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Hurricane Intensity, Sea Surface Temperature, and Stochastic Variation

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1. Introduction

"Hurricanes" are North Atlantic Ocean (NAO) cyclones that attain a maximum sustained surface-wind speed, v_{max}, of ≥119 km/h (Bell et al., 2000), which corresponds to Saffir-Simpson storm-intensity categories ≥1 (NOAA, 2006). A key climate-change concern involves the question of whether an increasing trend in sea surface temperature (SST)—considered a signal of global warming by being induced or enhanced by increased atmospheric greenhouse-gas concentrations—portends increased tropical cyclone intensities. Historical data, physical theories, and modeling all appear to link increasing SST to increased cyclone activity, intensity, or potential destructiveness in the NAO and other ocean basins (Saunders & Harris, 1997; Emanuel 2000, 2004; Goldenberg et al., 2001; Knutson & Tuleya, 2004; Emanuel, 2005; Trenberth, 2005; Webster et al., 2005; Hoyos et al., 2006; Mann & Emanuel, 2006; Santer et al., 2006; Trenberth & Shea, 2006). Correlations between cyclonic storm intensity, in particular, and increased SST beginning around 1950 to 1970 (Emanuel, 2000, 2004; Goldenberg et al., 2001; Knutson & Tuleya 2004; Emanuel, 2005; Trenberth, 2005; Webster et al., 2005; Hoyos et al., 2006; Mann & Emanuel, 2006; Santer et al., 2006; Trenberth & Shea, 2006) are claimed to support the "SST hypothesis" that local SST directly affects cyclonic intensity, just as predicted by models of storm-related heat-transfer dynamics (Emanuel, 2000, 2004; Knutson & Tuleya, 2004). For example, tropical cyclone frequency, duration, and intensity over the past 35 years showed an increased number and proportion of hurricanes reaching Saffir-Simpson categories 4 or 5 (most notably in the North Pacific, Indian, and Southwest Pacific Oceans; less so in the NAO), but a decreased number of cyclones and cyclone days in all ocean basins except the North Atlantic during the past decade (Webster et al., 2005). This conclusion is consistent with those from studies that focused instead on recent trends toward increased hurricane destructive potential, largely reflecting hurricanes of category 4 or 5 (Emanuel, 2005; Trenberth, 2005).

Other studies have questioned a direct, causal link between SST and hurricane intensity, and support an alternative, "extreme-value hypothesis" that recent strong hurricanes like Katrina are simply extreme samples from an essentially stationary intensity distribution that has not increased appreciably over at least the last half century (Landsea et al., 1996; Michaels et al., 2005; Landsea et al., 2006; Bogen et al., 2007). Among factors that are thought to influence hurricane activity—such as multidecadal oscillations in oceanic thermohaline circulation, upper tropospheric high-pressure regions, dips in tropospheric vertical wind

shear that inhibit vortex formation, atmospheric stability, and equatorial shear winds that favor hurricane development—only some are clearly correlated with SST (Elsner et al., 2000; Goldenberg et al., 2001; Elsner, 2003; Chu, 2004; Trenberth, 2005; Gray, 2006).

Studies supporting the SST hypothesis (e.g., Goldenberg et al., 2001; Emanuel, 2005; Trenberth, 2005; Webster et al., 2005; Hoyos et al., 2006; Mann & Emanuel, 2006; Santer et al., 2006; Trenberth & Shea, 2006) share a focus on annual or multi-decadal mean SST estimates averaged over large ocean areas, such as the NAO Main Development Region (MDR), also referred to as the "Atlantic cyclogenic region," in which most hurricanes develop (here assumed to denote the region within 6° to 18° N latitude by 20° to 60° W longitude). Relatively elevated MDR SST during 1995 was hypothesized to increase the frequency of hurricane formation by transferring a relatively greater amount of heat to the usual number of easterly waves of wind (typically ~60) that enter the MDR each year between May and November after leaving the west coast of Africa, each acting to stimulate shallow cumulus convection that may evolve into cyclonic behavior (Saunders & Harris, 1997). The SST hypothesis has extended this frequency-specific observation, based on NAO data gathered in a single year, to pertain generally to cyclone intensity. However, the physical basis for this hypothesized extension involving local SST effects is dubious, in view of the great distances typically traversed by these storms.

