Atlantic hurricanes and natural variability in 2005

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[1] The 2005 North Atlantic hurricane season (1 June to 30 November) was the most active on record by several measures, surpassing the very active season of 2004 and causing an unprecedented level of damage. Sea surface temperatures (SSTs) in the tropical North Atlantic (TNA) region critical for hurricanes (10° to 20°N) were at record high levels in the extended summer (June to October) of 2005 at 0.9°C above the 1901–70 normal and were a major reason for the record hurricane season. Changes in TNA SSTs are associated with a pattern of natural variation known as the Atlantic Multi-decadal Oscillation (AMO). However, previous AMO indices are conflated with linear trends and a revised AMO index accounts for between 0 and 0.1°C of the 2005 SST anomaly. About 0.45°C of the SST anomaly is common to global SST and is thus linked to global warming and, based on regression, about 0.2°C stemmed from after-effects of the 2004–05 El Niño.
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1. Introduction

[2] The record 2005 North Atlantic hurricane season featured the largest number of named storms (28) (sustained winds over 17 m s^{-1}) and is the only time names have ventured into the Greek alphabet. In fact the season extended well beyond the official dates into December by Epsilon and Zeta (Dec. 30). It had the largest number of hurricanes (15) (sustained winds > 33 m s^{-1}) recorded (note Cindy was belatedly upgraded to hurricane status), and is the only time there has been four category 5 storms (maximum sustained winds > 67 m s^{-1}). These included the most intense Atlantic storm on record (Wilma, recorded surface pressure in the eye 882 hPa), the most intense storm in the Gulf of Mexico (Rita, 897 hPa), and the most damaging storm on record (Katrina), with over 1000 people killed and 1 million homeless in the United States. (See http://www.ncdc.noaa.gov/oa/climate/research/2005/hurricanes05.html for details on these storms. Some estimates place total losses as high as $200B (http://www.whartonsp.com/articles/article.asp?p=416413&rl=1) and insured losses up to $60B http://www.rms.com/Publications/KatrinaReport_LessonsandImplications.pdf.) Following on the heels of the very active 2004 hurricane season [*Trenberth*, 2005], such statistics raise legitimate questions about whether global warming is playing a role in changing such storms or whether natural variability associated with the AMO dominates. Indeed, claims have been made that the AMO is the main source of the recent increase in hurricane activity since 1995 [*Mayfield*, 2005] and that global warming has played little or no role [e.g., *Pielke et al.*, 2005; *Landsea*, 2005]. In this paper, we propose a new AMO index to overcome influences from global effects that contaminate previous indices that have been used (section 2). This also facilitates a partitioning of the record 2005 SST anomaly into components linked to different physical processes using statistical relationships (section 3).

[3] Theory [*Trenberth*, 2005; *Emanuel*, 2005a, 2005b] and modeling [*Knutson and Tuleya*, 2004] suggest that the intensity, not the frequency, of tropical storms should increase with warming, higher SSTs and associated increases in water vapor in the atmosphere [*Trenberth et al.*, 2005]. The large natural variability on interannual and decadal time scales, and variations from one ocean basin to another, however, mean that small changes are difficult to detect but can be brought out by appropriate diagnostics. Large and significant increases in intensity and duration of tropical storms are evident since the mid-1970s [*Emanuel*, 2005a, 2005b], as seen through a power dissipation index (PDI) that is proportional to the cube of the wind speed in the storms. Moreover the PDI is highly correlated with SST. A more conventional analysis [*Webster et al.*, 2005] found a significant increase in category 4 and 5 storms worldwide since 1970, even as total number remains about the same. Both analyses are dependent on the quality of the historical tropical storm record, which is most reliable only after about 1970 owing to the advent of satellite observations, and the reliability of the PDI record even during the satellite era has been questioned [*Landsea*, 2005; *Emanuel*, 2005b].

