. Residuals in comparison to ONI averages: (a) ≥0.25 day and (c) ≥2 days (1945–2012); (b) ≥0.25 day and (d) ≥2 days (1966–2012); and (e) January–June and (f) July–December (1950–2012).

Figure 11 shows the scatter plots of LOS (based on the determination using TCs having duration NSD ≥ 0.25 day) directly against the (a) January–June and (b) July–December averages of ONI, respectively. Plainly, one infers no statistically important correlation between LOS and either the January–June or July–December ONI averages, although a curious result is apparent regarding LN events based on the January–June ONI averages (fig. 11(a)). Namely, of the 14 years when LN-like conditions prevailed in the January–June ONI averages, for 10 of those years, the yearly LOS ≥ 131 days, thus yielding a probability of success $P = 6.1\%$ (i.e., the probability due to chance, calculated using the binomial formula[2]). For these 10 years, the LOS averaged about 162.4 ± 19.6 days (i.e., the mean ± 1 *sd* interval). The 4 years having January–June ONI averages suggestive of LN-like conditions but having LOS < 131 days include the years 1950, 1955, 1974, and 2000, and they had an average LOS = 87 ± 13.7 days.

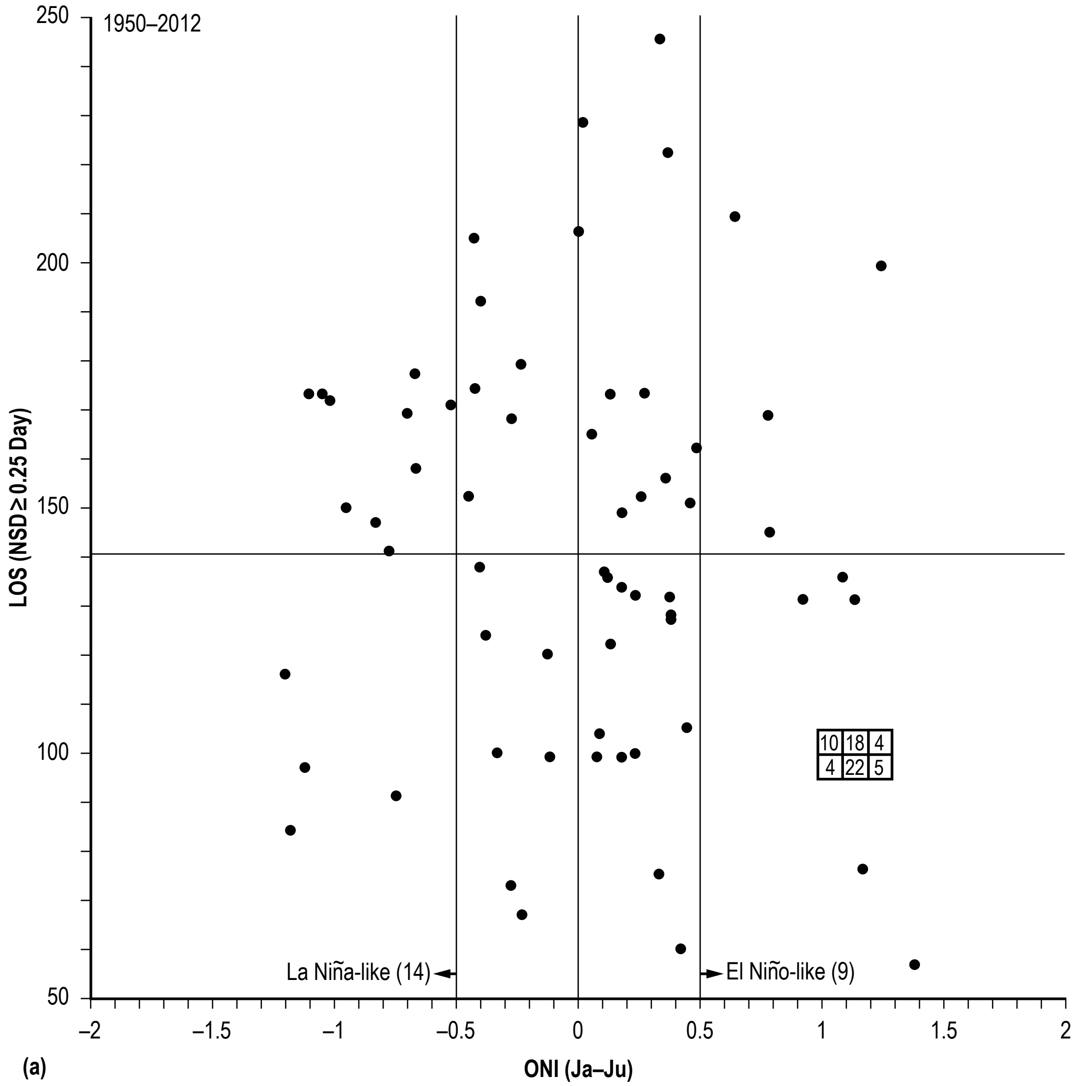

Figure 11. Scatter diagram of (a) LOS versus January–June ONI averages and (b) LOS versus July–December ONI averages (1950–2012).

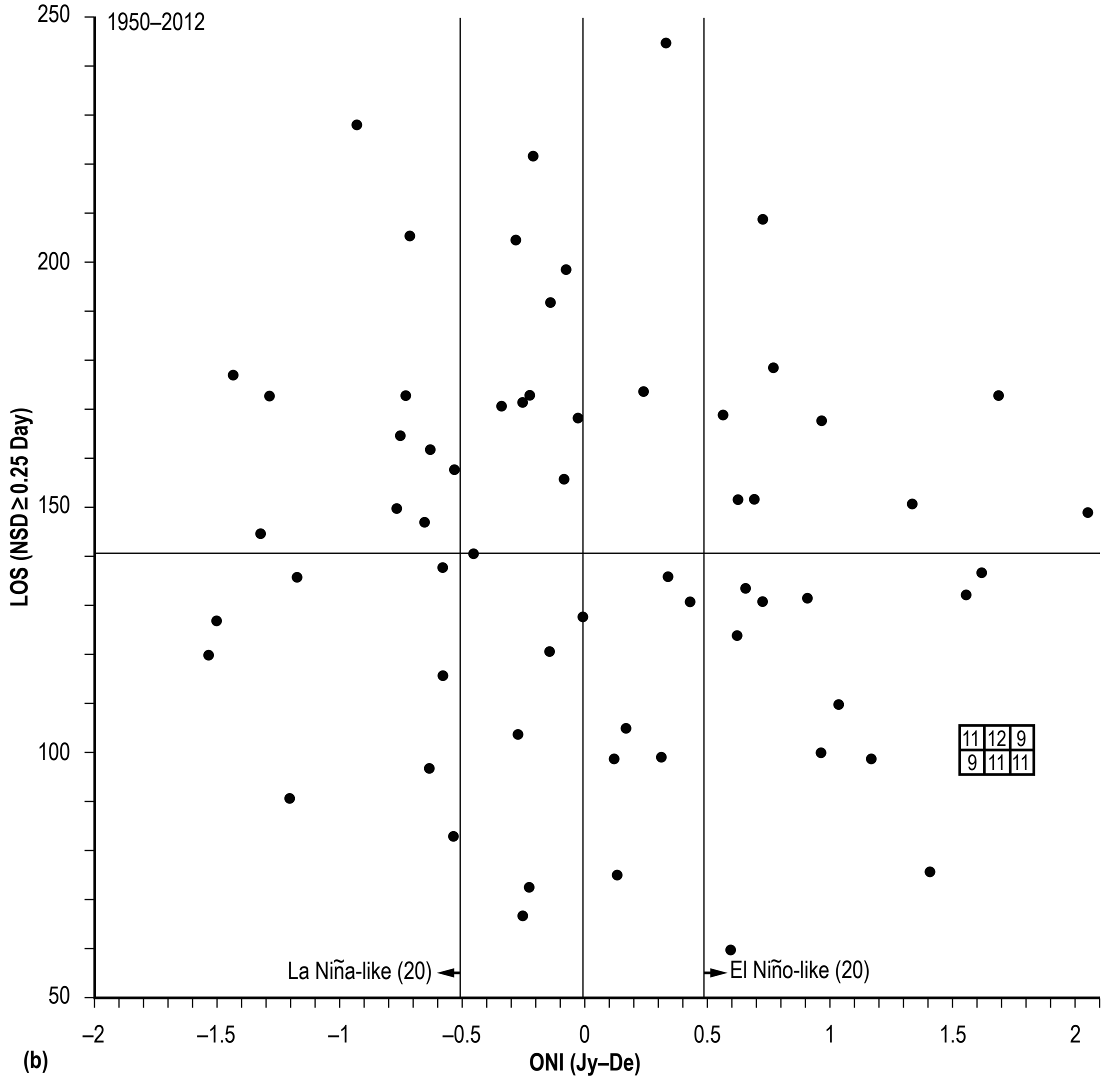

Figure 11. Scatter diagram of (a) LOS versus January–June ONI averages and (b) LOS versus July–December ONI averages (1950–2012) (Continued).

2.5 Surface-Air and Sea-Surface Temperature, Wind, and NAO During the Interval 1945–2012

Figure 12 displays the yearly variation of surface-air and sea-surface temperature, wind, and the North Atlantic air pressure for the overall interval 1945-2012, as determined using (a) the Armagh surface-air temperature (ASAT), (b) the AMO, (c) the Atlantic Meridional Mode (AMM) index based on SST, (d) the AMM index based on wind, (e) the NAO index, and (f) the Global Land-Ocean Temperature Index (GLOTI). As before, the annual values are drawn as thin lines and the 10-yma trend values as thick lines. Mean and *sd* values are given in each panel for the different time intervals. Clearly, the ASAT, AMO, AMM(SST), and AMM(wind) were trending downwards from the 1950s through the 1970s and 1980s, then began trending upwards thereafter. In contrast, the NAO has been essentially flat throughout the interval 1945–2012, while the GLOTI has been slowly rising, especially since the early 1970s.