Over the last century, local NAO SST has varied in a large and predictable way along individual hurricane tracks, which typically extend many thousands of kilometers (km) from their points of origin (Fig. 1). The magnitude of this variation is sufficient to allow historical hurricane-activity records to serve as "natural experiments" that can be used to perform a direct test of the SST hypothesis, by examining the historical correlation between estimated hurricane intensities, and corresponding estimated historical changes in local SST (Smith & Reynolds, 2003, 2004), along individual hurricane tracks. To perform this test, we examined paired differences (Δv_{max}) in estimated local hurricane intensity v_{max}, and corresponding differences (ΔSST) in local (i.e., year-, month-, latitude-, and longitude-specific) SST, over various non-overlapping intervals $\Delta t = t_{i+1} - t_i$ over time t for adjacent positions (indexed by i) along each hurricane track. Over all such intervals that occurred prior to attainment of each peak hurricane intensity, Max(v_{max}), the causal SST hypothesis requires that any detectable correlation between Δv_{max} and ΔSST be positive. Below we describe methods and historical data on individual hurricane tracks that we used to implement this direct test of the SST hypothesis, and results we obtained that indicate that variation in SST is not causally linked to variation in hurricane intensities.

If SST variations do not explain the historically observed pattern of hurricane intensities, what other factor(s) might explain this pattern? Statistical and trend analysis for hurricane activity traditionally has focused on annual frequency, landfall likelihood, storm duration, storm intensity (maximum sustained storm-specific wind speed v_{max}), or Saffir-Simpson-scale wind-intensity category (Fisher, 1958; Solow, 1989; Wilson, 1999; Emanuel, 2000; Elsner et al., 2000; Elsner & Bossak, 2004; Webster et al., 2005). Normalized values of v_{max}, in particular, were shown to have a strikingly uniform statistical distribution in the North Atlantic and North Pacific (Emanuel, 2000). It has been argued that this pattern demonstrates that hurricanes opportunistically extract potential energy created by the difference between SST and upper-atmosphere temperature under relatively rare but continually (and randomly) recurring initial conditions, and so supports the hypothesis that increased SST is associated with increase hurricane intensities (Emanuel, 2004; Knutson et
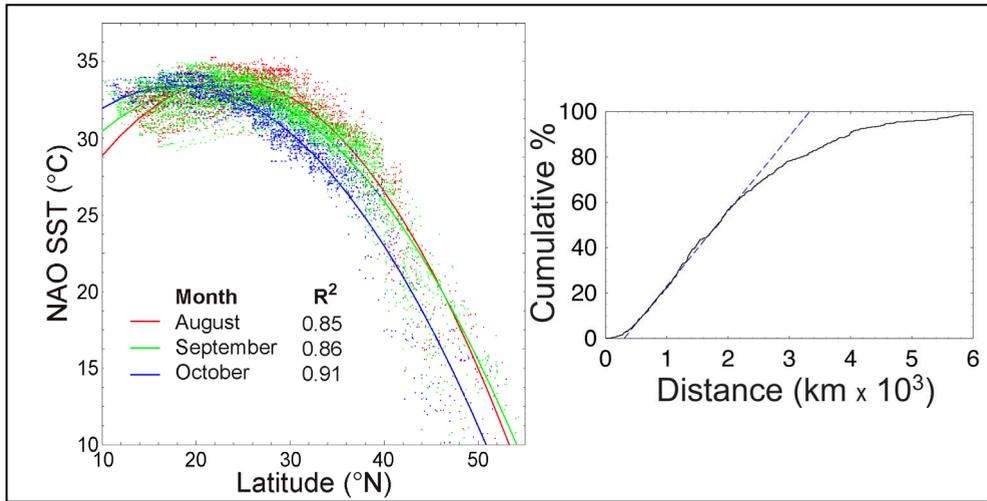
Fig. 1. **(left)** Historical NAO SST vs. corresponding latitude, at a total of *n* 6-hourly positions along tracks of all 593 recorded hurricanes in Aug (*n* = 2,598), Sept (*n* = 5,269) or Oct (*n* = 1,971) of 1880–2002, with corresponding least-squares parabolic fits and coefficients (R2) indicating regression-explained fractions of month-specific SST variance. **(right)** Cumulative frequency distribution of distance travelled along each estimated track of 629 recorded hurricanes with increasing intensities during 1880–2002.

specific hurricane intensities and corresponding local (as opposed to regional) SST. Despite fundamental uncertainty about forces driving long-term trends in hurricane activity, which limit the ability to forecast trends in hurricane intensity, some of the fairly well-understood physical processes that underlie hurricane development exhibit substantial underlying regularity. Extreme-value theory is often used to characterize the statistical behavior of extreme events that arise from homogeneous physical processes. Therefore, we also explored the extent to which specific hurricane intensities and corresponding local (as opposed to regional) SST have been correlated historically, the stochastic pattern of historical hurricane intensities, and how the observed pattern can be used to forecast future extremes in hurricane intensity over the next century.

Methods we used to undertake this second aspect of our study, and the results we obtained, are presented below. Following the presentation of results obtained from our comparison of Δv_{max} and ΔSST, and from our stochastic characterization of historical SST variation, we discuss these results and summarize the overall conclusions implied by this study.

