NOTES AND CORRESPONDENCE

Multidecadal Variability in North Atlantic Tropical Cyclone Activity

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ABSTRACT

Recent increases in Atlantic basin tropical cyclone activity since 1995 and the associated destructive U.S. landfall events in 2004 and 2005 have generated considerable interest into why there has been such a sharp upturn. Natural variability, human-induced global warming, or a combination of both factors, have been suggested. Several previous studies have discussed observed multidecadal variability in the North Atlantic over 25–40-yr time scales. This study, using data from 1878 to the present, creates a metric based on far North Atlantic sea surface temperature anomalies and basinwide North Atlantic sea level pressure anomalies that shows remarkable agreement with observed multidecadal variability in both Atlantic basin tropical cyclone activity and in U.S. landfall frequency.

1. Introduction

There has been a considerable increase in Atlantic basin tropical cyclone (TC) activity since 1995 (Goldenberg et al. 2001; Klotzbach 2006). Also, the very active seasons of 2004 and 2005 produced record amounts of damage in the United States (Blake et al. 2007). This increase in both Atlantic basin activity as a whole as well as U.S. landfalling activity had been anticipated by as early as the late 1980s (Gray 1989, 1990). Considerable debate has ensued over the past few years as to the causes of this increase. Recent papers by Emanuel (2005) and Webster et al. (2005) have implied that there has been a large increase in global TC intensity since the 1970s, while others have questioned this interpretation of the data (Landsea et al. 2006) or have found little trend in global TC activity when evaluating subsets of the data (Klotzbach 2006; Kossin et al. 2007). Regardless of global trends, there is a general consensus that Atlantic basin TC activity has increased dramatically since 1995, similar to amounts of activity observed from the late 1940s through the mid-1960s (Goldenberg et al. 2001; Klotzbach and Gray 2006).

Using "best-track" data from the National Hurricane Center (NHC; Jarvinen et al. 1984), previous studies have documented multidecadal variability in TC activity in the Atlantic basin since the latter part of the nineteenth century (Gray 1990; Gray et al. 1997). Associated with this variability are fluctuations in basinwide (defined as the Atlantic Ocean north of the equator) North Atlantic sea surface temperatures (SSTs; Goldenberg et al. 2001) and Atlantic sea level pressure (SLP). This variability is most pronounced in SSTs for the far North Atlantic (north of 50°N) and in Atlantic SLP equatorward of 50°N. This paper augments previous research by documenting that through the combined use of far North Atlantic SSTs and a basinwide measure of North Atlantic SLP, multidecadal variability can be clearly documented since the latter part of the nineteenth century. Atlantic basin atmospheric–oceanic variability can be clearly linked to variability in both Atlantic basin TC activity as well as the number of U.S. landfalling TCs. A combination of SST and SLP appears to work better than either of these two parameters by themselves in defining these multidecadal periods. Section 2 discusses the datasets used, while section 3 shows the resulting multidecadal variability in North Atlantic SST and SLP that is observed. Section 4 compares this observed multidecadal variability with observed Atlantic basin TC activity. Section 5 compares observed multidecadal variability with observed

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U.S. landfalls, while section 6 summarizes and concludes.

2. Data

Information on basinwide TC activity for the North Atlantic as well as U.S. landfalling TCs was calculated from the best-track dataset produced by the NHC from 1878 to 2006 (Jarvinen et al. 1984). Storm data from 1878 to 1914 were tabulated using the updated best-track data that are based upon revisions from the Atlantic Oceanographic and Meteorological Laboratory/Hurricane Research Division (AOML/HRD) reanalysis project (Landsea et al. 2004). If a storm made landfall in two distinct locations, and the center of the circulation traveled over open ocean in between the two landfalls (e.g., Hurricane Katrina in 2005 in Florida and Louisiana), it was counted as two landfalls.

There are likely considerable underestimates in the early portion of the best-track dataset as discussed in Landsea (2007). There was no satellite data prior to the 1960s, and no aircraft reconnaissance was conducted in the Atlantic basin prior to 1944. Therefore, storms in the eastern Atlantic may have been underestimated or even missed completely prior to the middle part of the twentieth century. These underestimates are likely highest for the weaker storms, as short-lived tropical cyclones are more likely to have remained under or unobserved during the early part of the twentieth century. The U.S. landfalling tropical cyclone record should be quite good, especially since the start of the twentieth century, as the Gulf Coast and East Coast have been fairly densely populated since 1900.

