North Atlantic decadal variability and the formation of tropical storms and hurricanes

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[1] Both the annual number of Atlantic tropical storms forming south of 23.5°N and of Atlantic major hurricanes increased between the 1970's/1980's and 1995–2000. These increases are coincident with a multi-decadal warming in North Atlantic SST suggesting that the high activity of 1995–2000 may persist for the next ~10 to 40 years. However, during 1950–2000 strong decadal oscillations are superimposed on the multi-decadal changes in both SST and tropical storms (positive SST anomalies, increased storm activity). We appear to be entering a negative phase of the decadal SST signal implying that tropical storm, and most likely major hurricane, activity may be reduced in the next several years rather than remain at the very high 1995–2000 level when both signals were in their positive phase. Tropical storm activity during 2001 and 2002 is less than the expected only from the multi-decadal signal but for 2002 the main cause may be El Niño. *INDEX TERMS:* 4504 Oceanography: Physical: Air/sea interactions (0312); 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; 3399 Meteorology and Atmospheric Dynamics: General or miscellaneous. **Citation:** Molinari, R. L., and A. M. Mestas-Nuñez, North Atlantic decadal variability and the formation of tropical storms and hurricanes, *Geophys. Res. Lett.*, *30*(10), 1541, doi:10.1029/2002GL016462, 2003.

1. Introduction

[2] Multi-decadal oscillations have been identified in both the distribution of North Atlantic sea surface temperature, SST, [*Schlesinger and Ramankutty*, 1994; *Delworth and Mann*, 2000; *Mestas-Nuñez and Enfield*, 1999; *Enfield et al.*, 2001] and the formation of major hurricanes (winds > 50 m/s) in the basin [*Landsea et al.*, 1999, hereinafter LPMK; *Goldenberg et al*, 2002, hereinafter GLMG; *Elsner et al.*, 2000a]. In particular, there has been a 2.5-fold increase in major hurricane activity between 1971–1994 and 1995–2000. This increase in major hurricane activity was attributed to both the multi-decadal increase in Atlantic SST and a decrease in vertical wind-shear in GLMG and to variability in the North Atlantic Oscillation (NAO) in *Elsner et al.* [2000b]. Because of the long (multi-decadal) scales of these oscillations, it was argued in GLMG that the present high level of hurricane activity is likely to persist for an additional ~10 to 40 years.

[3] Other authors have also identified decadal signals in hurricane occurrences. For example, *Elsner et al.* [1999] separate total hurricane events into tropical only (TO) and baroclinically enhanced (BE), based on the formation mechanism of the storm. TO storms originate as tropical easterly waves and BE storms, typically as tropical depressions that are intensified by baroclinic disturbances in the subtropics [*Elsner et al.*, 1996]. *Elsner et al.* [1999] found the largest contribution to decadal signals in hurricane occurrences was due to BE storms.

[4] *Elsner et al.* [2000b] studied hurricanes reaching the U.S. coast. They found a correlation between the NAO and both hurricane formation areas and hurricane landfalls on decadal time scales. Specifically, hurricane activity was out of phase between low and high latitudes and the Gulf Coast (East Coast) experienced more major hurricane strikes during low (high) NAO index years.

[5] Finally, correlations have been found in both modeling [e.g., *Groetzner et al.*, 1998] and observational [e.g., *Tourre et al.*, 1999] studies between the NAO and the distribution of the SST in the North Atlantic. In both types of studies, the North Atlantic SST distribution associated with the NAO at decadal time scales is characterized by a tripole pattern, that is, a node of one sign SST anomalies centered in the subtropics is bounded north and south by nodes of opposite sign. The central and southern nodes connect between 20°N and 30°N, depending on the particular model or analyses used. The Main Development Region (MDR) for Atlantic tropical cyclones has been identified as the latitudinal strip between 10°N and 20°N that extends across the Atlantic basin, *Goldenberg and Shapiro* [1996]. The southern North Atlantic SST node is approximately coincident with the MDR.

[6] Herein, we build on the results of these earlier works to study further the possible decadal connections between tropical storm and hurricane activity, SST and the NAO. Specifically, we consider interplay between the decadal and multidecadal signals in these variables and how this interplay could alter the earlier suggestion of GLMG for sustained hurricane activity for several decades. Because of the phasing and amplitude of the decadal signals we will argue that there are breaks to be expected in this high level of activity, one presently active.

2. Data and Methods

[7] We use accountings of tropical storms formed south of 23.5°N and occurrences of major hurricanes from 1944 to 1996 presented in previous studies [LPMK, GLMG] as indicators of Atlantic tropical storm activity. We obtained similar information for the years 1997 through 2001 from the National Climatic Data Center (www.ncdc.noaa.gov).