2. Methods

2.1 Hurricane data

Historical "best track" data on 6-hourly maximum-estimated velocity *v* and latitude/longitude position of NAO hurricanes during 1880 through 2002 were obtained from the National Hurricane Center HURDAT database, including updated "best track" data through 1910 (Jarvinen et al., 1984; Landsea et al., 2004). Enhanced data reliability begins in this record since 1944, when aerial reconnaissance of Atlantic tropical cyclones began, and yet higher reliability began in the mid-1960s with the onset of operational

satellite detection (Neumann et al., 1999; Martin & Gray, 1993). HURDAT estimates of v (in m/s) between 1945 and 1970 were adjusted to new corresponding values, $v(1 - 2 \times 10^{-5} v^2)$, to account for systematic overestimation of v by aerial reconnaissance in the NAO during that period (Emanuel, 2000, 2005). The peak storm intensity Max(v) recorded for each storm within its corresponding HURDAT best-track data is hereafter denoted v_{max}.

2.2 Sea surface temperature (SST) data and local SST-specific maximum wind speed

The Extended Reconstruction SST (ERSST.v2) database (Smith & Reynolds, 2003, 2004) was used to obtain monthly SST estimates (in °C) at 2-degree NAO grid points during 1880 through 2005. At other positions, SST was estimated by linear interpolation from surrounding ERSST.v2 data points. The historical trend of annual v_{max}-weighted average values of SST was examined in relation to corresponding values of latitude and longitude estimated (for each storm) at their joint position (LL_{max}) at which v_{max} occurred. Storm intensities v_{max} were compared to storm-specific September SST values, with each contributing SST estimated either: (1) at the LL_{max} position, (2) at the position where the storm first attained tropical-storm status, or (3) averaged over all positions between positions (1) and (2). Storm-specific SST, and 1950–2005 NAO-basin September SST, were also compared to corresponding values of latitude and longitude. The NAO basin analysis involved 56 annual sets of September SST values at those 582 joint values of latitude (y) from 6 to 40 °N by 2° and longitude (x) from 2 to 90 °W by 2° that neither violate $x \leq (y+70°)$ nor fall on land, where the ith such set S_i of SST values S_{ij} ($i = 1,\ldots,56$; $j = 1,\ldots,582$) was normalized via scaling by the ratio (SST_o/SST_i) in which $SST_i = Mean(S_{ij} | i)$ over all j, and $SST_o = Mean(S_{ij})$ over all i and $j = 26.7$ °C. September SST was used because this month accounts for ~90% of all v_{max}-weighted average values of the month of hurricane occurrence, >50% of total dissipated hurricane power, and >40% of hurricane occurrence frequency (Bogen et al., 2007).

2.3 Statistical, extreme-value and trend analyses

Temporal and geographic patterns of individual historical hurricane tracks were characterized statistically. F-tests from analysis of covariance for linear regression (ANOCOVAR) (Selvin, 1995) were used to analyze change (Δv_{max}) in estimated v_{max}, vs. change (ΔSST) in corresponding estimated values of SST. SST values were estimated at track-specific pairs of non-overlapping positions separated by duration Δt hours along each of the recorded tracks of all hurricanes lasting ≥36 h that occurred in 1880–2002. Data sets were grouped by subsets of Saffir-Simpson wind-intensity categories 1–5 identified by ANOCOVAR to have least-squares linear fits with common slopes. Common regression slopes and intercepts within category subsets were taken in each case to be category-specific values determined not to differ significantly ($p \leq 0.01$) by a corresponding ANOCOVAR F-test, generating a corresponding $F_{df1,df2}$ statistic with df1 and df2 degrees of freedom. Reported values of R^2 denote coefficients of determination, i.e., fractions of total variance explained by regression.

Extreme values X generated by a homogeneous independent stochastic process can be modeled by fitting generalized extreme value (GEV) distributions (Coles, 2001; Coles & Pericchi, 2003). However, conditional on an estimated cumulative probability distribution function (cdf) $F_X(x) = Prob(X \leq x)$ modeling the value of X at each occurrence, the cdf of the greatest X-value attained after m occurrences can be calculated as $[F_X(x_m)]^m$ (Ang & Tang,

1984). The latter approach was used in the present study to forecast extreme values of future hurricane intensity. To reduce inter-annual variability effects, annual time series were smoothed by double application of the transformation: $x_i' = 0.25(x_i–1 + x_i+1) + 0.5x_i$, where x_i is the ith-year value and x_i' is the corresponding smoothed value. The same 5-year symmetric moving-average filter was used by Emanuel (2005). The significance of linear trends, and of the difference between means or between nested linear-regression slopes or intercepts, were assessed respectively by 2-tail t-tests for non-zero regression slope, and by F-tests from either analysis of variance (ANOVA) (Selvin, 1995) or analysis of covariance (ANOCOVAR) mentioned above. The significance of the difference between a sample cdf and an estimated corresponding Gaussian cdf was assessed using approximate Kolmogorov, Cramer-von-Mises, and Watson statistics (Stephens 1970). Significance of the difference between a sample cdf and an estimated non-Gaussian cdf was assessed heuristically using the exact Kolmogorov 1-sample test (Friedrich & Schellhaas, 1998).