SST data from 1878 to 2006 were calculated from the Kaplan SST dataset (Kaplan et al. 1998). The Kaplan SST dataset is in close agreement with both the second Hadley Centre SST (HadSST2) dataset (Rayner et al. 2006) and the International Comprehensive Ocean–Atmosphere Data Set (ICOADS; Worley et al. 2005). The Kaplan SST and HadSST2 datasets correlate at 0.93 over the period from 1904 to 2006 (where the HadSST2 dataset does not report any missing values), while the Kaplan SST and ICOADS datasets correlate at 0.94 over the period from 1946 to 2006 (where the ICOADS dataset does not report any missing values).

SLP data from 1878 to 2006 were obtained from the Hadley SLP2 dataset (Allan and Ansell 2006). With all datasets used in this study, it is acknowledged that individual-year data in the latter part of the nineteenth and earlier part of the twentieth century may be less reliable. However, since multidecadal variability is being evaluated in this study, any errors in year-to-year variability will likely be averaged out over the time periods being analyzed. In addition, there were fairly extensive ship observations in the late nineteenth century, even in the subtropical Atlantic. Most 2° by 2° grid boxes had at least 10 observations per month. Also, the Hadley SLP2 dataset and the ICOADS SLP dataset correlate at 0.96 over the period from 1886 to 2006 for the region under investigation (discussed in section 3).

3. Atlantic basin multidecadal variability observed in SST and SLP fields

Gray et al. (1997) and Goldenberg et al. (2001) have previously shown that there is strong multidecadal variability when evaluating SSTs in the far North Atlantic. Their study and others (e.g., Latif et al. 2006) have referred to this multidecadal variability in North Atlantic SSTs as fluctuations in the strength of the Atlantic multidecadal mode, the strength of the Atlantic multidecadal oscillation (AMO), or the strength of the thermohaline circulation (THC). For the remainder of this manuscript, we will refer to this multidecadal variability in the Atlantic basin as the AMO.

This study finds that an even stronger AMO signal is obtained when evaluating a combination of far North Atlantic SSTs from 50°–60°N and from 50°–10°W and North Atlantic SLP from 0°–50°N and from 70°–10°W. These two indices correlate with each other on an annually averaged basis at -0.50, indicating a correlation significant at the 99% level. However, this correlation level also implies that only 25% of the variance in the SST index is explained by the SLP index, and vice versa. These regions were selected since previous studies have used similar SST regions (e.g., Goldenberg et al. 2001), and marked fluctuations in SLP throughout the North Atlantic south of 50°N were observed to occur with these SST fluctuations. It should be noted that the combination of the SST and SLP indices does not alter the start and end dates of positive and negative AMO periods. SSTs rose and SLPs fell between 1925 and 1926 and 1994 and 1995, respectively. Conversely, lower SSTs and higher SLPs were observed to develop between 1899 and 1900 and 1969 and 1970, respectively. Including both SST and SLP helps strengthen the amplitude of the AMO index.

Our index of the AMO is calculated by taking annually averaged standardized anomalies of SST and SLP. The annually averaged SST index correlates with a hurricane season (June–November) SST index at 0.95, while an annually averaged SLP index correlates with a hurricane season (June–November) SLP index at 0.69.

The standardized anomalies of SLP and SST are then added together, and this combination is taken