[4] The North Atlantic hurricane record begins in 1851 and is the longest among global records [*Landsea et al.*, 2004]. Measurements from reconnaissance aircraft began in 1944 but values are considered reliable only after about 1950 [*Landsea et al.*, 2004; *Emanuel*, 2005a, 2005b]. Methods of estimating wind speed from aircraft have evolved over time and, unfortunately, changes were not always well documented. The North Atlantic record shows a fairly active period from the 1930s to the 1960s followed by a less active period in the 1970s and 1980s, similar to the fluctuations of the AMO [*Goldenberg et al.*, 2001].

2. Characterizing the AMO

[5] The AMO is identified as a coherent pattern of variability in basin-wide North Atlantic SSTs with a period of about 60–80 years [*Schlesinger and Ramankutty*, 1994]. It has been identified with changes in North American rainfall and river flow [*Enfield et al.*, 2001; *Rogers and Coleman*, 2003; *McCabe et al.*, 2004; *Sutton and Hodson*, 2005], and Sahel drought [*Rowell et al.*, 1995]. The AMO also affects the number of hurricanes and major hurricanes forming from tropical storms first named in the tropical

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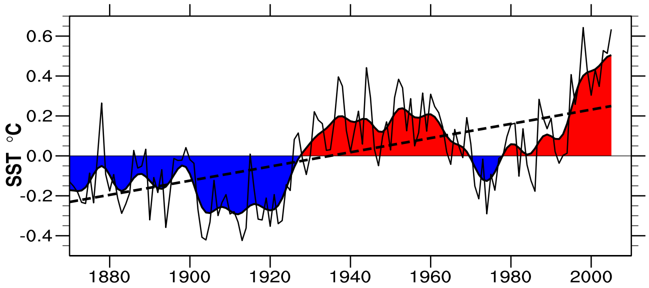

Figure 1. Annual SST anomalies averaged over the North Atlantic (0 to 60°N, 0 to 80°W) for 1870–2005, relative to 1901 to 1970 (°C). The heavy line with fill depicts the AMO and is from a low-pass symmetric filter with 13 total weights and a half-power point at 16 year periods, with the end points reflected. The linear trend fit is also shown (dashed).

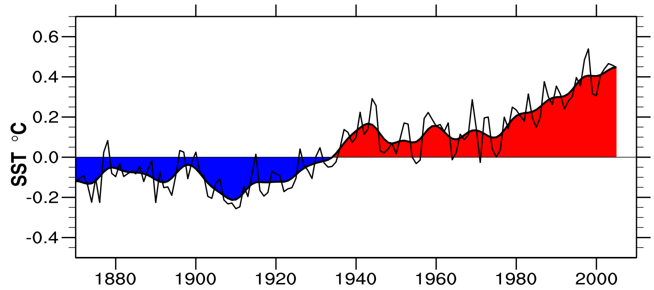

Figure 2. Annual SST anomalies averaged over the global oceans 60°N to 60°S for 1870–2005, relative to 1901 to 1970 (°C). The heavy line with fill is the low-pass filter.

Atlantic and Caribbean Sea [*Goldenberg et al.*, 2001; *Molinari and Mestas-Nuñez*, 2003].

[6] Indices of the AMO have traditionally been based on the average SST anomaly for the North Atlantic north of the equator [*Enfield et al.*, 2001] (Figure 1), where the SST (from HADISST [*Rayner et al.*, 2003]) northern limit was kept at 60°N to avoid problems with sea ice changes. We use a 70-year (1901–70) base period as it covers roughly one full cycle of the AMO. The AMO is given by smoothing from a 10-year running mean [*Goldenberg et al.*, 2001; *Enfield et al.*, 2001] or similar low-pass filter (Figure 1). In most cases the variability has been highlighted by detrending the data [*Enfield et al.*, 2001; *McCabe et al.*, 2004; *Sutton and Hodson*, 2005; *Knight et al.*, 2005], and a linear trend is provided in Figure 1 for reference. The index reveals a warm period from about 1930 to 1970, while cooler regimes occurred from 1902 to 1925 and 1970 to 1994. Since 1995 the AMO index has been positive and increasing. The instrumental record covers less than 2 cycles but paleoclimate data suggest that the AMO also occurred in previous centuries [*Delworth and Mann*, 2000; *Gray et al.*, 2004]. Suggestions that the mechanism is linked to fluctuations in strength of the Thermohaline Circulation (THC) accompanied by changes in northward ocean heat transport in the North Atlantic are borne out in model simulations [*Delworth and Mann*, 2000; *Collins and Sinha*, 2003; *Knight et al.*, 2005], but do not agree with apparent observed weakening [*Bryden et al.*, 2005].