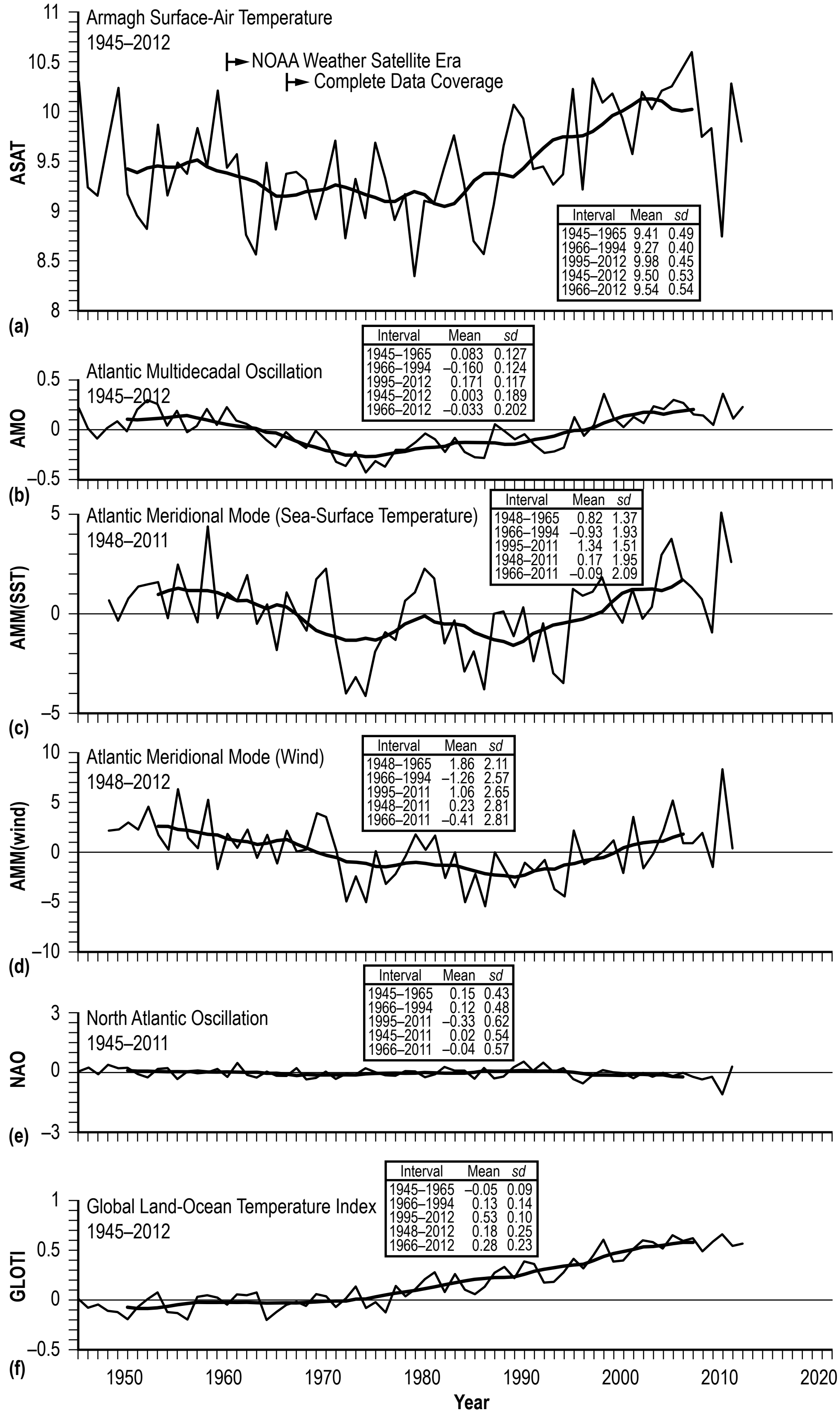

Figure 12. Yearly variation of (a) ASAT, (b) AMO, (c) AMM(SST), (d) AMM(wind), (e) NAO, and (f) GLOTI.

The ASAT is one of the longest thermometer-based temperature records available for study (since 1844), with annual mean temperatures based on readings using maximum and minimum thermometers.[24–30] The Armagh Observatory lies about 1 km northeast of the center of the ancient city of Armagh, Northern Ireland, and is located at 54°21'12" N. and 6°38'54" W., being 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. Previous studies have shown that its rural environment has ensured that the recorded temperatures suffer little or no urban microclimatic effects and that the recorded temperature record can serve as a good proxy for monitoring long term trends in both northern hemispheric and global annual mean temperature.[27,31] Monthly summaries of the ASAT data are available online at <http://climate.arm.ac.uk/scans>.

The AMO is a temperature oscillation in the detrended SST of the North Atlantic Ocean (0–70° N. latitude), having a period of about 65–70 years that fluctuates between warm (positive) and cool (negative) phases.[10,32–38] The SST pattern has been suggested to be linked to variations in the strength of the Atlantic thermohaline circulation (THC), a density-driven, global circulation pattern that involves the movement of warm equatorial surface waters to higher latitudes and the subsequent cooling and sinking of these waters in the deep ocean.[39] In particular, the warm phase of the AMO represents intervals of faster THC, while the cold phase represents intervals of slower THC. Monthly values of the AMO index are available online at <http://www.esrl.noaa.gov/psd/data/correlation/amon.us.long.data>.

The AMM(SST) and AMM(wind) are 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.[37,40–45] The AMM spatial pattern is defined by applying maximum covariance analysis (MCA[46]) to SST and the zonal and meridional components of the 10-m wind field over the interval 1950–2005, from the National Center for Environmental Predictions/National Center for Atmospheric Research reanalysis. To determine the spatial pattern, the data are first defined over the region bounded by latitude 21 °S. to 32 °N. and longitude 74 °W. to 15 °E. and spatially smoothed; the seasonal cycle is removed, the data are detrended, a 3-month running mean is applied, and the linear fit to the Cold Tongue index (a measure of ENSO variability) is subtracted from each spatial point. The spatial patterns are then defined as the first SST and wind maps resulting from singular value decomposition of the covariance matrix between the two fields, with the AMM time series being calculated by means of projecting SST (or the 10-m wind field) onto the spatial structure resulting from the MCA. Positive values of the AMM indicate warming and stronger easterly trade winds, while negative values represent cooling and weakening winds. Monthly values are available online at <http://www.esrl.noaa.gov/psd/data/timeseries/monthly/AMM>.

Like the Southern Oscillation, the NAO is one based on changes in surface-air pressure between two widely separated locations (e.g., Iceland and the subtropical Atlantic Ocean basin—the Azores, Portugal, or Gibraltar). The large-scale air-mass movements described by the NAO thus control the strength and direction of westerly winds and storm tracks across the North Atlantic Ocean. During the positive phase of the NAO, there is a stronger than usual subtropical high pressure center and a deeper than usual Icelandic low, while during the negative phase of the NAO, the opposite is true.[37,47–49] Monthly values of the NAO index are available online at <http://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Data/nao.long.data> and <http://www.cru.uea.ac.uk/~timo/datapages/naoi.htm>.

The GLOTI is a measure of the anomaly in the global land-ocean temperature relative to the base period of 1951–1980, where the data are taken from the Global Historical Climate Network, version 3, using elimination of outliers and homogeneity adjustment. Positive GLOTI indicates anomalous warm temperatures, and negative GLOTI indicates anomalous cold temperatures. The data, as used in figure 12(f), represent the January–December averages, available online at <http://data.giss.nasa.gov/gistemp>.[50–53]

Regarding the ASAT, the coolest annual surface-air temperature during the interval 1945–2012 occurred in 1979, measuring 8.36 °C, while the warmest annual temperature occurred in 2007, measuring 10.6 °C. Twelve of the past 24 years (i.e., since 1989) have had annual ASAT $\geq$ 10 °C, with the interval since 1989 being the warmest ever observed (based on the 10-yma trend) in the entire record of ASAT annual temperatures. During the intervals 1945–1965, 1966–1994, and 1995–2012, ASAT measured, respectively, 9.41 $\pm$ 0.49 °C, 9.27 $\pm$ 0.40 °C, and 9.98 $\pm$ 0.45 °C (mean $\pm$ 1 *sd* interval). Based on the *t*-statistic for independent samples, the difference in the means for the first two intervals measures $t = 1.11$, $cl < 90\%$, while measuring $t = 3.76$, $cl > 99.9\%$ when the mean for the first interval is compared to the mean for the current ongoing interval, and $t = 5.64$, $cl \gg 99.9\%$ when comparing the means for the second interval and the current ongoing interval. Hence, the surface-air temperature at Armagh in the North Atlantic basin is now undoubtedly warmer than anytime in recent history.

Regarding the AMO, it too shares a behavior similar to that of the ASAT. The interval means are, respectively, 0.083 $\pm$ 0.127 °C, –0.16 $\pm$ 0.124 °C, and 0.171 $\pm$ 0.117 °C. The differences in the means measure $t = 6.77$, $cl > 99.9\%$ for the first two intervals; $t = 9.09$, $cl > 99.9\%$ for the second and current ongoing intervals; and $t = 2.24$, $cl > 95\%$ for the first and current ongoing intervals. Thus, the interval 1945–1965 was anomalously warm (as was ASAT), the middle interval 1966–1994 was anomalously cold (as was the ASAT), and the current ongoing interval 1995–2012 is now once again anomalously warm, in fact, much warmer than the immediately preceding interval and even warmer than the first interval (as is ASAT). Such behavior suggests that much of the recent warming in surface-air temperature as described using ASAT quite probably results from the natural quasicyclic variation of the AMO.[1,10,54,55]

As with the ASAT and AMO, the AMM(SST) and AMM(wind) indices vary both in the positive and negative sense, being stronger (positive) in the 1950s and 1960s, weaker (negative) in the 1970s, 1980s, and early 1990s, and now once again stronger (positive) in the late 1990s through today. With respect to the ASAT and AMO, the AMM(SST) and AMM(wind) indices appear to be slightly delayed. For the AMM(SST) index, the differences in the means measure $t = 3.55$, $cl > 99.9\%$ for the first two intervals; $t = 4.24$, $cl > 99.9\%$ for the second and current ongoing intervals; and $t = 1.13$, $cl < 90\%$ for the first and current ongoing intervals. For the AMM(wind) index, the differences in the means measure $t = 4.56$, $cl > 99.9\%$ for the first two intervals; $t = 2.97$, $cl > 99.5\%$ for the second and current ongoing intervals; and $t = 1.05$, $cl < 90\%$, for the first and current ongoing intervals. Thus, the interval 1945–1965 was anomalously warm (as was ASAT and AMO) with strong easterlies, the middle interval 1966–1994 was anomalously cold (as was the ASAT and AMO) with weak easterlies, and the current ongoing interval 1995–2012 is once again anomalously warm (as is ASAT and AMO) with strong easterlies.

Regarding the NAO, based on its trend (i.e., the 10-yma values), it was positive during the interval 1950–1964, negative during the interval 1965–1976, positive during the interval 1977–1996, and negative again during the current ongoing interval (since 1997). In fact, it is now much more negative than it was during the first negative interval (measuring –0.42 in 2006). The difference in the means is statistically unimportant ($t = 0.07$, $cl < 90\%$) between the first two intervals; however, the differences are statistically important between either the first and current ongoing intervals ($t = 2.84$, $cl > 99\%$) or the second and current ongoing intervals ($t = 2.79$, $cl > 99\%$).

Regarding the GLOTI, based on its annual values, it has been continuously positive (warmer) from 1977 onwards. Based on its 10-yma trend, it has been positive from 1970 onwards, measuring 0.58 °C in 2007. A local peak in the annual values occurred in 2010, measuring 0.66 °C, followed by a slight decrease to 0.54 °C in 2011 and a rebound upwards to 0.56 °C in 2012. The difference in means is statistically important between all intervals: $t = 5.16$, $cl > 99.9\%$, between the first and second intervals; $t = 10.55$, $cl > 99.9\%$ between the second interval and current ongoing interval; and $t = 19.06$, $cl \gg 99.9\%$ between the first interval and current ongoing interval. During the interval 1950–2007, the 10-yma trend in GLOTI has increased from –0.07 °C to 0.58 °C, or about 0.011 °C per year.