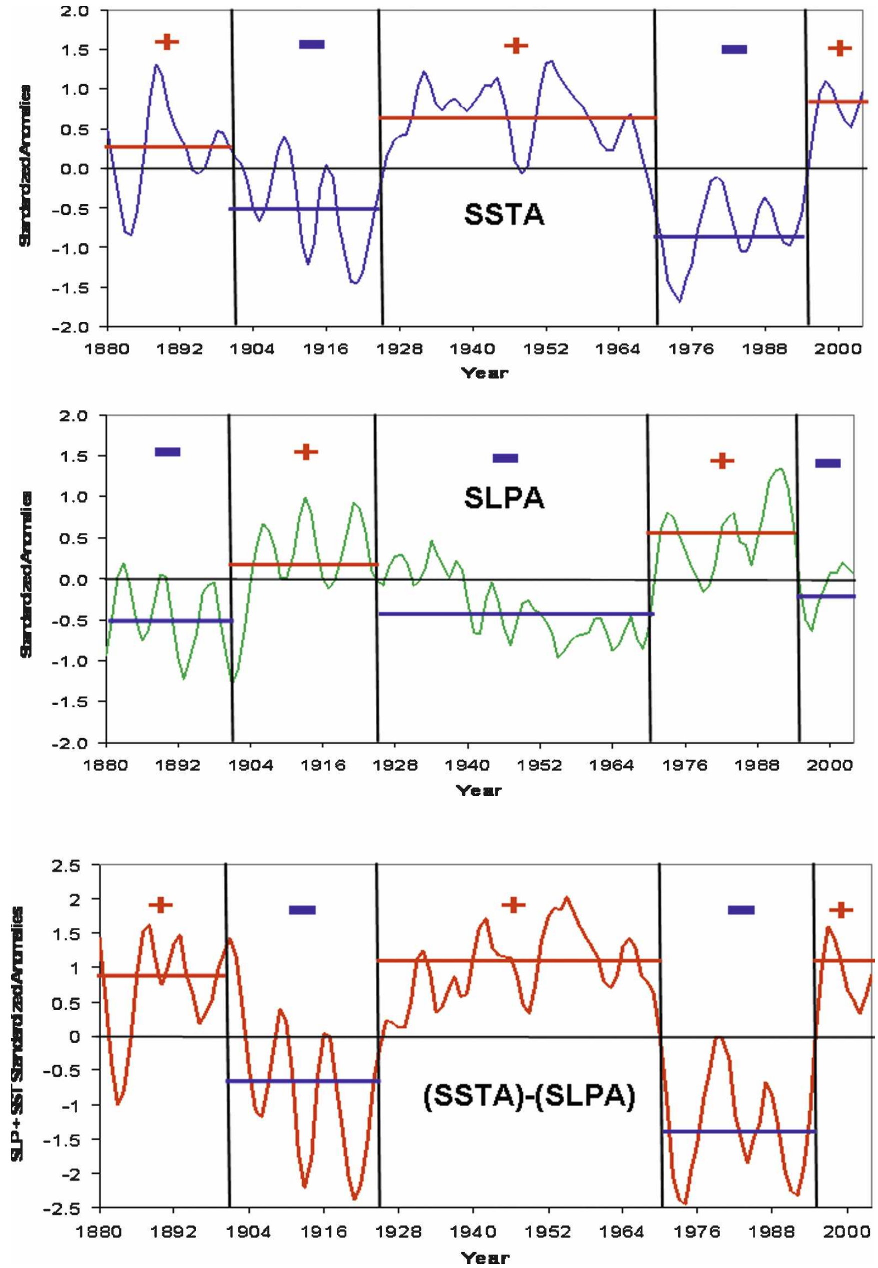

Fig. 1. Standardized values of (top) North Atlantic SSTA for the area from 50°–60°N and from 50°–10°W, (middle) North Atlantic SLPA for the area from 0°–50°N and from 70°–10°W, and (bottom) the combination of these two parameters (SSTA − SLPA) taken to be the strength of the AMO from 1880 to 2004. Horizontal lines indicate average values for the multidecadal period, while (+) and (−) symbols indicate that positive or negative values of the particular index predominated during that period. A 1–2–3–2–1 filter has been applied to the data.

as our index of the AMO. Figure 1 displays annually smoothed values of North Atlantic SST, SLP, and the combined AMO index from 1880 to 2004. A 1–2–3–2–1 filter has been applied to the data to smooth out some of the year-to-year variability, and therefore, the first two years and last two years of the data record are not displayed in the figure. In general, the AMO index is positive from 1880 to 1899, negative from 1900 to 1925, positive from 1926 to 1969, negative from 1970 to 1994, and positive from 1995 to 2004. This variability in length of AMO phases has been observed in previous studies (Goldenberg et al. 2001). Table 1 displays stan-