[7] The main difficulty with the traditional AMO index is that it is not possible to discriminate between variations arising from the THC and other phenomena with North Atlantic origins, and global anthropogenic changes. In particular, the recent warming of North Atlantic SSTs is known to be part of a global (taken here to be 60°N to 60°S) mean SST increase (Figure 2). While detrending [*Knight et al.*, 2005] the AMO series helps remove part of this signal, the SST changes are not simply linear and a linear trend has no physical meaning. To deal with purely Atlantic variability, it is highly desirable to remove the larger-scale global signal that is associated with global processes, and is thus related to global warming in recent decades [*Meehl et al.*, 2004; *Barnett et al.*, 2005; *Hansen et al.*, 2005]. Accordingly, the global mean SST has been subtracted to derive a revised AMO index (Figure 3).

[8] The magnitude of the AMO signal (Figure 3) is modest: the range is less than 0.4°C. The increase since 1995 in the traditional AMO index (Figure 1) is strongly muted in Figure 3, such that values are barely above the long-term mean. The revised index is about 0.35°C lower than the original after 2000, highlighting the fact that most of the recent warming is global. Relative to the global mean SSTs, the revised AMO index does, however, indicate that North Atlantic SSTs have recently been about 0.3°C warmer than during 1970–1990, emphasizing the role of the AMO in suppressing tropical storm activity then. Previous claims [e.g., *Enfield et al.*, 2001; *Knight et al.*, 2005] of a warm period in the AMO from 1870 to 1900 are revealed as an artifact of the detrending used.

[9] Unlike the original AMO index (Figure 1), which has relationships that are global in scale [e.g., *Enfield et al.*, 2001], the revised AMO index mainly features significant surface air temperatures (based on the work of *Jones and Moberg* [2003]) and SSTs in the North Atlantic (Figure 4), as expected, accompanied by low sea level pressures (correlations < -0.5) that extend eastward across southern Europe to the Indian Ocean (not shown). Because of the large scale, it is likely that the contrast in SST values between the North and South Atlantic is also significant, consistent with the idea that the THC may be a key process in the AMO [*Knight et al.*, 2005].

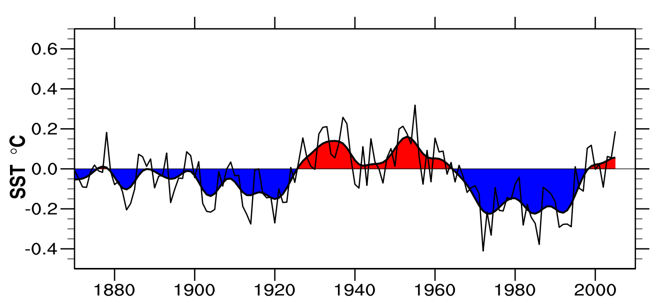

Figure 3. Annual SST anomalies averaged over the North Atlantic (0 to 60°N, 0 to 80°W) for 1870–2005, relative to 1901 to 1970 (°C) but with the global mean SST (Figure 2) removed. The heavy line with fill from the low-pass filter depicts the revised AMO.