2.6 Relationship of FSD, LSD, and LOS Against Surface-Air and Sea-Surface Temperature, Wind, and the NAO

Table 1 gives the statistics for the inferred regressions of FSD, LSD, and LOS against ASAT, AMO, AMM(SST), AMM(wind), NAO, and GLOTI for the intervals 1987–2007 and 1966–2007 based on using 10-yma values, where *a* refers to the *y*-intercept, *b* the slope, *r* the coefficient of correlation, r^2 the coefficient of determination (a measure of the amount of variance explained by the inferred regression), *se* the standard error of estimate, *t* a measure of the strength of the inferred correlation (based on the sample size), and *cl* the confidence level for the strength of the inferred correlation (based on sample size). All regressions are inferred to be highly statistically important at $cl > 99.9\%$, with the inferred regressions having larger *r* for the interval 1987–2007 as compared to the larger interval 1966–2007.

Table 1. Statistics for FSD, LSD, and LOS against ASAT, AMO, AMM(SST), AMM(wind), NAO, and GLOTI using 10-yma values for 1987–2007 and 1966–2007.

		1987–2007						1966–2007					
y	**Statistic**	**ASAT**	**AMO**	**AMM(SST)**	**AMM(wind)**	**NAO**	**GLOTI**	**ASAT**	**AMO**	**AMM(SST)**	**AMM(wind)**	**NAO**	**GLOTI**
FSD	a	398.644	177.318	175.600	173.283	175.499	193.793	340.048	177.692	178.442	177.110	179.922	185.278
	b	–22.799	–43.266	–4.913	–3.734	21.085	–45.069	–16.877	–34.871	–4.678	–4.091	26.361	–22.354
	r	–0.815	–0.740	–0.714	–0.709	0.680	–0.769	–0.733	–0.609	–0.497	–0.569	0.568	–0.533
	rxr	0.664	0.548	0.510	0.503	0.463	0.592	0.537	0.371	0.247	0.324	0.323	0.284
	se	4.458	5.063	5.268	5.301	5.509	4.811	5.729	6.748	7.272	6.888	6.896	7.201
	t	–6.004	–4.804	–4.323	–4.267	3.939	–5.253	–6.880	–4.856	–3.579	–4.324	4.312	–3.980
	cl	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%
LSD	a	118.236	313.064	315.001	317.612	315.111	296.388	188.738	314.215	313.670	313.836	311.956	306.049
	b	20.112	46.808	5.476	4.207	–22.837	45.971	12.991	35.104	5.130	2.734	–17.592	24.676
	r	0.791	0.881	0.874	0.878	–0.809	0.863	0.789	0.858	0.769	0.537	–0.535	0.823
	rxr	0.625	0.777	0.764	0.770	0.655	0.746	0.622	0.735	0.542	0.288	0.286	0.677
	se	4.184	3.218	3.350	3.296	4.003	3.462	3.731	3.133	3.804	5.007	5.027	3.466
	t	5.644	8.176	7.577	7.731	–5.871	7.447	8.133	10.530	7.502	3.975	–3.947	9.128
	cl	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%
LOS	a	–278.835	136.772	140.426	145.348	140.636	103.685	–149.606	137.553	136.266	137.774	133.081	121.860
	b	42.854	89.923	10.378	7.930	–43.848	90.869	29.799	69.763	9.784	6.827	–43.967	46.840
	r	0.965	0.970	0.962	0.961	–0.902	0.977	0.901	0.849	0.737	0.673	–0.672	0.778
	rxr	0.931	0.940	0.925	0.923	0.814	0.955	0.813	0.721	0.543	0.453	0.451	0.605
	se	3.148	2.936	3.232	3.259	5.084	2.524	5.249	6.445	7.990	8.745	8.760	7.671
	t	15.985	17.220	14.882	14.740	–8.876	20.193	13.260	10.171	6.812	5.683	–5.661	7.829
	cl	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%

Figure 13 shows the scatter plots of FSD, LSD, and LOS versus ASAT, AMO, and GLOTI for the interval 1966–2007, where the regressions (y) are drawn based on the interval 1966–2007 10-yma values. Also given in each panel is the result of Fisher's exact test for the observed result, or one more suggestive of a departure from independence. The arrows correspond to the 10-yma values for the year 2007, the last available year. Plainly, as surface-air temperature or SST warmed, the FSD occurred sooner and the LSD occurred later, with their combined effect making the LOS longer.

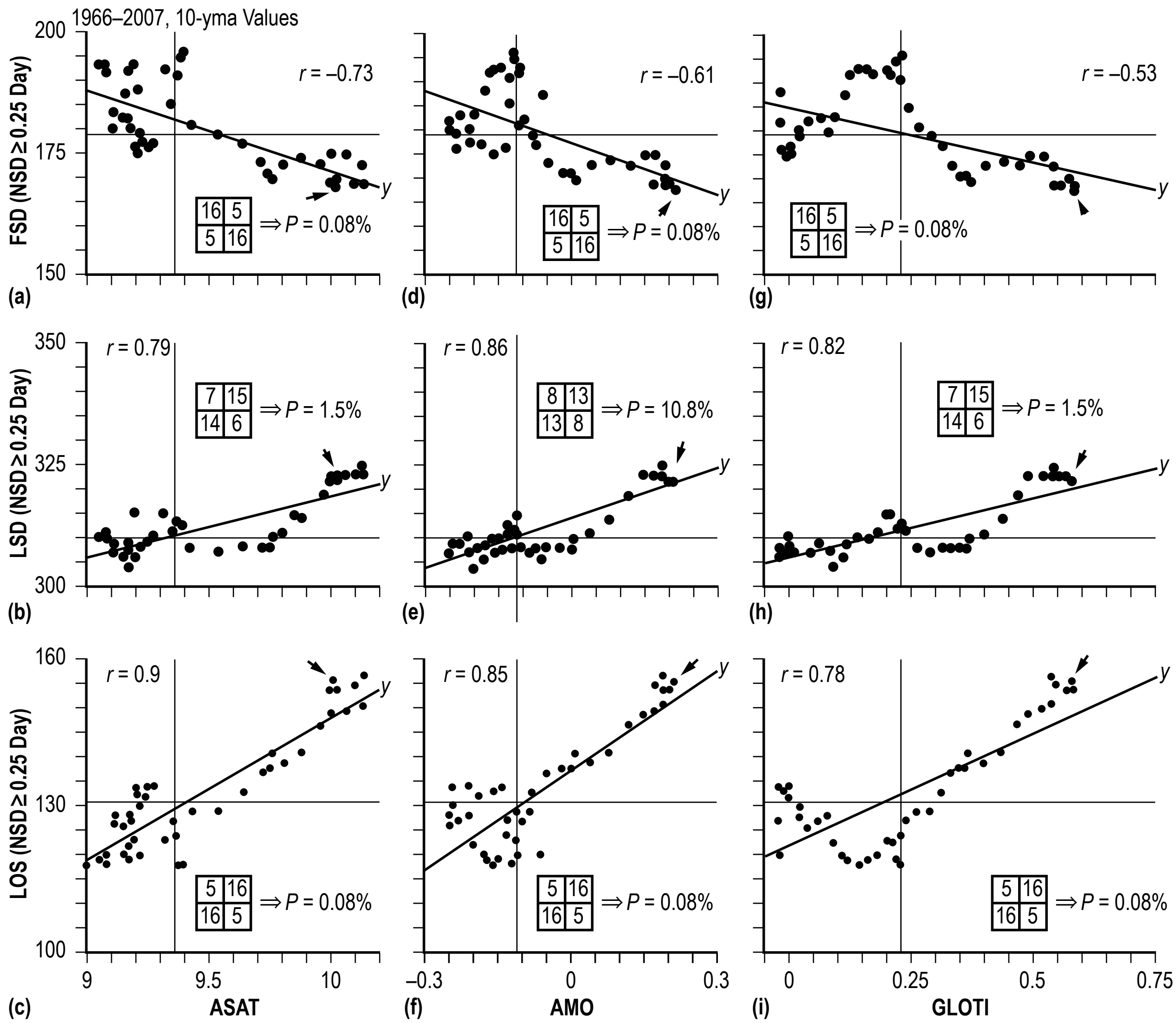

Figure 13. Scatter diagrams of FSD ((a), (d), and (g)); LSD ((b), (e), and (h)); and LOS ((c), (f), and (i)) versus ASAT, AMO, and GLOTI, respectively.

Figure 14 displays the first difference (*fd*) of the 10-yma values for FSD, LSD and LOS for the interval 1966–2006, where the first difference for year n is the 10-yma value for year $n+1$ minus the 10-yma value for year n. Clearly, *fd* values for FSD appear to be randomly distributed, while *fd* values for LSD and LOS appear to be nonrandomly distributed. Estimates of the 10-yma values for FSD, LSD, and LOS for the year 2008 are computed to be about $167.5-0.5\pm2.6$ ($=167\pm2.6$), $322.1+0.4\pm1.8$ ($=322.5\pm1.8$), and $155.5+0.9\pm2.9$ ($=156.4\pm2.9$), respectively. Likewise, figure 15 shows the *fd* values for ASAT, AMO, and GLOTI for the interval 1966–2006 (all found to be nonrandomly distributed). The expected 10-yma values for the year 2008 are estimated to be about $10.01+0.03\pm0.06$ ($=10.04\pm0.06$), $0.207+0.007\pm0.021$ ($=0.214\pm0.021$), and $0.58+0.01\pm0.01$ ($=0.59\pm0.01$), respectively. Hence, the expected 10-yma for FSD for the year 2008 undoubtedly will lie in the lower right-hand quadrants of figure 13, while the expected 10-yma values for LSD and LOS for the year 2008 will lie in the upper right-hand quadrants.