TABLE 1. Values of annually averaged standardized North Atlantic SSTA (50°–60°N, 50°–10°W), annually averaged standardized North Atlantic SLPA (0°–50°N, 70°–10°W) and the combined (SSTA − SLPA) annually averaged value (taken as the AMO index) over various multidecadal periods. Note the multidecadal periods when the AMO index was judged to be positive or to be negative. Actual annually averaged deviations in °C for SST and mb for SLP are provided in parentheses. The bottom two rows provide annually averaged data for the 77 yr during which the AMO was judged to be positive and the 51 yr when it was judged to be negative. For reference, the standard deviation of annual North Atlantic SSTA is 0.28°C, and the standard deviation of North Atlantic SLPA is 0.29 mb.

Period	SSTA (1)	SLPA (2)	AMO index (1) − (2)
1878–99	+0.3 (+0.08°C)	−0.5 (−0.15mb)	+0.8
1900–25	−0.5 (−0.18°C)	+0.2 (+0.08mb)	−0.7
1926–69	+0.7 (+0.16°C)	−0.4 (−0.07mb)	+1.1
1970–94	−0.8 (−0.27°C)	+0.6 (+0.19mb)	−1.4
1995–2006	+0.9 (+0.21°C)	−0.2 (−0.03mb)	+1.1
All positive	+0.6 (+0.14°C)	−0.4 (−0.09mb)	+1.0
All negative	−0.7 (−0.22°C)	+0.4 (+0.13mb)	−1.0

dardized values for both SST anomalies (SSTAs) and SLP anomalies (SLPAs). Actual deviations in degrees Celsius (for SSTA) and millibars (for SLPA) are given in parentheses as well as the combined SSTA minus the SLPA or AMO index for various multidecadal periods. When the AMO is in its positive phase, SSTAs in the far North Atlantic are usually above normal while SLPA values in the North Atlantic equatorward of 50°N are usually below normal. The opposite conditions occur when the AMO is in its negative phase. All SST and SLP means for each multidecadal period in either the positive or negative AMO phase are significant from the means in the opposite phase at the 95% level using a two-tailed Student's t test.

Active and inactive phases of the AMO have been shown to exert considerable influences in the tropical Atlantic. One of the primary influences is through a warming of tropical Atlantic SSTs (Goldenberg et al. 2001). Zhang (2007) documented a warming of tropical Atlantic SSTs and a cooling of tropical Atlantic subsurface ocean temperatures associated with a positive phase of the AMO. Zhang and Delworth (2006) have shown that a positive AMO phase leads to a northward shift of the intertropical convergence zone (ITCZ), both in observations and in the Geophysical Fluid Dynamics Laboratory (GFDL) fully coupled ocean–atmosphere general circulation model version 2.1 (CM2.1). Associated with this northward-shifted ITCZ are warmer SSTs, reduced vertical wind shear and lower sea level pressure. All of these three features lead to more active hurricane seasons.

Another study by Vimont and Kossin (2007) has shown similar results. They show that the AMO and the Atlantic meridional mode (AMM) are closely related on decadal time scales. Associated with a positive phase of the AMM are reduced vertical wind shear, increased sea surface temperatures, increased convergence, and increased low-level vorticity over the tropical Atlantic.

4. Atlantic basin multidecadal variability in TC activity

There is a considerable amount of interannual and multidecadal variability observed in Atlantic basin TC activity (Goldenberg et al. 2001; Klotzbach 2006). Previous studies (Gray 1990; Gray et al. 1997; Goldenberg et al. 2001) have shown that multidecadal variability is most significant for major (category 3–4–5) hurricanes, and results from this study confirm these previous studies.

Table 2 displays the average annual number of hurricanes (Hs), hurricane days (HDs), major hurricanes (MHs), and major hurricane days (MHDs) for the five

TABLE 2. Observed annually averaged Atlantic basin H, HD, MH, and MHD during the multidecadal periods of 1878–99, 1900–25, 1926–69, 1970–94, and 1995–2006. The bottom row provides the annually averaged ratio for the 77 positive AMO years and the 51 negative AMO years.