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The latitude 23.5°N was chosen for two reasons. First, *Elsner et al.* [1996] show the distribution of TO and BE hurricanes between 1950–1993 and indicate that "A line of latitude near 20–23°N offers a good first guess at objectively dividing the two groups...". Second, as was described above, this latitude approximates the boundary between two of the nodes of the decadal SST pattern associated with the NAO. We do not differentiate between BE and TO storms as we assume that both are affected by SST, as will be discussed further.

[8] For SST, we updated the Atlantic multi-decadal mode of *Mestas-Nuñez and Enfield* [1999] that was used to argue for an extended period of increased hurricane activity [GLMG]. They used a rotated empirical orthogonal function (EOF) approach to estimate the empirical modes of SST variability. Their leading rotated mode in the Atlantic described multi-decadal SST oscillations with larger amplitudes over the northern North Atlantic. The update was done using global monthly SST anomaly data [*Kaplan et al.*, 1998] for 1870–2001. These SST anomalies are relative to a 1950–1991 climatology and are averaged onto a 5-degree latitude-longitude grid. This dataset was originally developed for the 1856–1991 period but updates are available online from the Lamont data library (http://ingrid.ldeo.columbia.edu).

[9] We also generated an average SST time series for the MDR from the *Kaplan et al.* [1998] dataset. Finally, to investigate associations with atmospheric variability we use an updated (1865–2000) version of the North Atlantic Oscillation (NAO) index [*Hurrell*, 1995]. The North Atlantic Oscillation (NAO) index is computed as the difference in normalized sea level pressure anomalies between weather stations in Portugal (i.e., Azores High) and Iceland (i.e., Iceland Low). A positive (negative) NAO is characterized by stronger (weaker) westerlies and northeast trade winds.

[10] For the time-series of the Atlantic multi-decadal mode, SST in the MDR and NAO, we started with a common record length (1870–2000). For each of these time-series, we computed a yearly-mean summer anomaly using the months representing the hurricane season, June–November. The temporal mean was removed from the resulting annual time-series, including the shorter hurricane record (1944–2001), and normalized by the record length standard deviation. Finally, we smoothed all time series with an eleven-year running mean filter to highlight multi-decadal oscillations and with a similar three-year filter to highlight decadal oscillations.

[11] In this paper, quantitative comparisons of the various time-series are made using conventional linear correlation analysis. To estimate the statistical significance of the correlations given the high degree of serial correlation in the low-pass filtered time-series we use the method of *Davis* [1976], which requires estimating an effective number of degrees of freedom (N*). The results are verified using the non-parametric test of *Ebisuzaki* [1997], based on phase-randomization of one of the time series in the frequency domain thus preserving its power spectrum. We generated 10,000 synthetic random time series with same spectrum of one of the original time-series and correlated them with the other original time-series. This distribution of correlations was compared to the original correlation and used to determine the significance levels.

3. Results

[12] A multi-decadal signal is evident in the 11 year filtered summer time-series of the NAO and of the two Atlantic temperature records (Figure 1, solid lines, upper three panels). The three records include a one-plus cycle of an approximately 60-year signal. Similar periodicity is seen in North Atlantic paleoclimatic proxy records since 1650 A.D. [*Delworth and Mann*, 2000]. Also shown in Figure 1 is the time series of major hurricane activity. Although the length of this record (1944–2001) is shorter than the one of the SST time series (1870–2000), during the overlapping time the shape of the four curves in Figure 1 are very similar. This phasing of major hurricane activity and Atlantic SST led to the suggestion of a period of persistent high level of Atlantic hurricane activity [GLMG].

[13] As described above, decadal signals in hurricane activity have been identified previously. Time series highlighting the decadal signals for 1950–2001 (the time period of overlapping records in Figure 1) are shown in Figure 2. They include yearly and summer (June through November) NAO indexes, the MDR SST for the same summer months, the number of tropical storms formed south of 23.5°N, and the number of major hurricanes. Both yearly and summer NAO indexes show similar features during 1950–2000. However the summertime NAO has larger variability at the beginning of the record and the annual NAO larger variability at the end.

[14] After 1965, all records exhibit decadal fluctuations superimposed on an increasing trend (i.e., the multi-decadal signal, Figure 1). In particular, the SST and tropical storm activity curves have large amplitude decadal signals with similar phase (Figure 2). Prior to 1993, the amplitude of the decadal signal in major hurricane activity is smaller than that of tropical storm activity. After 1995, these two records of activity have very large amplitudes because both their decadal and multi-decadal signals are in their positive phase.