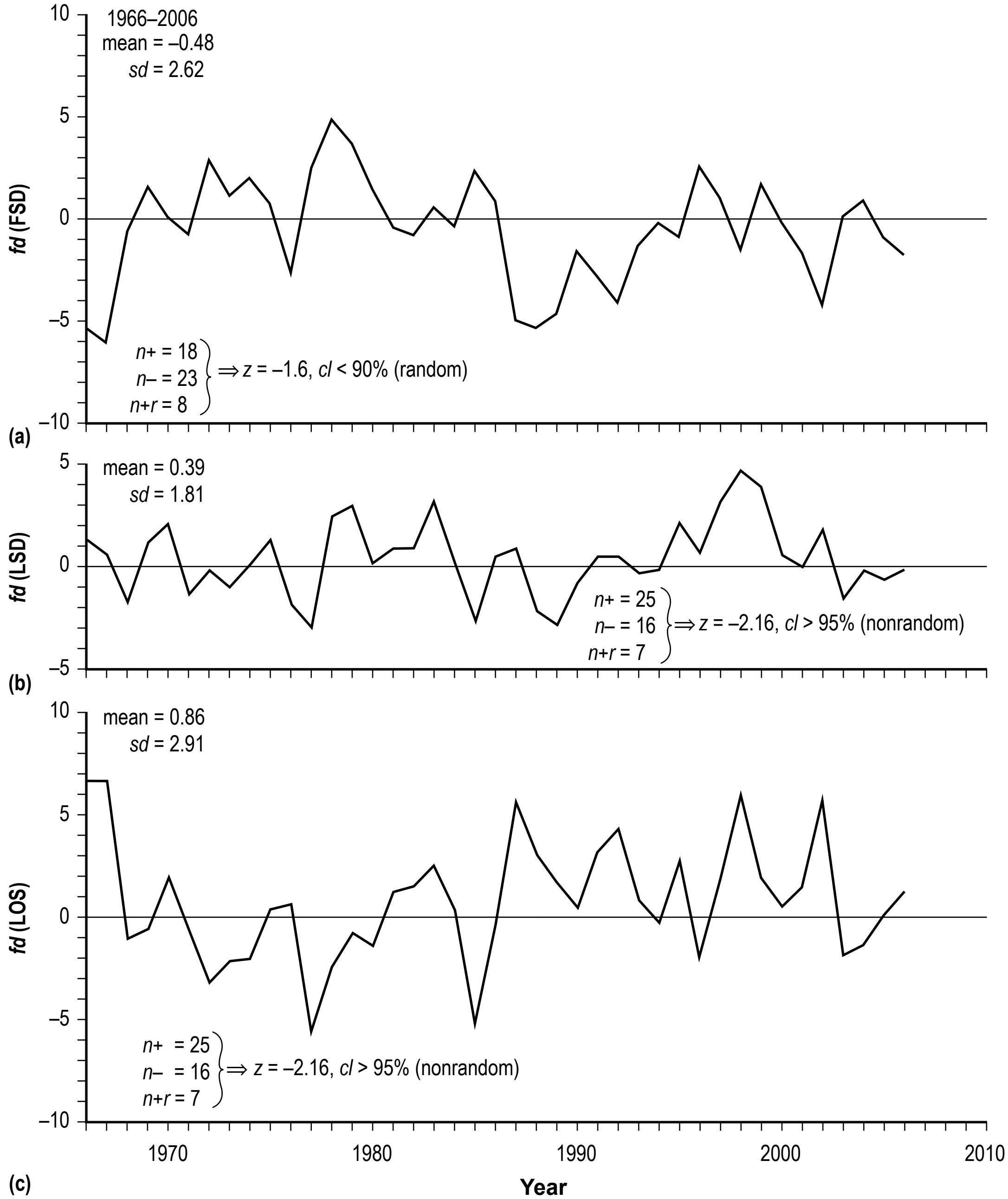

Figure 14. First differences of (a) FSD, (b) LSD, and (c) LOS for the interval 1966–2006.

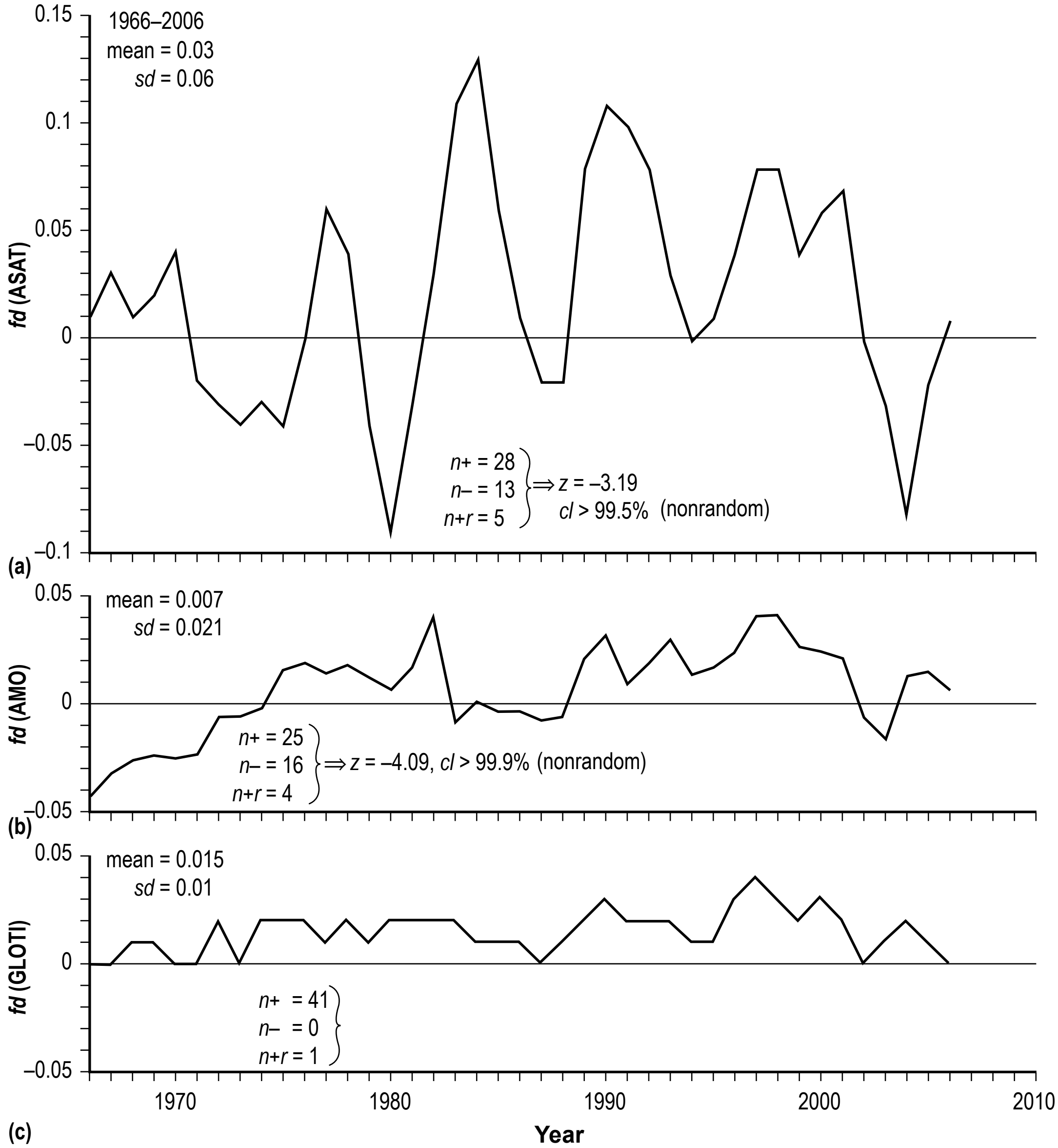

Figure 15. First differences of (a) ASAT, (b) AMO, and (c) GLOTI for the interval 1966–2006.

2.7 Relationship of Tropical Cyclone Activity Against Surface-Air and Sea-Surface Temperature, Wind, and the NAO

It has been well established that SST > 26 °C is a basic requirement for TC formation.[56–58] Hence, one expects more TCs to form when SST is warmer than when SST is cooler.[21,59,60] Additionally, other factors have been linked to the variability of TC activity as well, such as the ENSO, Atlantic Niños, the Quasibiennial Oscillation, West African monsoon rainfall, vertical wind shear, sea level pressure, African and volcanic dust, and anthropogenic gas emissions.[6,20,61–71]

Table 2 gives the statistics for the inferred regressions of NTC(all), NTC (short-lived, SL; i.e., NSD < 2 days), and NTC (long-lived, LL; i.e., NSD ≥ 2 days) against ASAT, AMO, AMM(SST), AMM(wind), NAO, and GLOTI for the intervals 1987–2007 and 1966–2007 using 10-yma values. All regressions are inferred to be highly statistically important at *cl* > 99.9%. As above for FSD, LSD, and LOS, the inferred regressions have larger *r* for the interval 1987–2007 as compared to the overall interval 1966–2007.

Table 2. Statistics for NTC(all), NTC(SL), and NTC(LL) against ASAT, AMO, AMM(SST), AMM(wind), NAO, and GLOTI using 10-yma values for 1987–2007 and 1966–2007.

		1987–2007						1966–2007					
y	Statistic	ASAT	AMO	AMM(SST)	AMM(wind)	NAO	GLOTI	ASAT	AMO	AMM(SST)	AMM(wind)	NAO	GLOTI
NTC(all)	a	–72.865	11.587	12.329	13.361	12.374	4.601	–43.096	11.932	11.685	11.932	10.991	8.719
	b	8.712	19.103	2.171	1.663	–9.328	19.201	5.704	14.359	2.105	1.365	–8.471	9.570
	r	0.944	0.991	0.992	0.993	–0.947	0.993	0.917	0.928	0.865	0.734	–0.705	0.844
	rxr	0.890	0.981	0.985	0.987	0.896	0.987	0.840	0.862	0.747	0.538	0.497	0.713
	se	0.832	0.341	0.297	0.273	0.768	0.274	0.911	0.852	1.088	1.475	1.539	1.231
	t	12.289	31.490	33.931	36.898	–12.499	39.248	14.628	15.837	10.762	6.735	–6.207	9.965
	cl	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%
NTC(SL)	a	–23.353	2.455	2.685	3.015	2.699	0.235	–11.916	2.630	2.575	2.641	2.370	1.733
	b	2.663	5.956	0.679	0.532	–2.943	6.088	1.507	3.943	0.623	0.394	–2.457	2.688
	r	0.881	0.943	0.946	0.969	–0.910	0.962	0.828	0.872	0.879	0.728	–0.703	0.811
	rxr	0.776	0.890	0.895	0.940	0.828	0.925	0.686	0.761	0.773	0.529	0.494	0.658
	se	0.385	0.272	0.252	0.192	0.323	0.224	0.371	0.329	0.303	0.434	0.449	0.394
	t	8.130	12.308	12.510	16.810	–9.365	15.232	9.494	11.246	11.456	6.609	–6.178	8.748
	cl	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%
NTC(LL)	a	–49.333	9.119	9.629	10.330	9.660	4.362	–30.980	9.291	9.100	9.282	8.614	6.987
	b	6.029	13.111	1.487	1.128	–6.347	13.086	4.175	10.365	1.476	0.969	–5.981	6.847
	r	0.955	0.995	0.994	0.986	–0.942	0.991	0.929	0.928	0.835	0.718	–0.686	0.836
	rxr	0.913	0.990	0.988	0.972	0.887	0.981	0.862	0.861	0.698	0.515	0.471	0.699
	se	0.544	0.183	0.192	0.265	0.548	0.238	0.631	0.622	0.864	1.097	1.145	0.911
	t	13.019	40.276	35.807	25.761	–11.923	30.830	15.454	15.665	9.501	6.429	–5.892	9.639
	cl	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%

Figure 16 shows the scatter plots of NTC(all), NTC(SL), and NTC(LL) versus ASAT, AMO, and GLOTI for the interval 1966–2007 based on using 10-yma values. Also given in each panel is the result of Fisher's exact test for the observed result, or one more suggestive of a departure from independence. The arrows once again correspond to the 10-yma values for the year 2007, the last available year. Plainly, as surface-air temperature or SST warmed, the number of TCs as described by