All p-values $<10^{-10}$ are reported as ~0. All data analysis was done using *Mathematica*® 5.2 (Wolfram Research, Champaign, IL; Wolfram Research, 2010) and related *RiskQ* computer software (Bogen, 2002).

3. Results

3.1 Historical relationship between ΔSST and Δv_{max} along individual hurricane tracks, 1880–2002

During 1880–2002, tracking records indicate that only 79 (7.1% of all) hurricanes regained hurricane status after having lost it. In even more rare cases in which ≥1 peak intensity attained the same peak (i.e., Max(v_{max})) value, the peak-intensity position was taken to be the first occurrence of this peak hurricane intensity value. Nearly all hurricanes during 1880–2002 persisted for ≤12 days; durations ≤6 days were approximately uniformly distributed, and the median duration was ~4 days. Most of these hurricanes therefore persisted sufficiently long to travel far from the MDR, with most (>90%) attaining peak intensity outside the MDR. Only six HURDAT records (for hurricanes during 1880–1898) show intensities that failed to increase along each recorded track. The distribution of cumulative track (i.e., hurricane-migration) lengths of each of the remaining 629 hurricanes was calculated from each corresponding track origin to the location at which peak hurricane intensity (i.e., Max(v_{max})) occurred (Fig. 1, right). This distribution has a mean (±1 SD) of 2,100 ± 1,400 km. Approximately 66% of these migration distances were nearly uniformly distributed between 300 and 2,300 km, approximately 90% of them were ≥600 km, and approximately 10% of them were ≥4,000 km (Fig. 1, right). The track lengths were also approximately linearly proportional to hurricane duration ($R^2 = 0.69$), covering an average of about 660 km/day, with 81% (±31%) of each distance occurring outside the MDR. The historical data thus clearly indicate that only a small portion of the total duration of growth of each MDR-origin hurricane is spent within the MDR.

Consequently, there is no clear physical basis through which historical variation in MDR-specific SST could have causally influenced the magnitude of hurricane-specific values of Max(v_{max}). Results described in the next paragraph address the question of whether elevations in local SST encountered over the course of specific hurricane tracks (as indicated above, mostly outside the MDR) may tend to act to increase hurricane intensity.

Table 1 presents ANOCOVAR results pertaining to track-specific {Δv_{max}, ΔSST} data for hurricanes lasting ≥36 h during 1880–2002, conditional on a specified non-overlapping time

interval Δt applied along each hurricane track. Data within subsets of Saffir-Simpson intensity category were grouped by common values of least-squares linear-regression slope, which were identified by ANOCOVAR as summarized in Table 1. This table lists only category subsets with common slope values, where common values of regression slope and intercept within category subsets were taken in each case to be category-specific values determined not to differ significantly ($p \leq 0.01$) by corresponding ANOCOVAR F-test. For each listed duration Δt, the "combined model" pertaining to the rightmost two columns of the table refers to all subset-specific linear fits obtained that have a common slope, together with corresponding common intercept values, unless the ANOCOVAR p-value listed for intercept homogeneity was ≤ 0.01, in which case the combined model included the corresponding category-specific intercept estimates (not listed). Results of this analysis corresponding to $\Delta t = 6$ h and 24 h are summarized in Fig. 2 (similar results not shown were obtained using $\Delta t = 12$ h). Common regression slopes and intercepts within category subsets were taken in each case to be category-specific values determined not to differ significantly ($p \leq 0.01$) by a corresponding ANOCOVAR F-test, as summarized in Table 1.

All of the estimated slopes listed in Table 1 and plotted in Fig. 2 are negative, indicating a consistent pattern of negative correlations between Δv_{max} and ΔSST that is just the opposite of the pattern of positive associations that is posited by the SST hypothesis. The binomial likelihood (i.e., p-value) of by chance alone estimating nine negative slopes under the null hypothesis that the slopes are in fact all zero or positive is <0.2%. For each of three values of Δt considered, highly significantly predictive fits ($p = \sim 0$) were obtained to corresponding paired-difference data grouped by hurricane categories, each exhibiting a common slope identified by ANOCOVAR. At least one estimated slope was found to be statistically significantly negative ($p \leq 0.05$) within each Δt-specific set of results listed in Table 1. A total of five of the nine slope estimates listed in Table 1 are significantly negative ($p \leq 0.05$). For $\Delta t = 24$ h in particular, the longest time period considered, both of the two slopes that together correspond to all five hurricane categories are significantly negative ($p \leq 0.05$) (Table 1). Interestingly, there is a general tendency among the estimated negative slopes to