[15] The correlations of SST with tropical storm activity (0.5) is higher than with major hurricane activity (0.43) but both are significant with greater than 90% confidence using the test of *Davis* [1976]. The respective values of the effective number of degrees of freedom (N*) for these correlations are 15 and 17 and their respective significance levels using the test of *Ebisuzaki* [1997] are 95% and 90%. The correlation between tropical storm and major hurricane activity is 0.71 (N* = 12) and is significant with greater than 95% (99%) confidence using the test of *Davis* [1976] (*Ebisuzaki* [1997]).

[16] The magnitude of the decadal changes in tropical storms can be estimated by considering that there are three cycles in storm formation during the past 25 years (Figure 2). The annual numbers of storms averaged over three years during the troughs of these events are 2.33 (1976), 1.67 (1983), and 2.33 (1992). The numbers of storms during the following peak formation periods are 6.00 (1980), 8.00 (1989) and 10.00 (1995). Thus, the respective trough-to-peak increases for these three cycles are 3.7, 6.3, and 7.7.

[17] Historically, most studies of air-sea coupling in the North Atlantic concentrated on the wintertime NAO index because of the larger climatic variability during this season [*Deser and Blackmon*, 1993; *Kushnir*, 1994; *Tourre et al.*, 1999]. During the winter, the NAO is negatively correlated with SST in the MDR on decadal time scales. The negative

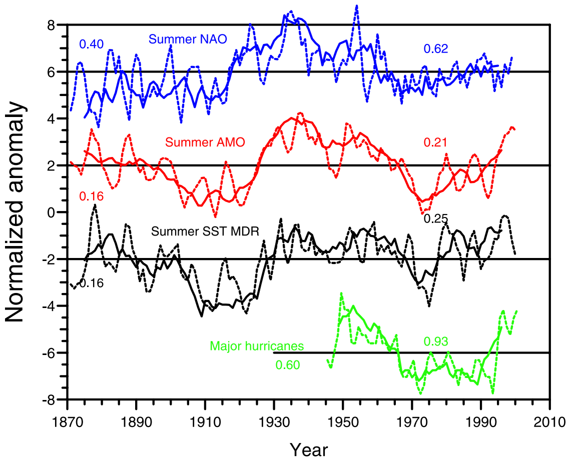

Figure 1. Normalized time series of the summer North Atlantic Oscillation (NAO) index, displaced by +6 units; the summer Atlantic multi-decadal mode, (+2 units); summer SST anomalies in the region bounded by 10–20°N and 17.5–87.5°W, (−2 units); and annual number of Atlantic major hurricanes, (−6 units). Time series smoothed with a 3(11) year running mean filter are dashed (solid). The normalization factors are the standard deviations over the length of each time series and are given to the left (right) of the figure for the dashed (solid) curves. Standard deviation units are non-dimensional for the NAO index, °C for both the Atlantic multi-decadal mode and SST, and annual number for major hurricanes.

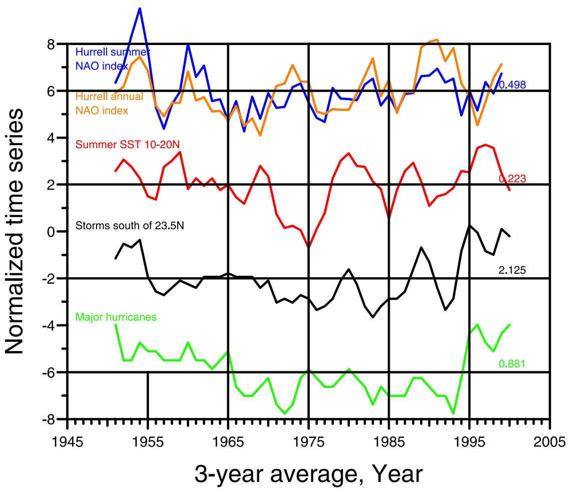

Figure 2. Normalized time series for 1950–2001 of the annual and summertime North Atlantic Oscillation indexes, displaced by +6 units; SST from the region bounded by 10–20°N and 17.5–87.5°W, (+2 units); Atlantic storms formed south of 23.5°N, (−2 units); and Atlantic major hurricanes (−6 units). The time series have been smoothed with a 3-year running mean filter and normalized by the record-length standard deviation (given on the figure). Standard deviation units are non-dimensional for the NAO index, °C for SST, and annual number for tropical storms and major hurricanes. The 1950–2001 average numbers of storms and major hurricanes removed from the two respective bottom time series are 5.23 and 2.18.