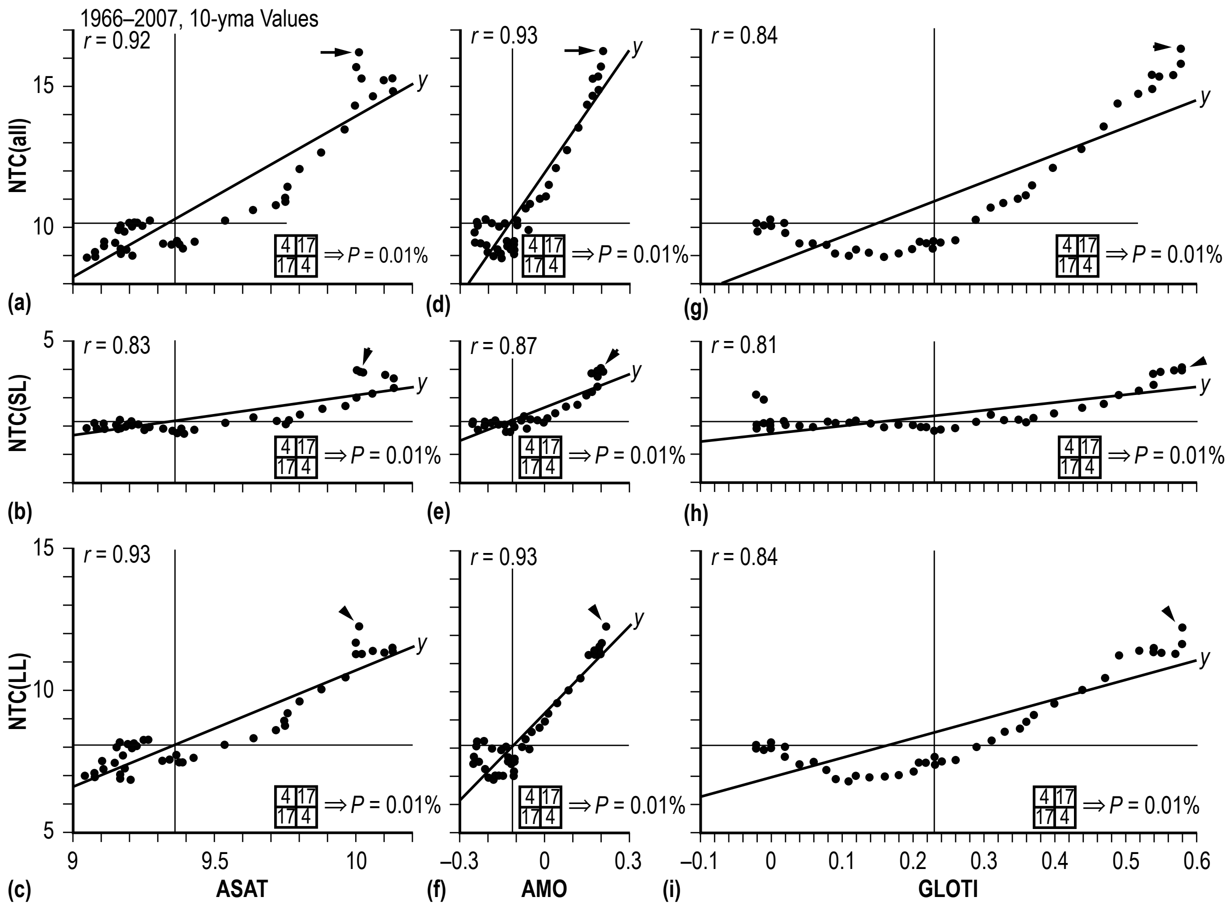

Figure 16. Scatter diagrams of NTC(all) ((a), (d), and (g)); NTC(SL) ((b), (e), and (h)); and NTC(LL) ((c), (f), and (i)) versus ASAT, AMO, and GLOTI, respectively, for the interval 1966–2007.

NTC(all), NTC(SL), and NTC(LL) each increased in number. Hence, warming temperature appears to be the root cause for the increase in the number of TCs forming in the North Atlantic basin, especially since 1987.

Figure 17 depicts the *fd* values for (a) NTC(all), (b) NTC(SL), and (c) NTC(LL). All *fd* values appear to be randomly distributed, based on runs-testing. For 2008, its 10-yma values are expected to measure about 16.4 ± 0.3, 4 ± 0.12, and 12.4 ± 0.25, respectively (i.e., the ± 1 *sd* interval), indicating that the 10-yma values of NTC(all), NTC(SL), and NTC(LL) for the year 2008 will lie in the upper right-hand quadrants of figure 16.

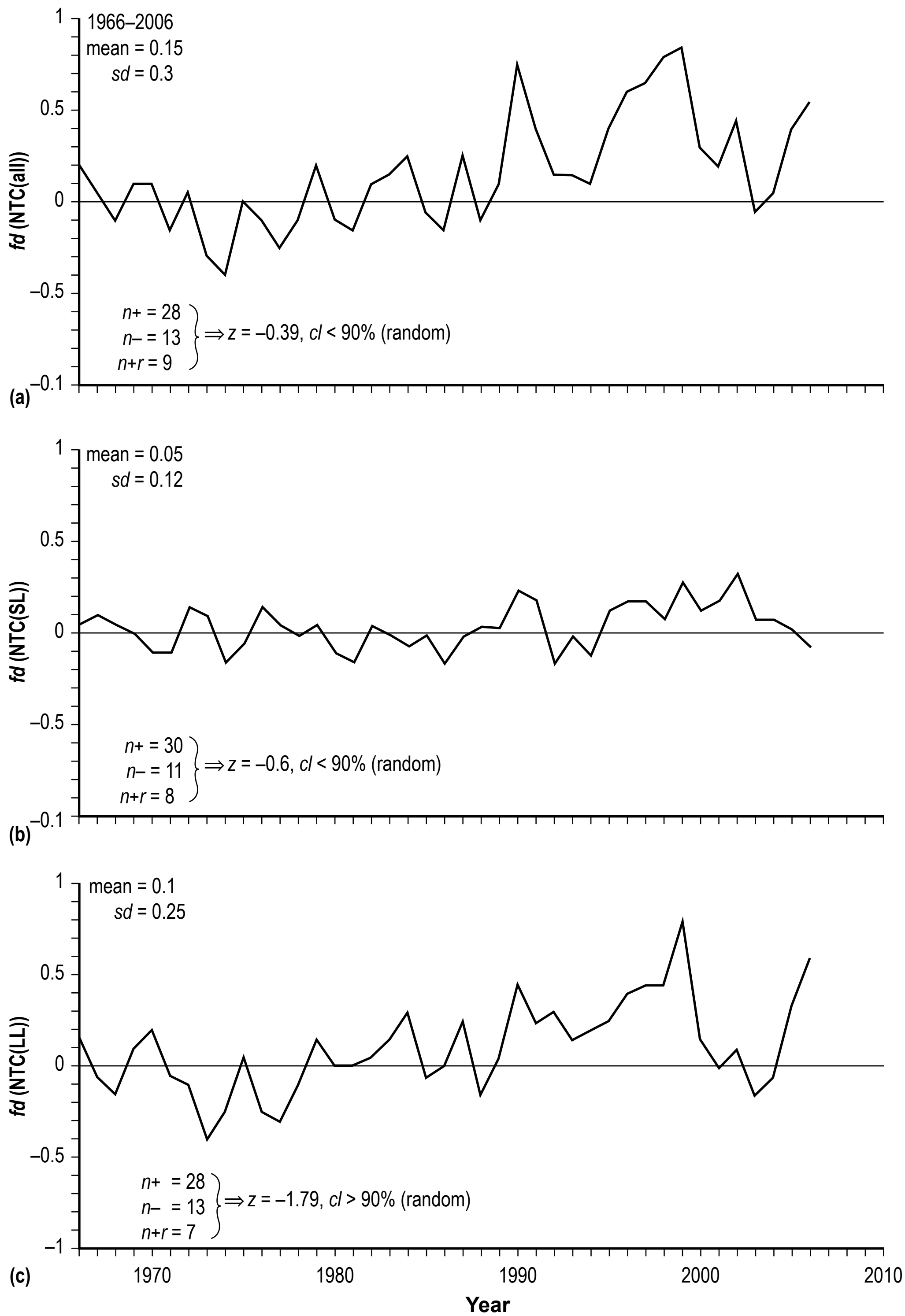

Figure 17. First differences of (a) NTC(all), (b) NTC(SL), and (c) NTC(LL) for the interval 1966–2006.

Table 3 provides the statistics for the inferred regressions between NTC(all) and NTC(SL) against ASAT, AMO, and GLOTI for the intervals 1987–2007 and 1966–2007 using the adjusted values for NTC(all) and NTC(SL). While there is some improvement (strengthening) in the inferred regressions for the interval 1987–2007, the improvement generally is lacking for the larger interval 1966–2007.

Table 3. Statistics for adjusted values of NTC(all) and NTC(NSD < 2 days) against ASAT, AMO, and GLOTI for 1987–2007 and 1966–2007.

		1987–2007			1966–2007		
y	**Statistic**	**ASAT**	**AMO**	**GLOTI**	**ASAT**	**AMO**	**GLOTI**
NTC(all)	a	–63.353	12.454	6.288	–35.931	12.776	9.986
	b	7.819	16.935	16.955	5.048	12.849	8.231
	r	0.960	0.996	0.994	0.910	0.930	0.814
	rxr	0.922	0.991	0.989	0.878	0.864	0.662
	se	0.637	0.197	0.220	0.877	0.754	1.190
	t	14.404	48.358	43.171	13.443	15.983	8.871
	cl	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%
NTC(SL)	a	–13.921	3.310	1.897	–4.717	3.472	2.999
	b	1.777	3.829	3.881	0.847	2.411	1.335
	r	0.929	0.958	0.969	0.722	0.827	0.625
	rxr	0.862	0.918	0.938	0.521	0.683	0.390
	se	0.215	0.152	0.123	0.302	0.243	0.337
	t	9.704	14.119	17.763	6.551	9.329	5.087
	cl	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%	>99.9%

2.8 Relationship of Tropical Cyclone Activity Against the FSD and LOS

Table 4 gives the statistics for the inferred regressions between NTC(all), NTC(SL), and NTC(LL) against FSD and LOS for the intervals 1987–2007 and 1966–2007 using 10-yma values. All correlations are inferred to be highly statistically important at $cl > 99.5\%$.

Table 4. Statistics for NTC(all), NTC(SL), and NTC(LL) against FSD and LOS using 10-yma values for 1987–2007 and 1966–2007.