Δt (h)	Number of hurri- canes	{ΔSST, Δv_{max}} data		Common intercept (km/h)	Common slope (km/h-°C)	p-value for = slopes	p-value for = intercepts	2-tail p-value for slope = 0	Combined model	
		Category (k)	Number (n)						R^2	p-value
6	481	1	1,944	3.80	–0.304	–	–	0.43	0.091	~0
		2–3	2,094	7.99	–1.76	0.50	0.00021	0.028		
		4–5	217	12.5	–5.26	0.049	0.081	0.11		
12	449	1	755	5.49	–1.15	–	–	0.059	0.18	~0
		2	728	14.9	–1.79	–	–	0.011		
		3	394	15.5	–6.82	–	–	0.000018		
		4–5	135	25.3	–3.38	0.27	0.013	0.31		
24	372	1–3	788	19.8	–1.62	0.53	~0	0.0070	0.36	~0
		4–5	97	49.0	–7.07	0.51	0.0057	0.036		

Table 1. Results of covariance analysis of track-specific data for hurricanes persisting ≥36 h during 1880–2002.
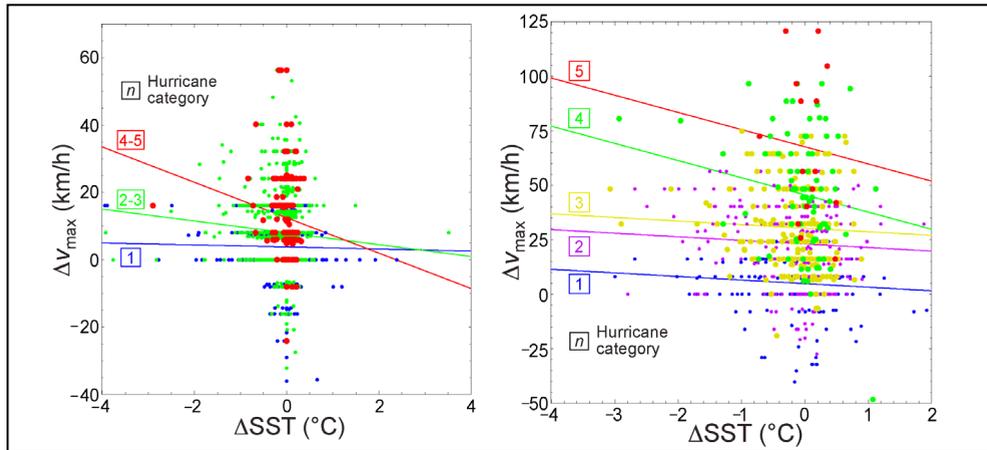
Fig. 2. Change in v_{max} for track-specific pairs of **(left)** adjacent 6-hourly positions (Δt = 6 h), and **(right)** daily positions (Δt = 24 h), along recorded tracks of 481 hurricanes during 1880–2002 that lasted ≥36 h, vs. corresponding change in estimated SST. Least-squares linear fits are shown to data grouped by Saffir-Simpson intensity category, using common, significantly negative (p < 0.01) slopes in categories 1, 2–3, and 4–5 identified by ANOCOVAR. The consistent pattern of negative slopes exhibited by the plotted historical data are not consistent with the SST hypothesis, which posits a causal link between increased SST and increased hurricane intensity.

increase in absolute magnitude in proportion to Saffir-Simpson hurricane category. This pattern is again contrary to the SST hypothesis and is statistically significant (by unweighted least-squares linear regression, R^2 = 0.69, p = 0.020) for those seven slopes listed in Table 1 that differ (at a significance level of p ≤ 0.15) most significantly from zero.

3.2 Historical variation and covariance of hurricane-specific SST and intensity

Fig. 3 (left) shows the decadal-average percentage of all (1,089) NAO tropical storms, and of all (838) storms that attained a Saffir-Simpson category ≥1, since 1880, that subsequently attained a category ≥4. Over this period, the average fraction of all tropical or greater-intensity storms that never attained a category ≥1 remained about 40%, without any significant overall temporal trend. The decadal data are consistent with the hypothesis that the period 1880–1909 shown reflects censoring due to relatively fewer observations during that period prior to a subsequent surge in steam-powered transatlantic shipping, which occurred after the demise of major passenger cartels that operated prior to World War I (Deltas et al., 1999; Keeling, 1999). Excluding the three earliest points, the plotted decadal percentages show no significant temporal trend, but do show evidence of oscillation with a period of approximately 40 y. The annual frequency of all storms since 1910 for which v_{max} ≥ 145 km/h also shows no temporal trend (Fig. 3, right). The distribution of these annual frequencies has significantly extra-Poisson variance (χ^2 = 126.4, df = 92, p = 0.01), and is consistent (χ^2 = 8.85, df = 9, p = 0.26) with a negative binomial distribution with a mean of 3.4 events/year and an over-dispersion parameter of 0.106. Likewise, there is no temporal trend in v_{max} during this period (p = 0.71), this period prior to 1970 (p = 0.89), or since 1970