Period	AMO phase	H	HD	MH	MHD
1878–99	Positive	5.9	29.0	1.6	4.4
1900–25	Negative	3.6	15.4	1.2	3.2
1926–69	Positive	5.6	24.8	2.6	6.5
1970–94	Negative	5.0	16.0	1.5	2.5
1995–2006	Positive	8.2	35.3	3.9	10.1
Ratio (1878–99/1900–25)	Positive/negative	1.6	1.9	1.3	1.4
Ratio (1926–69/1900–25)	Positive/negative	1.6	1.6	2.2	2.0
Ratio (1926–69/1970–94)	Positive/negative	1.1	1.6	1.7	2.6
Ratio (1995–2006/1970–94)	Positive/negative	1.6	2.2	2.6	4.0
All positive/all negative	Positive/negative	1.4	1.8	1.8	2.2

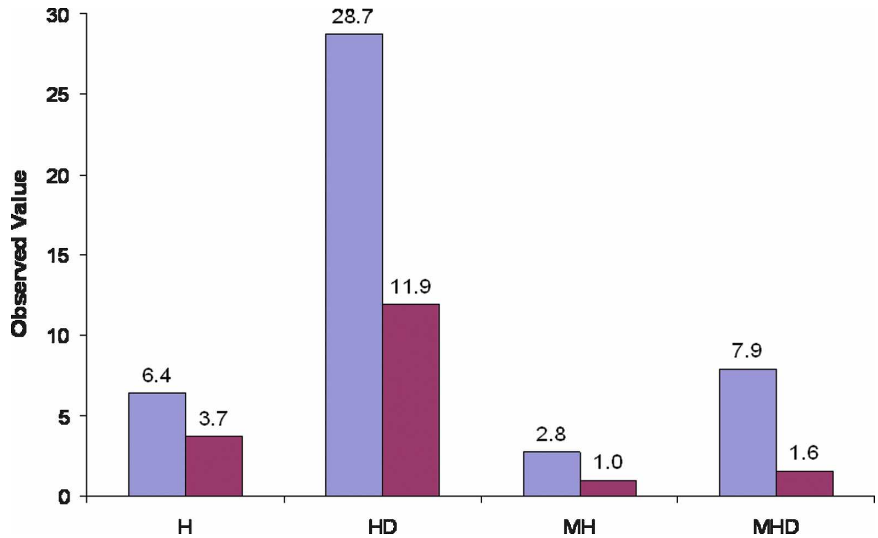

Fig. 2. Annually averaged Atlantic basin H, HD, MH, and MHD for the top 20 AMO years (blue bar) and the bottom 20 AMO years (red bar).

consecutive positive–negative multidecadal periods during 1878–99, 1900–25, 1926–69, 1970–94, and 1995–2006, respectively. Note the large amount of multidecadal variability between positive and negative AMO periods, especially for MH and MHD. The annual number of storms is higher during the 1878–99 period than during the 1900–25 period, even considering the likely larger underestimate of storms during the earlier period. The considerable ratio in tropical cyclone activity that is evident between the positive and negative AMO periods provides additional support for our AMO index definition.

This variability is even more striking when evaluating the 20 yr when the AMO was the most positive (in descending order from highest positive: 1955, 1942, 1878, 1888, 1893, 1952, 1966, 1958, 1997, 1902, 1909, 2005, 1932, 2006, 1899, 1960, 1945, 1881, 1937, and 1998) compared with the 20 yr when the AMO was the most negative (in ascending order from lowest negative: 1913, 1914, 1986, 1972, 1922, 1974, 1921, 1883, 1920, 1973, 1991, 1993, 1976, 1994, 1982, 1990, 1992, 1984, 1923, and 1983). Figure 2 displays the average number of H, HD, MH, and MHD for the top 20 and bottom 20 AMO years, respectively. Note the large differences between the two periods, with a ratio approaching 5:1 for MHD. It should be noted that the storms that form also last longer in the positive phase of the AMO. This is to be expected, since conditions that favor tropical cyclogenesis also tend to favor longer-lived TCs. Very similar ratios would be obtained for the 10 most positive AMO years since 1950 compared with the 10 most negative AMO years since 1950 (not shown).