		1987–2007		1966–2007	
y	**Statistic**	**FSD**	**LOS**	**FSD**	**LOS**
NTC(all)	a	54.2492	–15.906	47.643	–12.938
	b	–0.2382	0.201	–0.203	0.180
	r	–0.722	0.968	–0.753	0.956
	rxr	0.521	0.938	0.567	0.914
	se	1.7196	1.052	1.133	0.669
	t	–4.5518	9.961	–9.639	20.757
	cl	>99.9%	>99.9%	>99.9%	>99.9%
NTC(SL)	a	15.632	-6.2341	11.675	–4.0812
	b	–0.074	0.0636	–0.052	0.0485
	r	–0.681	0.934	–0.654	0.882
	rxr	0.464	0.873	0.428	0.778
	se	0.768	0.3012	0.647	0.3389
	t	–3.167	11.0096	–4.325	11.0499
	cl	>99.5%	>99.9%	>99.9%	>99.9%
NTC(LL)	a	38.536	9.643	35.849	-8.793
	b	–0.164	0.137	–0.151	0.131
	r	–0.729	0.967	–0.775	0.963
	rxr	0.531	0.935	0.600	0.927
	se	0.928	0.934	0.953	0.325
	t	–5.807	7.652	-8.526	31.130
	cl	>99.9%	>99.9%	>99.9%	>99.9%

Figure 18 displays the scatter plots of NTC(all), NTC(SL), and NTC(LL) versus FSD and LOS for the interval 1966–2007. Also given in each panel is the result of Fisher's exact test for the observed result, or one more suggestive of a departure from independence. The arrows correspond to the 10-yma values for the year 2007, the last available year. Plainly, as the 10-yma value of FSD shortens (i.e., occurs sooner) and/or the 10-yma of LOS lengthens (i.e., becomes longer), NTC(all), NTC(SL), and NTC(LL) each increase in number. As previously noted above, estimates of the 10-yma values for FSD and LOS for the year 2008 are computed to be about 167 ± 2.6 and 156.4 ± 2.9, respectively, and 10-yma values of NTC(all), NTC(SL), and NTC(LL) are computed to be about 16.4 ± 0.3, 4 ± 0.12, and 12.4 ± 0.25, respectively. Hence, expected values for the year 2008 will lie in the upper left-hand quadrant for NTC(all), NTC(SL), and NTC(LL) given FSD, and they will lie in the upper right-hand quadrant given LOS. (Now that FSD for the 2013 hurricane season is known, occurring on DOY 156, the 10-yma of FSD for 2008 is computed to be 167.)

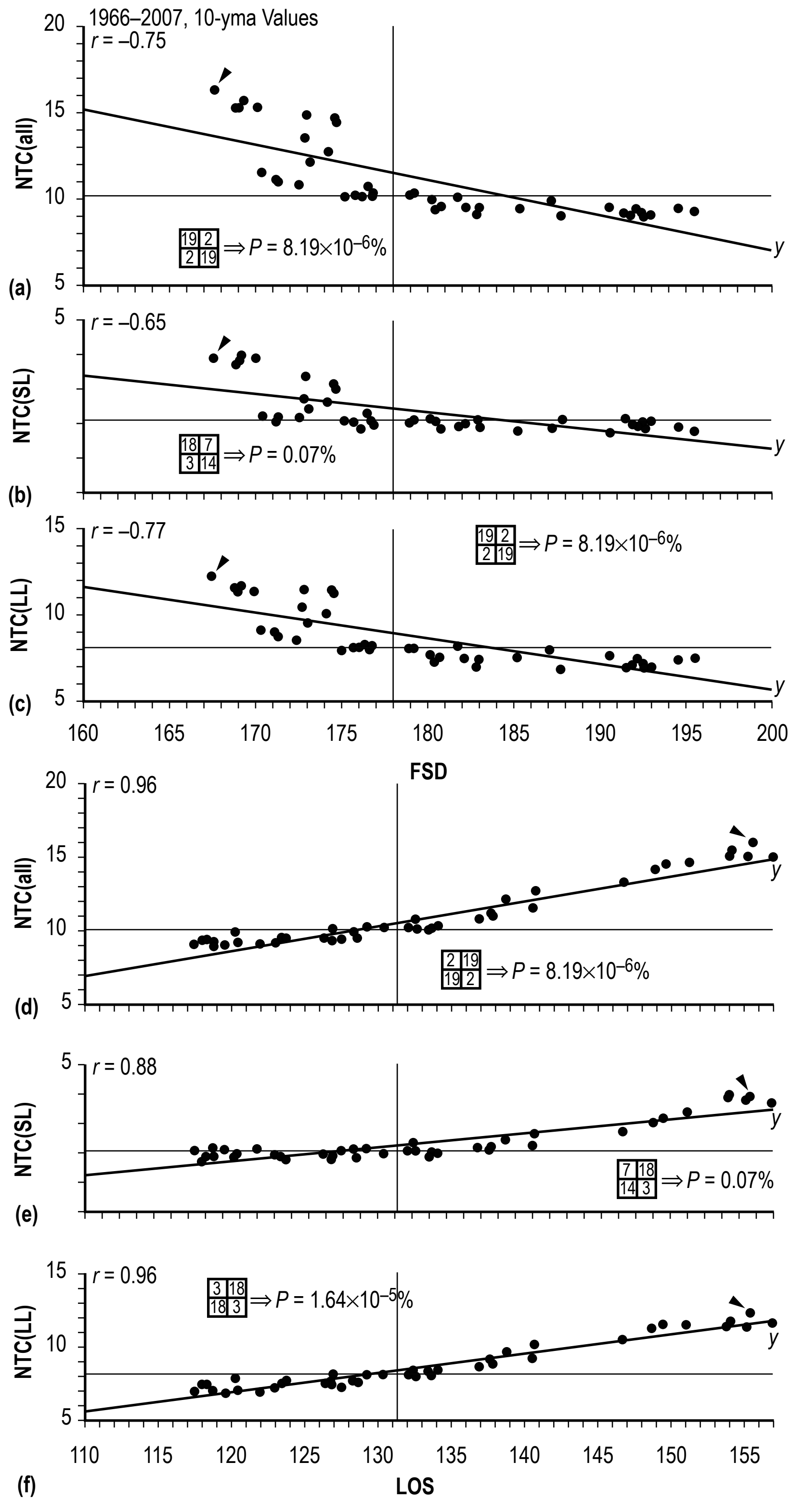

Figure 18. Scatter diagrams of (a) NTC(all), (b) NTC(SL), and (c) NTC(LL) versus FSD and (d) NTC(all), (e) NTC(SL), and (f) NTC(LL) versus LOS for the interval 1966–2007.

3. DISCUSSION AND CONCLUSION

This TP has demonstrated that the upward trend in both NTC activity (all, SL, and LL) and LOS that is presently being experienced, in particular during the current ongoing active interval 1995–2012 as compared to the earlier years 1945–1994, appears real and is not simply due to an underestimation of TC activity in recent years nor due to the recent use of improved tools and analysis techniques and new data sources. The observed increase in NTC activity and LOS appears to be directly related to the ongoing warming that is currently underway in the North Atlantic basin, primarily as manifested through the AMO and AMM (both indicative of a continuing warm phase that began in the mid-to-late 1990s and both expected to persist, at least, for another 10–20 years), although one cannot strictly rule out a contribution from anthropogenic gas emissions, especially as related to the GLOTI.[54,55,58,72,73] During the current ongoing active interval (since 1995), the trend in FSD and LSD has been towards earlier-occurring yearly season starts and later-occurring yearly season ends, respectively, leading to increased LOS, thus confirming the earlier results of Kossin that the length of the hurricane season has increased due to FSD and LSD occurring sooner and later, respectively, and that this behavior appears to be related to the warming SST in the North Atlantic basin.[42]

NTC activity in the North Atlantic basin is now higher than has ever been seen in the recorded past. Since 1995, the NTC is found to average about 15 ± 5 storms per yearly hurricane season, with about 3 ± 2 storms per season being short-lived storms (NSD < 2 days). Of the remaining 12 ± 4 storms per season having duration NSD ≥ 2 days, about 8 ± 3 have duration NSD ≥ 4 days and about 4 ± 2 storms per season have duration NSD ≥ 8 days. During the current ongoing active TC interval, about 40% of the time, the year's first and/or last storm of the season has been a short-lived event, a ratio found to be similar for the previous interval 1945–1994, as well.

Because of satellite imagery, more and more short-lived storms are now being identified today than were identified prior to the use of satellites. Also, many of these storms are now being identified farther out in the open Atlantic, especially eastward of longitude 50° W. During the present ongoing active interval (since 1995), of the 274 recorded TCs, 61 have been short-lived events (similar to that seen during the immediately preceding interval 1966–1994) and 10 have had their genesis location eastward of longitude 50° W. (about 3 times more than was observed in the immediately preceding interval 1966–1994).

On average, during the current ongoing active interval, the FSD of the yearly season has occurred about DOY $= 170 \pm 32$ (i.e., on or after May 18) and the LSD about DOY $= 319 \pm 24$ (i.e., on or before December 19). Hence, the LOS during the current ongoing active interval spans about 150 ± 43 days (i.e., about 1 month longer than that found for the previous interval 1945–1994).

Given the FSD for a hurricane season, on average, one can predict the LOS to within about 23 days (the ± 1 *se* prediction interval). For the interval 1945–2012, LOS (predicted) $= 323.2 - 1.069$

FSD (observed), having $r = -0.84$ and $se = 23$ days. Hence, the earlier the season begins, the longer the season is expected to last, while the later the season begins, the shorter the season is expected to last. For the current 2013 hurricane season, because the FSD = 156 (June 5), one anticipates its LOS to be about 156 ± 23 days (i.e., the ± 1 *se* prediction interval), inferring that the season should end about DOY = 312 ± 23, or about November 8 (± 23 days), with only a 16% chance of ending either after December 1 or before October 16.

The LOS for a hurricane season does not appear to be related to the occurrences of ENSO anomalies, whether based on January–June or July–December averages of the monthly ONI values. While true, an oddity is found regarding January–June ONI averages indicative of LN-like conditions. Namely, of the 14 years when LN-like conditions were apparent in the January–June ONI averages (during the interval 1950–2012), 10 of the years had LOS $\geq$ 131 days, averaging about 162 ± 20 days. The 4 years having January–June ONI averages suggestive of LN-like conditions, but having LOS < 131 days, averaged only about 87 ± 14 days in length. Based on the binomial formula,[2] one easily computes a probability of success $P = 6.1\%$ that the LOS would exceed 131 days when the January–June ONI monthly average is indicative of LN-like conditions (i.e., being due to chance alone).

As noted earlier, the current ongoing active interval appears to be directly related to changes in the physical conditions now manifested in the North Atlantic basin. Namely, the trend in surface-air temperature as measured at Armagh Observatory is now higher than has ever been recorded there (since 1844). On average, ASAT measures about 10 °C during the current ongoing active interval as compared to about 9.3 °C during the preceding quiet interval 1966–1994 and about 9.4 °C during the previous active interval 1945–1965. Similarly, the AMO, AMM(SST), and AMM(wind) are each reflective of an ongoing warm phase (with strong easterlies) that began in the mid-to-late 1990s, with these conditions expected to persist for at least another 10–20 years or longer. Likewise, the 10-yma trend in NAO is now reflective of predominantly negative values, with the largest annual negative value during the interval 1950–2012 occurring in 2011, and the GLOTI has been reflective of anomalous warming since the early 1970s, having a peak annual value (to date) of 0.66 °C in 2010. During the current ongoing active interval, GLOTI averages about 0.5 °C as compared to 0.1 °C during the preceding quiet interval 1966–1994 and –0.05 °C during the previous active interval 1945–1965.