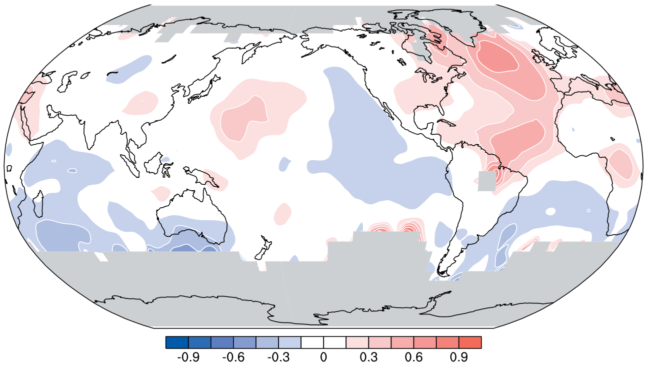

Figure 4. Correlation of the revised AMO index with global surface air temperatures for 1900 to 2004 based on annual values. In the TNA region, 5% significance levels are 0.26 (allowing for autocorrelation of the data); only values in the North Atlantic can be considered significant.

3. Tropical North Atlantic in 2005

[10] Many factors are known to be important for hurricanes [*Trenberth*, 2005]. In particular, the atmospheric circulation was extraordinarily favorable during the 2005 Atlantic hurricane season for disturbances to develop into tropical storms, although global-scale tropical atmospheric patterns are not independent of the SSTs. The detailed nature of the atmospheric circulation is beyond the scope of the current study: here the focus is only on the unusually high SSTs that are strongly correlated with the observed increases in intensity and hurricane activity [*Emanuel*, 2005a, 2005b; *Webster et al.*, 2005].

[11] In the TNA, the critical region for hurricanes, the SST anomaly for the extended summer season pertinent to hurricanes, June to October 2005, was 0.92°C, the highest on record (1998 at 0.71°C was second) (Figure 5). For the North Atlantic basin (Figure 1) the 2005 SST anomaly was 0.65°C (January to October), matching the highest (1998) on record. In the following, we briefly explore the extent to which the TNA June–October SST anomaly is related to other factors using regression. As for the AMO, the smoothed global mean SST T_G is removed. Essentially we fit a multiple regression model to the SST anomalies for the tropical Atlantic T_{TNA} to the smoothed AMO plus ENSO

$$T_{TNA} - \overline{T_G} = r_1 \overline{T_{AMO}} + [r_2 T_{N34} + r_3 T_{TNI}] + \varepsilon$$

where the overbar is the low frequency (decadal time filter or 5 year mean) value, r_i i = 1, 2, 3 are the 3 regression coefficients for SSTs for the AMO, Niño 3.4 region and the Trans Niño Index (TNI) [*Trenberth and Stepaniak*, 2001], as given below, and the error ε contains a low frequency and transient component. The two terms in square brackets are those related to El Niño and involve lags.

[12] In the tropics (20°N to 20°S) the linear SST warming trend from 1970 to 2004 is 0.50 ± 0.25°C. The relatively high 95% uncertainty in this trend value reflects strong interannual variability associated mainly with the El Niño-Southern Oscillation (ENSO) phenomenon. For 1996 to 2005 the ten-year mean SST anomaly for the globe (60°N to 60°S) using values through October 2005 was 0.42°C (Figure 2) and in the TNA for June to October it was 0.44°C, also the highest on record. To approximately assign a global value to the 2005 season, we use the global mean SST 5-year anomaly for 2001 to 2005 of 0.45°C. These values depend on the base period (1901–70) and relative to 1870 to 1920 the total global SST warming is an additional 0.15°C, for a total of 0.60°C (Figure 2). For the AMO, the 5-year AMO anomaly for 2001 to 2005 of 0.04°C is representative of the multi-decadal oscillation (Figure 3) and this converts to 0.03°C for the TNA SST in summer, which is considered the contribution of the AMO to the 2005 anomaly.