(p = 0.47). While there is a slight upward trend in annual Max(v_{max}) (R^2 = 0.074, p = 0.0083), no such trend is evident (p > 0.089) when examined during either 1909–1969 or 1970–2002.
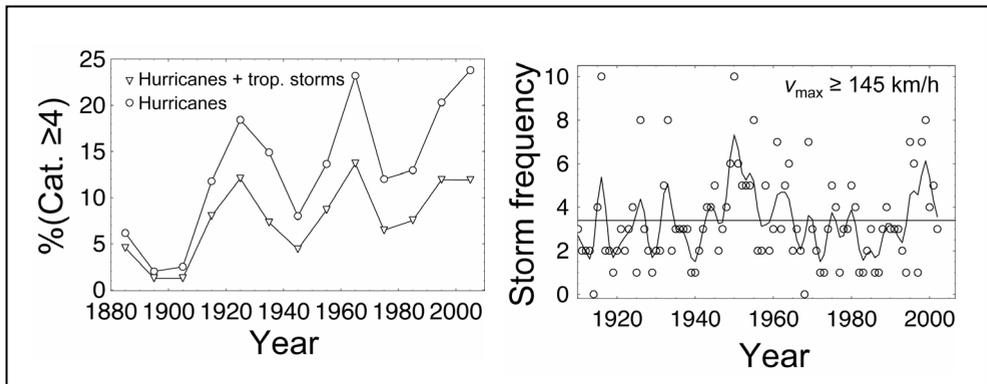

Fig. 3. **(left)** Decadal-average percent of all NAO tropical storms, and of all storms that attained a Saffir-Simpson category ≥1, that subsequently attained a category ≥4. Neither temporal trend is significant for the corresponding post-1909 data (R^2 = 0.088 with p = 0.41, and R^2 = 0.15 with p = 0.26, respectively). **(right)** Annual frequency of all storms since 1910 in which v_{max} attained 145 km/h, together with smoothed trend (curve) and mean frequency of 3.4 (horizontal line).

Figure 4 contrasts the historical pattern of annual v_{max}-weighted mean values of storm-specific local SST (shown on the left), with that of storm-specific adjusted latitude (shown on the right), since 1880, using HURDAT and corresponding interpolated SST data for tropical storms and hurricanes (n = 1,079). The additive latitude adjustment (by –2.45°) was selected to make the median value of each data set coincide, which helps to reveal the significant negative correlation between these two variables (R^2 = 0.55, p = ~0), together with their approximate common ~80-year period of oscillation. This correlation is indicated more directly in Fig. 4 (right), which shows that the storm-specific data are generally consistent with the pattern exhibited by 32,592 normalized September SST grid-points covering the entire NAO basin during the period 1950–2005. The negative correlation shown was found by ANOCOVAR to be weaker at latitudes <30 °N for both storm data ($F_{1, 119}$ = 5.04, p = 0.027) and NAO basin data ($F_{1, 32588}$ = 1,407, p = ~0). A positive but somewhat weaker correlation was found between annual v_{max}-weighted means of storm-specific SST and corresponding longitude (R^2 = 0.37, p = ~0). Multiple linear regression yielded even better models predicting storm-specific SST from corresponding latitude (y), longitude (x), and year (t):

$$SST = 28.8 \text{ °C} + 0.0833x - 0.288y \quad (R^2 = 0.69), \text{ and} \tag{1}$$

$$SST = 28.6 \text{ °C} + 0.0709x - 0.249y + 0.547 \text{ Sin}[2\pi (t - 1915)/78.9] \quad (R^2 = 0.75), \tag{2}$$

where x and y have a weak negative correlation (R^2 = 0.11, p = 0.00017). The latter regression was conditioned on a separately optimized displacement year (1915) and period (78.9 years), and all three of its linear coefficients are significantly positive by F-to-remove criteria ($F_{1,119}$ ≤ 26.7, p < 10^{-6}).
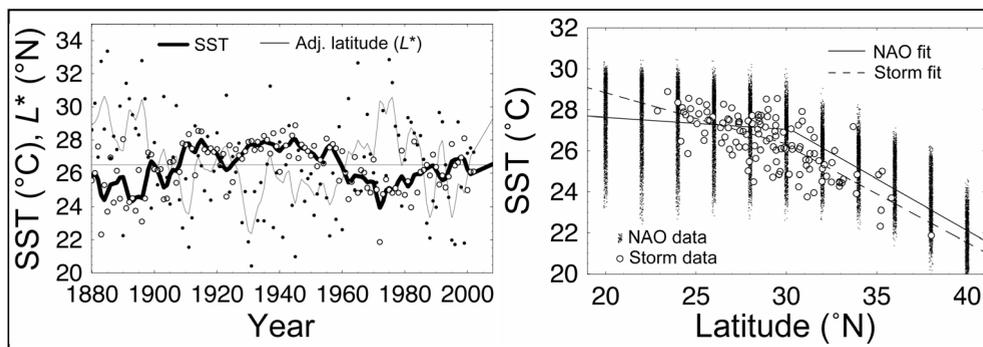
Fig. 4. **(left)** Annual v_{max}-weighted mean values of storm-specific local SST (open points, bold curve), and of corresponding values of adjusted-latitude (solid points, thin curve), are shown with corresponding smoothed trends ($R^2 = 0.55$ with p = ~0 for $n = 122$ annual data values; horizontal line shows joint median value). **(right)** Values of annual v_{max}-weighted mean SST values for storms (open points, with ordinates equal to those of the corresponding open points plotted in the left panel), and annually normalized September SST values at NAO-basin grid points (small solid points at 2° latitude intervals, which were randomly twittered to enhance data-cloud visibility), are compared to corresponding latitudes, together with corresponding bi-linear fits assuming a common breakpoint at 30 °N.