Clearly, as the trend (based on 10-yma values) in temperature for the North Atlantic basin has warmed, the trend in FSD has been to sooner-occurring TCs, and the trend in LSD has been to later-occurring TCs, with the result being a longer LOS. For 2008, based on *fd* values, the trend (10-yma value) in FSD, LSD, and LOS is expected to measure, respectively, about DOY = 167 ± 2.6, DOY = 322.5 ± 1.8, and 156.4 ± 2.9 days, inferring the LOS for the 2013 hurricane season to be about 179 ± 58 days in length. Because the FSD for the 2013 hurricane season is now known to be DOY = 156 (June 5), one expects the LOS and LSD for the 2013 hurricane season to be about 156 ± 23 days and DOY = 312 ± 23 (November 8 ± 23 days), respectively, with LSD having only a 16% chance of occurring after DOY 335 (December 1) or before DOY = 289 (October 13). (Given FSD = 156 for the 2013 hurricane season, the 10-yma of FSD for 2008 is computed to be 167.)

Similarly, as the trend (i.e., 10-yma values) in temperature for the North Atlantic basin has warmed, the trend in NTC(all), NTC(SL), and NTC(LL) has increased. For 2008, based on *fd* values, the trend in NTC(all), NTC(SL), and NTC(LL) is expected to measure about 16.4 ± 0.3, 4 ± 0.12, and 12.4 ± 0.25, respectively. Hence, for the 2013 hurricane season, one expects NTC(all) = 12 ± 6, NTC(SL) = 5 ± 2, and NTC(LL) = 7 ± 5, regardless of whether ENSO is reflective of EN, LN, or neutral conditions. Based on Poisson probability distributions (not shown), one expects NTC(all) = 15 ± 5 ($P = 84.5\%$), NTC(SL) = 3 ± 2 ($P = 83.7\%$), and NTC(LL) = 11 ± 4 ($P = 80.7\%$). Expressed as lower limits, then, one expects NTC(all) ≥ 10 ($P = 93.6\%$), NTC(SL) ≥ 1 ($P = 96.7\%$), and NTC(LL) ≥ 7 ($P = 94.9\%$) for the 2013 North Atlantic basin hurricane season. (The official NOAA prediction for the 2013 hurricane season calls for 13 to 20 named storms; see <http://www.noaanews.noaa,gov/stories2013/20130523_hurricaneoutlook_atlantic.html>.)

REFERENCES

1. Wilson, R.M.: "Statistical Aspects of Tropical Cyclone Activity in the North Atlantic Basin, 1945–2010," NASA/TP–2012—217465, Marshall Space Flight Center, AL, 272 pp., August 2012.

2. Lapin, L.L.: *Statistics for Modern Business Decisions*, 2nd ed., Harcourt Brace and Jovanovich, Inc., New York, NY, 788 pp., 1978.

3. Davis, G.: "History of the NOAA satellite program," *J. Appl. Remote Sens.*, Vol. 1, No. 1, 18 pp., doi:10.1117/1.2642347, January 2007.

4. Davis, G.: "History of the NOAA satellite program—Updated June 2011," June 2011, <http://www.osd.noaa.gov/download/JRS012504-GD.pdf>.

5. Landsea, C.W.: "Counting Atlantic tropical cyclones back to 1900," *Eos*, *Transactions American Geophysical Union*, Vol. 88, No. 18, pp. 197–208, doi:10.1029/2007EO180001, June 2007.

6. Gray, W.M.: "Atlantic Seasonal Hurricane Frequency. Part I: El Niño and 30 mb Quasi-Biennial Oscillation influences," *Mon. Weather Rev.*, Vol. 112, No. 9, pp. 1649–1668, September 1984.

7. Kossin, J.P.: "Is the North Atlantic hurricane season getting longer?" *Geophys. Res. Lett.*, Vol. 35, No. 23, 3 pp., doi:10.1029/2008GL036012, December 2008.

8. Koenker, R.; and Hallock, K.F.: "Quantile Regression," *J. Econ. Perspect.*, Vol. 15, No. 4, pp. 143–156, 2001.

9. Chang, E.K.M.; and Guo, Y.: "Is the number of North Atlantic tropical cyclones significantly underestimated prior to the availability of satellite observations?" *Geophys. Res. Lett.*, Vol. 34, No. 14, 5 pp., doi:10.1029/2007GL030169, July 2007.

10. Goldenberg, S.B.; Landsea, C.W.; Mestas-Nuñez, A.M.; and Gray, W.M.: "The Recent Increase in Atlantic Hurricane Activity: Causes and Implications," *Science*, Vol. 293, No. 5529, pp. 474–479, doi:10.1126/science.1060040, July 2001.

11. Vecchi, G.A.; and Knutson, T.R.: "On Estimates of Historical North Atlantic Tropical Cyclone Activity," *J. Climate*, Vol. 21, pp. 3580–3600, doi:10.1175/2008JCLI2178.1, July 2008.

12. Vecchi, G.A.; and Knutson, T.R.: "Estimating Annual Numbers of Atlantic Hurricanes Missing from the HURDAT Database (1878–1965) Using Ship Track Density," *J. Climate*, Vol. 24, No. 6, doi:10.1175/2010JCLI3810.1, pp. 1736–1746, March 2011.

13. Landsea, C.W.; Vecchi, G.A.; Bengtsson, L.; and Knutson, T.R.: "Impact of Duration Thresholds on Atlantic Tropical Cyclone Counts," *J. Climate*, Vol. 23, No. 10, pp. 2508–2519, doi:10.1175/2009JCLI3034.1, May 2010.

14. Villarini, G.; Vecchi, G.A.; Knutson, T.R.; and Smith, J.A.: "Is the recorded increase in short-duration North Atlantic tropical storms spurious?" *J. Geophys. Res.*, Vol. 116, No. D10, 11 pp., doi:10.1029/2010JD015493, May 2011.

15. Villarini, G.; Vecchi, G.A.; Knutson, T.R.; et al.: "North Atlantic Tropical Storm Frequency Response to Anthropogenic Forcing: Projections and Sources of Uncertainty," *J. Climate*, Vol. 24, No. 13, pp. 3224–3238, doi:10.1175/2011JCLI3853.1, July 2011.

16. Wilson, R.M.: "Estimating the Length of the North Atlantic Basin Hurricane Season," NASA/TP–2012—217470, Marshall Space Flight Center, AL, 28 pp., October 2012.

17. Nyberg, J.; Malmgren, B.A.; Winter, A.; et al.: "Low Atlantic hurricane activity in the 1970s and 1980s compared to the past 270 years," *Nature*, Vol. 447, No. 7145, pp. 698–701, doi:10.1038/nature05895, June 2007.

18. Everitt, B.S.: *The Analysis of Contingency Tables*, John Wiley & Sons, New York, NY, 168 pp., 1977.

19. Santer, B.D.; Wigley, T.M.L.; Gleckler, P.J.; et al.: "Forced and unforced ocean temperature changes in Atlantic and Pacific tropical cyclogenesis regions," *Proc. Natl. Acad. Sci. USA*, Vol. 103, No. 38, pp. 13,905–13,910, doi:10.1073/pnas.0602861103, September 2006.

20. Holland, G.J.; and Webster, P.J.: "Heightened tropical cyclone activity in the North Atlantic: natural variability or climate trend?" *Phil. Trans. R. Soc. A.*, Vol. 365, No. 1860, pp. 2695–2716, doi:10.1098/rsta.2007.2083, November 2007.

21. Saunders, M.A.; and Lea, A.S.: "Large contribution of sea surface warming to recent increase in Atlantic hurricane activity," *Nature*, Vol. 451, pp. 557–560, doi:10.1038/nature06422, January 2008.

22. Kim, H.-M.; Webster, P.J.; and Curry, J.A.: "Impact of Shifting Patterns of Pacific Ocean Warming on North Atlantic Tropical Cyclones," *Science*, Vol. 325, No. 5936, pp. 77–80, doi:10.1126/science.1174062, July 2009.

23. Smith, T.M.; Reynolds, R.W.; Peterson, T.C.; and Lawrimore, J.: "Improvements to NOAA's Historical Merged Land-Ocean Surface Temperature Analysis (1880–2006)," *J. Climate*, Vol. 21, No. 10, pp. 2283–2296, doi:10.1175/2007JCLI2100.1, May 2008.

24. Butler, C.J.: "Maximum and minimum temperatures at Armagh Observatory, 1844–1992, and the length of the sunspot cycle," *Sol. Phys.*, Vol. 152, pp. 35–42, doi:10.1007/978-94-011-0950-5_6, 1994.

25. Butler, C.J.; and Johnston, D.J.: “The link between the solar dynamo and climate—the evidence from a long mean air temperature series from Northern Ireland,” *Irish Astron. J.*, Vol. 21, Nos. 3–4, pp. 251–254, 1994.

26. Butler, C.J.; and Johnston, D.J.: “A provisional long mean air temperature series for Armagh Observatory,” *J. Atmos. Sol.-Terr. Phys.*, Vol. 58, No. 15, pp. 1657–1672, doi:10.1016/0021-9169(95)00148-4, November 1996.

27. Coughlin, A.D.S.; and Butler, C.J.: “Is urban spread affecting the mean temperature at Armagh Observatory?” *Irish Astron. J.*, Vol. 25, No. 2, pp. 125–128, 1998.

28. Butler, C.J.; García Suárez, A.M.; Coughlin, A.D.S.; and Morrell, C.: “Air temperatures at Armagh Observatory, Northern Ireland, from 1796–2002,” *Int. J. Climatol.*, Vol. 25, No. 8, pp. 1055–1079, doi:10.1002/joc.1148, June 2005.

29. Butler, C.J.; García Suárez, A.M.; Pallé, E.: “Trends and cycles in long Irish meteorological series,” *Biol. Environ.*, Vol. 107B, No. 3, pp. 157–165, December 2007.

30. Wilson, R.M.; and Hathaway, D.H.: “Examination of the Armagh Observatory Annual Mean Temperature Record, 1844–2004,” NASA/TP—2006–214434, Marshall Space Flight Center, AL, 24 pp., July 2006.

31. Wilson, R.M.: “Evidence for solar-cycle forcing and secular variation in the Armagh Observatory temperature record (1844–1992),” *J. Geophys. Res.*, Vol. 103, No. D10, pp. 11,159–11,171, doi:10.1029/98JD00531, May 1998.

32. Schlesinger, M.E.; and Ramankutty, N.: “An oscillation in the global climate system of period 65–70 years,” *Nature*, Vol. 367, No. 6465, pp. 723–726, doi:10.1038/367723a0, February 1994.

33. Gray, W.M.; Sheaffer, J.D.; and Landsea, C.W.: “Climate trends associated with multi-decadal variability of Atlantic hurricane activity,” *Hurricanes*: *Climate and Socioeconomic Impacts*, H.F. Diaz and R.S. Pulwarty (eds.), Springer-Verlag, New York, NY, pp. 15–53, 1997.