5. Atlantic basin multidecadal variability in U.S. TC landfalls

There is a strong multidecadal signal in the number of U.S. TC landfalls, as there is with Atlantic basin activity as a whole. There were 50%–100% more H and MH that made landfall in active multidecadal periods compared with inactive multidecadal periods. For the top 20–bottom 20 AMO years, the ratio is even more striking, with a total of 19 MH making U.S. landfall in the top 20 yr compared with only 7 MH making landfall in the bottom 20 yr (nearly a 3 to 1 ratio). Similar ratios would be obtained if the 10 most positive AMO years since 1950 were compared with the 10 most negative AMO years since 1950.

It should be noted that there tends to be a weaker subtropical ridge when the AMO is positive. This may indicate that storm recurvature is more likely and that there may be fewer U.S. landfalls. However, pressures are lower across the entire Atlantic basin, and therefore, since pressure gradients across the basin do not change much, the possibilities of storm recurvature are not necessarily increased. In addition, storm motion is governed by day-to-day weather patterns, not by annual averages. Therefore, it does not necessarily follow that the lower SLPs observed in the active phase of the AMO will lead to more storm recurvature.

Multidecadal variability in landfalls is even stronger when considering storms making landfall along the Florida Peninsula and the U.S. East Coast. While it is acknowledged that there may be an underestimate of TCs making landfall in south Florida during the latter

TABLE 3. Observed annually averaged Florida Peninsula and U.S. East Coast named storm (NS), H, and MH landfalls during the multidecadal periods of 1878–99, 1900–25, 1926–69, 1970–94, and 1995–2006. The bottom row provides the annually averaged ratio for the 77 positive AMO years and the 51 negative AMO years.

Period	AMO phase	NS	H	MH
1878–99	Positive	2.2	1.1	0.3
1900–25	Negative	1.3	0.7	0.2
1926–69	Positive	2.0	1.3	0.6
1970–94	Negative	1.3	0.6	0.2
1995–2006	Positive	2.4	1.2	0.3
Ratio (1878–99/1900–25)	Positive/negative	1.7	1.6	1.5
Ratio (1926–69/1900–25)	Positive/negative	1.5	1.9	3.0
Ratio (1926–69/1970–94)	Positive/negative	1.5	2.2	3.0
Ratio (1995–2006/1970–94)	Positive/negative	1.8	2.0	1.5
All positive/all negative	Positive/negative	1.7	1.8	2.1

part of the nineteenth century due to small coastal populations during this period (e.g., Blake et al. 2007), there are still considerably more landfalls from 1878 to 1899 than from 1900 to 1925. The Florida Peninsula is defined from approximately 100 miles north of Tampa, Florida (approximately 29°N, 83°W) southward to the Florida Keys and then up the east coast of the state. MH landfalls occurred 3 times more frequently along the Florida Peninsula and U.S. East Coast during 1926–69 then during either 1900–25 or 1970–94 (Table 3). For the top 20–bottom 20 AMO years, the ratio is also quite striking, with a total of 11 MH making landfall in the top 20 yr compared with only 4 MH making landfall in the bottom 20 yr (nearly a 3 to 1 ratio).

This dramatic multidecadal landfall variability is even more pronounced when considering MH landfalls along the Florida Peninsula. During the 33-yr period from 1933 to 1965, 11 MH made landfall, while during the following 38-yr period (1966–2003), only one MH made landfall (Hurricane Andrew in 1992). Although the years above deviate somewhat from the positive–negative AMO years outlined in previous sections, this example was utilized to show the marked multidecadal variability that exists in landfalls along the Florida Peninsula based on the historical record.

6. Conclusions

This paper expounds upon previous research by highlighting Atlantic basin multidecadal variability in both large-scale atmospheric–oceanic fields as well as Atlantic basin TC activity. Using an index of basinwide SLP and far North Atlantic SSTs, positive and negative periods for the AMO can be clearly delineated. When the AMO is in its positive phase, TC activity in the Atlantic basin is heightened, especially for MH activity. Landfalling hurricanes along the U.S. coastline also become more frequent, with the most dramatic increases in a positive AMO phase being seen for the U.S. East Coast and the Florida Peninsula. Additional research involving potential physical drivers of the AMO should be conducted.

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