Data	SST$_{peak}$ constraint	Value of $100\% \times R^2$ between v_{max} and SST$_x$ at SST-position x, and corresponding value of n^b					
		x = peak	n	x = mean	n	x = start	n
All storms[a]	≥ 25˚C	1.9[c]	822	0.4[e]	996	0.03	1025
	≥ 20˚C	1.2[c]	993	2.0[c]	1065	0.3	1066
	None	0.1[d]	1074	2.5[c]	1074	0.7[e]	1074
All hurricanes	≥ 25˚C	3.9[c]	493	4.5[c]	602	0.1	613
	≥ 20˚C	8.8[c]	590	8.2[c]	631	1.0[e]	630
	None	11.[c]	633	8.3[c]	633	1.7[e]	633
Category ≥ 3 Hurricanes	≥ 25˚C	9.3[c]	218	1.7[e]	232	0.2	230
	≥ 20˚C	9.0[c]	231	1.7[e]	232	0.3	232
	None	8.9[c]	232	1.7[e]	232	0.3	232

[a] v_{max} = maximum wind speed. SST was estimated at each year- and month-specific position recorded in the HURDAT 6-hourly storm track database, for years 1880–2002. SST$_{peak}$ = SST at v_{max}; SST$_{start}$ = SST at the position at which the system first attained "tropical storm" (TS) status (wind speeds ≥ 62 km/h); SST$_{mean}$ = arithmetic mean SST at all 6-hourly positions at or after the system first became a TS. Only storms that attained or exceeded TS status were included in this analysis.

[b] R^2 = squared Pearson product-moment correlation coefficient, or fraction of total variance explained by the corresponding linear regression.

[c] $p \leq 10^{-5}$.

[d] $p \leq 0.001$.

[e] $p \leq 0.05$.

Table 2. Correlation between storm-specific v_{max} and sea surface temperature (SST).[a]

Thus, substantial predictability was observed for SST throughout the NAO basin, and even more so for annual v_{max}-weighted mean SST estimated at v_{max}-occurrence points within individual storm tracks. In contrast, storm-specific v_{max} was predicted poorly or not at all by corresponding local SST, regardless of whether SST was estimated at the position (LL_{max}) of each v_{max} occurrence, estimated at the position where each storm first attained tropical-storm status, or estimated by averaging SST between these two positions over each storm-growth track (Table 2, on the previous page). The greatest of these correlations explains just 11% of v_{max} (Table 2). Small correlations detected between v_{max} and SST were a bit larger with SST estimated at LL_{max} than with SST estimated at the beginning of, or averaged over, each storm-growth track. Values of v_{max} were predicted by storm-specific latitude or longitude at least as poorly as they were predicted by corresponding local SST (data not shown).

The empirical cumulative distribution function (cdf) of v_{max} for all NAO storms during 1910–2002 was found to reflect a mixture of values containing ~62% distributed approximately uniformly below v_o = 145 km/h, and the remainder approximately gamma-distributed (Fig. 5, left). The relatively high v_{max} values ($\geq v_o$) have a sample mean and variance of μ = 193 km/h and σ^2 = 905 km^2/h^2, respectively. Parameters a and β of the gamma distribution used to model adjusted conditional intensities $(v–v_o) \mid (Max(v_{max}) \geq v_o)$ were derived by the method of moments as the corresponding estimates μ'^2/σ^2 and σ^2/μ', respectively, with $\mu' = \mu – v_o$. The corresponding v_o-shifted gamma distribution shown in Fig. 5 (left) shall be denoted $F(v)$.