34. Landsea, C.W.; Pielke Jr., R.A.; Mestas-Nuñez, A.M.; and Knaff, J.A.: “Atlantic Basin Hurricanes: Indices of Climatic Changes,” *Climate Change*, Vol. 42, No. 1, pp. 89–129, doi:10.1023/A:1005416332322, May 1999.

35. Dijkstra, H.A.; te Raa, L.; Schmeits, M.; and Gerrits, J.: “On the physics of the Atlantic Multidecadal Oscillation,” *Ocean Dynam.*, Vol. 56, No. 1, pp. 36–50, doi:10.1007/s10236-005-0043-0, May 2006.

36. Klotzbach, P.J.; and Gray, W.M.: “Multidecadal Variability in North Atlantic Tropical Cyclone Activity,” *J. Climate*, Vol. 21, No. 15, pp. 3929–3935, doi:10.1175/2008JCLI2162.1, August 2008.

37. Grossmann, I.; and Klotzbach, P.J.: "A review of North Atlantic modes of natural variability and their driving mechanisms," *J. Geophys. Res.*, Vol. 114, No. D24, 14 pp., doi:10.1029/2009JD012728, December 2009.

38. Ting, M.; Kushnir, Y.; Seager, R.; and Li, C.: "Forced and Internal Twentieth Century SST trends in the North Atlantic," *J. Climate*, Vol. 22, No. 6, pp. 1469–1481, doi:10.1175/2008JCLI2561.1, March 2009.

39. Knight, J.R.; Allan, R.J.; Folland, C.K.; et al.: "A signature of persistent natural thermohaline circulation cycles in observed climate," *Geophys. Res. Lett.*, Vol. 32, No. 20, 4 pp., doi:10.1029/2005GL024233, October 2005.

40. Chiang, J.C.H.; and Vimont, D.J.: "Analogous Pacific and Atlantic Meridional Modes of Tropical Atmosphere-Ocean Variability," *J. Climate*, Vol. 17, No. 21, pp. 4143–4158, doi:10.1175/JCLI4953.1, November 2004.

41. Vimont, D.J.; and Kossin, J.P.: "The Atlantic Meridional Mode and hurricane activity," *Geophys. Res. Lett.*, Vol. 34, No. 7, 5 pp., doi:10.1029/2007GL029683, April 2007.

42. Kossin, J.P.; and Vimont, D.J.: "A More General Framework for Understanding Atlantic Hurricane Variability and Trends," *B. Am. Meteorol. Soc.*, Vol. 88, No. 11, pp. 1767–1781, doi:10.1175/BAMS-88-11-1767, November 2007.

43. Chylek, P.; and Lensins, G.: "Multidecadal variability of Atlantic hurricane activity: 1851–2007," *J. Geophys. Res.*, Vol. 113, No. D22, 9 pp., doi:10.1029/2008JD010036, November 2008.

44. Dailey, P.S.; Zuba, G.; Ljung, G.; et al.: "On the Relationship between North Atlantic Sea Surface Temperatures and U.S. Hurricane Landfall Risk," *J. Appl. Meteorol. Clim.*, Vol. 48, No. 1, pp. 111–129, doi:10.1175/2008JAMC1871.1, January 2009.

45. Smirnov, D.; and Vimont, D.J.: "Variability of the Atlantic Meridional Mode during the Atlantic Hurricane Season," *J. Climate*, Vol. 24, No. 5, pp. 1409–1424, doi:10.1175/2010JCLI3549.1, March 2011.

46. Jolliffe, I.T.: *Principal Component Analysis*, 2nd ed., Springer-Verlag, New York, NY, 2002.

47. Hurrell, J.W.; Kushnir, Y.; and Visbeck, M.: "The North Atlantic Oscillation," *Science*, Vol. 291, No. 5504, pp. 603–605, doi:10.1126/science.1058761, January 2001.

48. Visbeck, M.H.; Hurrell, J.W.; Polvani, L.; and Cullen, H.M.: "The North Atlantic Oscillation: Past, present, and future," *Proc. Natl. Acad. Sci. USA*, Vol. 98, No. 23, pp. 12,876–12,877, doi:10.1073/pnas.231391598, November 2001.

49. Hurrell, J.W.; and Deser, C.: "North Atlantic climate variability: The role of the North Atlantic Oscillation," *J. Marine Syst.*, Vol. 78, No. 1, pp. 28–41, doi:10.1016/j.jmarsys.2008.11.026, August 2009.

50. Jones, P.D.: "Recent warming in global temperature series," *Geophys. Res. Lett.*, Vol. 21, No. 12, pp. 1149–1152, doi:10.1029/94GL01042, June 1994.

51. Hansen, J.R.; Sato, M.; Ruedy, R.; et al.: "Global temperature change," *P. Natl. Acad. Sci. USA*, Vol. 103, No. 39, pp. 14,288–14,293, doi:10.1073/pnas.0606291103, September 2006.

52. Hansen, J.R.; Ruedy, R.; Sato, M.; and Lo, K.: "Global surface temperature change," *Rev. Geophys.*, Vol. 48, 29 pp., doi:10.1029/2010RG000345, December 2010.

53. Smith, E.M.: "Summary report on v1 vs v3 GHCN," June 20, 2012, <http://chiefio.wordpress.com/2012/06/20/summary-report-on-v1-vs-v3-ghcn/>.

54. Wilson, R.M.: "Estimating the Mean Annual Surface Air Temperature at Armagh Observatory, Northern Ireland, and the Global Land-Ocean Index for Sunspot Cycle 24, the Current Ongoing Sunspot Cycle," NASA/TP–2013—217484, Marshall Space Flight Center, AL, 60 pp., July 2013.

55. Wilson, R.M.: "The Global Land-Ocean Index in Relation to Sunspot Number, the Atlantic Multidecadal Oscillation Index, the Mauna Loa Atmospheric Concentration of CO_2 and Anthropogenic Carbon Emissions," NASA/TP–2013—217485, Marshall Space Flight Center, AL, 32 pp., July 2013.

56. Gray, W.M.: "Global View of the Origin of Tropical Disturbances and Storms," *Mon. Weather Rev.*, Vol. 96, No. 10, pp. 669–700, October 1968.

57. Lighthill, J.; Holland, G.; Gray, W.; et al.: "Global Climate Change and Tropical Cyclones," *B. Am. Meteorol. Soc.*, Vol. 75, No. 11, pp. 2147–2157, November 1994.

58. Webster, P.J.; Holland, G.J.; Curry, J.A.; and Chang, H.R.: "Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment," *Science*, Vol. 309, No. 5742, pp. 1844–1846, doi:10.1126/science.1116448, September 2005.

59. Klotzbach, P.J.: "Trends in global tropical cyclone activity over the past twenty years (1986–2005)," *Geophys. Res. Lett.*, Vol. 33, No. 10, 4 pp., doi:10.1029/2006GL025881, May 2006.

60. Latif, M.; Keenlyside, N.; and Bader, J.: "Tropical sea surface temperature, vertical wind shear, and hurricane development," *Geophys. Res. Lett.*, Vol. 34, No. 1, 4 pp., doi:10.1029/2006GL027969, January 2007.

61. Landsea, C.W.; and Gray, W.M.: "The Strong Association between Western Sahelian Monsoon Rainfall and Intense Atlantic Hurricanes," *J. Climate*, Vol. 5, No. 5, pp. 435–453, May 1992.

62. Prospero, J.M.; and Lamb, P.J.: "African Droughts and Dust Transport to the Caribbean: Climate Change Implications," *Science*, Vol. 302, No. 5647, pp. 1024–1027, doi:10.1126/science.1089915, November 2003.

63. Mann, M.E.; and Emanuel, K.A.: “Atlantic hurricane trends linked to climate change,” *Eos*, *Transactions American Geophysical Union*, Vol. 87, No. 24, pp. 233–241, doi:10.1029/2006EO240001, June 2006.

64. Bell, G.D.; and Chelliah, M.: “Leading Tropical Modes Associated with Interannual and Multidecadal Fluctuations in North Atlantic Hurricane Activity,” *J. Climate*, Vol. 19, No. 4, pp. 590–612, doi:10.1175/JCLI3659.1, February 2006.

65. Evan, A.T.; Dunion, J.; Foley, J.A.; et al.: “New evidence for a relationship between Atlantic tropical cyclone activity and African dust outbreaks,” *Geophys. Res. Lett.*, Vol. 33, No. 19, 5 pp., doi:10.1029/2006GL026408, October 2006.

66. Evan, A.T.; Foltz, G.R.; Zhang, D.; and Vimont, D.J.: “Influence of African dust on ocean-atmosphere variability in the tropical Atlantic,” *Nat. Geosci.*, Vol. 4, pp. 762–765, doi:10.1038/ngeo1276, October 2011.

67. Lau, W.K.M.; and Kim, K.-M.: “How nature foiled the 2006 hurricane forecasts,” *Eos*, *Transactions American Geophysical Union*, Vol. 88, No. 9, pp. 105–107, doi:10.1029/2007EO090002, February 2007.

68. Klotzbach, P.J.: “The Influence of El Niño-Southern Oscillation on Caribbean Tropical Cyclone Activity,” *J. Climate*, Vol. 24, No. 3, pp. 721–731, doi:10.1175/2010JCLI3705.1, February 2011.

69. Evan, A.T.: “Atlantic hurricane activity following two major volcanic eruptions,” *J. Geophys. Res.*, Vol. 117, No. D6, 8 pp., doi:10.1029/2011JD016716, March 2012.

70. Lübbecke, J.F.: “Tropical Atlantic warm events,” *Nat. Geosci.*, Vol. 6, No. 1, pp. 22–23, doi:10.1038/ngeo1685, December 2013.

71. Lübbecke, J.F.; and McPhaden, M.J.: “On the Inconsistent Relationship Between Pacific and Atlantic Niños,” *J. Climate*, Vol. 25, No. 12, pp. 4294–4303, doi: 10.1175/JCLI-D-11-00553.1, June 2012.

72. Bender, M.A.; Knutson, T.R.; Tuleya, R.E.; et al.: “Modeled Impact of Anthropogenic Warming on the Frequency of Intense Atlantic Hurricanes,” *Science*, Vol. 327, No. 5964, pp. 454–458, doi:10.1126/science.1180568, January 2010.

73. Booth, B.B.B.; Dunstone, N.J.; Halloran, P.R.; et al.: “Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability,” *Nature*, Vol. 484, No. 7393, pp. 228–232, doi:10.1038/nature10946, April 2012.

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14. ABSTRACT
Since 1995, the mean number of observed tropical cyclones in the North Atlantic basin has been higher and the mean length of the yearly hurricane season has been longer than that found for the preceding years 1945–1994. For the current interval 1995–2012, the mean number of tropical cyclones forming in the North Atlantic basin is about 15, and the mean length of the yearly hurricane season is about 150 days. The increase in tropical cyclone activity and the lengthening of the yearly hurricane season are related to the warming now being experienced. For the 2013 hurricane season, because the first storm day occurred on June 5, 2013, its length of season is estimated to be about 156 ± 23 days, with a 94% probability that 10 or more storms will form.

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