[13] Another factor was the 2004–05 El Niño. El Niño is characterized by two key independent indices, given by the Niño 3.4 region (170°W–120°W, 5°N–5°S) SST anomalies, and the TNI that is based on differences in normalized SST anomalies across the tropical Pacific between Niño 4 (160°E to 150°W) and Niño 1 + 2 (80–90°W) regions [*Trenberth and Stepaniak*, 2001]. The Niño 3.4 anomaly peaked at 0.78°C in late 2004 (relative to 1901–70). Niño 3.4 SST anomalies lead those in TNA by 8 months [*Trenberth and Stepaniak*, 2001]. For SSTs in the entire TNA region, the post-1977 monthly regression coefficient with Niño 3.4 SST is 0.14 to 0.17°C per degree C with 4 to 8 months lead. An important factor may have been that this El Niño was unusual because below-normal SSTs remained in the eastern Pacific, leading to a very low TNI. The TNI values were below −2.0 standard deviations from May 2004 to May 2005; see http://www.cdc.noaa.gov/Pressure/Timeseries/Data/tni.long.data. Further, TNI is significantly negatively correlated with SST anomalies in the TNA region at 12 to 24 months lead with a regression coefficient of −0.06 to −0.07. Together these predictors hindcast TNA SST anomalies >0.2°C with 4 to 8 months lead for June 2005.

[14] Although the northern winter 2004–05 featured only a weak El Niño in the tropical Pacific, with SST anomalies in the central tropical Pacific of about 0.8°C, it was enough to completely alter the atmospheric circulation and storm tracks across the United States, for instance alleviating the drought in the Southwest. Following such an El Niño, SSTs rise in the tropical Atlantic 4 to 8 months later [*Trenberth et al.*, 2002; *Chikamoto and Tanimoto*, 2005] by about 0.2°C, as given above, in association with changes in atmospheric

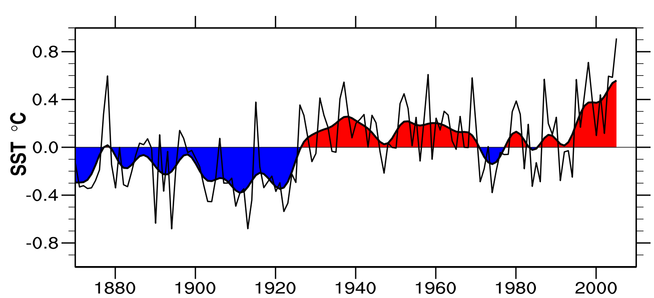

Figure 5. SST anomalies (°C) relative to 1901–70 for 10–20°N 0–80°W in the tropical North Atlantic for June to October seasonal averages plus the low-pass filtered values (shaded).

circulation and, in particular, in radiation and winds over the tropical North Atlantic [*Trenberth et al.*, 2002]. Reduced latent heat (evaporative) fluxes in the TNA from January through July the year following an El Niño arise from reduced winds and reduced air-sea specific humidity differences [*Chikamoto and Tanimoto*, 2005].

[15] Accordingly, assuming linearity (which is an excellent assumption), we can approximately apportion the record summer SST anomaly relative to 1901–70 in the TNA of 0.92°C as 0.45°C for global SST, <0.1°C for the smoothed AMO, and 0.2°C for ENSO. The remaining ~0.2°C is the order of the change associated with phenomena that vary from year to year, including the departure of the annual AMO value from the smoothed decadal value.

[16] Over the post-1970s period, the global SST increase is attributed to human activities (global warming) [*Meehl et al.*, 2004; *Barnett et al.*, 2005; *Hansen et al.*, 2005] and only this component is guaranteed to continue. Indeed, the El Niño component is likely to be missing in 2007, suggesting a less active year for Atlantic hurricanes. Forecasts of the AMO [*Knight et al.*, 2005] and other Atlantic variability [*Molinari and Mestas-Nuñez*, 2003] also indicate that future SSTs in the critical region will not go up remorselessly, as variability will continue. Nonetheless, the global warming influence provides a new background level that increases the risk of future enhanced activity.

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