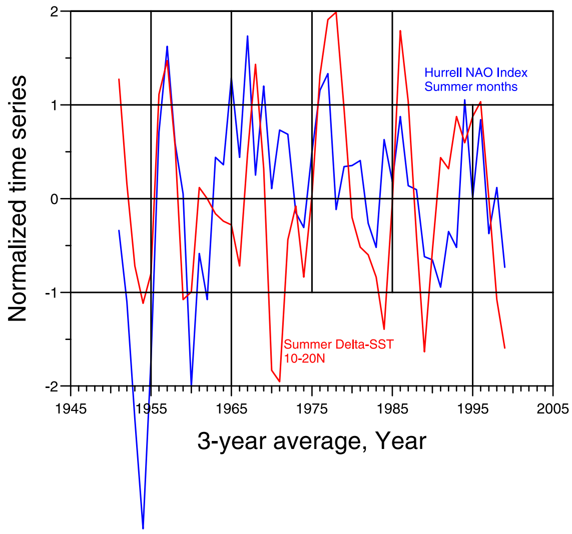

Figure 3. Three-year filtered time series of the negative of the summertime NAO index shown in Figure 2 (blue) and the tendency of SST anomalies computed from the normalized SST time series in Figure 2 using centered differences (red). The correlation coefficient of these time series (0.39) is significant with greater than 90% confidence accounting for serial correlations.

phase of the NAO reflects above-normal pressure across the high latitudes of the North Atlantic and below-normal pressure over the central North Atlantic. During the negative (positive) phase of the NAO, the higher (lower) SST in the MDR reflects the reductions (increases) of the northeast trade winds and the associated surface heat fluxes from the ocean to the atmosphere [*Cayan*, 1992].

[18] The summertime NAO and MDR SST time series in Figure 2 are not significantly correlated at zero lag. However, there is significant correlation ($\approx$ 0.4, N* $\approx$ 20) with greater than $\approx$90% confidence when SST leads the NAO by 1–3 years using both *Davis* [1976] and *Ebisuzaki* [1997] significance tests. This lagged correlation can be explained by considering the tendency (change over time) of SST anomalies rather than the SST anomaly itself [*Cayan*, 1992]. The SST tendency is proportional to the negative of the anomalies of the surface heat flux (i.e. positive sea to air fluxes, negative SST tendency). The MDR SST tendency is compared in Figure 3 to the NAO index, which can be taken as a first approximation of the surface wind speed. The correlation of these time series is about 0.4 (N* = 23) and is significant with greater than 90% confidence using both significance tests. Considering that the surface wind speed is not the only factor controlling surface heat fluxes [*Cayan*, 1992], the comparison is favorable.

4. Discussion

[19] Many other studies have identified similar empirical relationships between SST and tropical storm activity. For example, *Shapiro and Goldenberg* [1998], in a data study, find that vertical shear plays the largest role in Atlantic hurricane development, but that their "results support the conclusion that warmer SST's directly enhance development". Among other empirical studies that show a relationship between SST and tropical storm activity are *DeMaria*

and Kaplan [1994], *Saunders and Harris* [1997] and *Kimberlain and Elsner* [1998]. There have also been theoretical and numerical modeling studies identifying SST as a factor in hurricane activity [e.g., *Emanuel*, 1986, 1999; *Schade and Emanuel*, 1999].

[20] The superposition of the decadal signal on the multi-decadal variability of SST and tropical hurricane activity modifies the proposal of *GLMG*, 2002 for an extended period of very high North Atlantic hurricane activity (~10 to 40 years). Their statement was based mostly on the multi-decadal signals of SST and major hurricane activity. The analysis of this paper shows that the phase transition in storm activity variability is not smooth, but it is perturbed by significant decadal variability (i.e., of similar magnitude as the multi-decadal signals, Figure 1). As shown in Figure 2, the decadal oceanic (SST) and atmospheric (NAO) time series appear to be entering respective periods of negative and positive phase, which is typically associated with lower storm activity.

[21] Tropical storm activity during 2001 and the recently completed 2002 storm seasons do show a reduction in occurrences from the highs of the late 1990's. In 2001, 7 tropical storms were formed south of 23.5°N compared to an average of 9.5 storms from 1995 to 2000. However, the number of major hurricanes formed during 2001, 4, is similar to the 1995 to 2000 average, 3.8.

[22] The total number of Atlantic tropical storms during 2002, 12, was close to the long time average of 10. However, only 3 of the named tropical storms originated south of 23.5°N. Only 2 major hurricanes formed during 2002, less than the GLMG projection. However, 2002 was an El Niño year in the Pacific, an event typically characterized by reduced hurricane activity in the Atlantic. Thus, the reduction of storms formed south of 23.5°N during this year can't be attributed to only the decadal signals previously described.

[23] The potential interaction between El Niño and decadal signals in storm formation highlights the difficulty in using any one of the variables as the sole predictor for hurricane activity. The problem is further complicated by the many other factors that have been implicated in storm formation, including vertical shear, the Quasi-Biennial Oscillation, Sahelian rainfall, the Madden-Julian Oscillation, etc. Until the relative importance of these all factors on tropical activity are determined the utility of these findings on decadal signals must be considered suggestive and worthy of additional study rather than as offering a verified predictive tool.

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