The distribution, $Prob(Max(v_{max}) \leq v)$ for all $v \geq 0$, estimated from historical hurricane data (Fig. 5, left) can be used to estimate the cdf of the most extreme $Max(v_{max})$ after m seasons past a reference year such as the year 2000. Specifically, the cdf of extreme values $v_m = Max(v_{max})) \mid m$, with $m = t–s$ for calendar year t and reference year s = 2000, is just $Prob(v_m \leq v) = F(v)^m$ (see Methods), conditional on all storms randomly sampled from the high v_{max} category considered. Because the estimated distribution for relatively low v_{max} is approximately uniform with upper bound v_o (Fig. 5, left), the cdf of v_m can be estimated directly after scaling m by the fraction p of all high-v_{max} storms, estimated above as p = 100% – 62% = 38%. The temporal v_m model as a function of year t is therefore given by

$$\text{Prob}(v_m \leq v) \ = \ \prod_{t=s}^{p(t-s)} F(v) \ = \ \left[F(v) \right]^{p(t-s)} . \tag{3}$$

Figure 5 (right) shows how this model predicts v_m over the 21st century. These predictions indicate that over the next 50 years, v_{max} is as likely as not to exceed about 310 km/h, and is unlikely to exceed about 380 km/h. By the end of this century, these median and upper-bound extreme-value estimates increase to about 330 and 400 km/h, respectively.

4. Discussion

Results involving combined SST and hurricane characteristics estimated for the NAO basin since 1880, or even since 1910, must be interpreted cautiously in view of uncertainty about the accuracy of reconstructed historical SST maps and best-track hurricane records used for this analysis. Greater confidence might be acquired in results of future similar analyses by incorporating existing estimates of SST uncertainty (Smith & Reynolds, 2004), and planned improvements to the HURDAT database for post-1910 hurricanes (Landsea et al., 2004) into

analytic methods applied. Awaiting clearly warranted further research along these lines, the following results from the present study appear to be sufficiently coherent and robust as to be unlikely due to chance alone or to substantial bias in estimated historical data relied upon.

4.1 Lack of evidence for a causal relationship between SST and hurricane intensity

During 1880–2002, tracking records indicate that hurricanes persisted sufficiently long to travel far from the MDR, with most (>90% of) attaining peak intensity outside the MDR. Any direct physical link between MDR conditions (such as SST) at the time of cyclogenesis, and v_{max} behavior days later and hundreds to thousands of km away from the MDR, is not plausible. The SST hypothesis is clearly inconsistent with historical data on hurricanes lasting ≥36 h for which track statistics were estimated between 1880 and 2002 (Fig. 2). As hurricanes intensified, those that migrated into *colder* waters tended to experience significantly *greater* intensification regardless of absolute position within the NAO basin, and this trend was more pronounced for hurricanes of greater intensity. Although effects of global warming on hurricanes may be plausible theoretically, the most directly pertinent historical data, which compare changes in SST and v_{max} along hundreds of individual hurricane tracks, are clearly inconsistent with any direct link between increased SST *per se* and increased hurricane intensity.
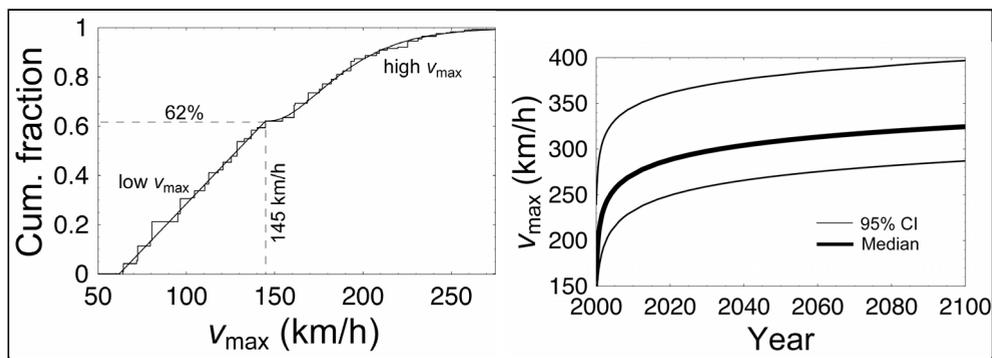

Fig. 5. **(left)** Cumulative empirical distribution of storm-specific v_{max}, shown with a corresponding composite uniform-gamma distribution (solid line for low v_{max} region, curve for high v_{max} region). **(right)** Estimated median trend (bold curve) in Max(v_{max}) extremes, v_m = Max(v_{max}) | m with $m = t–s$ for calendar year t and reference year s = 2000, and corresponding 2-tail 95% confidence limits (light curves) predicted by the extreme-value model given by Eq. 3.

4.2 Stochastic characterization of historical hurricane intensities, and related forecasts

Despite clear evidence of a significant recent positive trend in NAO SST since about 1970 (Goldenberg et al., 2001; Knutson & Tuleya, 2004; Knutson et al., 2004; Emanuel, 2005; Trenberth, 2005; Bogen et al., 2007), a similarly significant trend was not found in HURDAT data pertaining to v_{max}. While storm-specific SST was discovered to be largely predictable from corresponding data on storm latitude, longitude, and year of occurrence, this was not

evident in the case of v_{max}. Rather, HURDAT estimates of historical v_{max} since 1910 appear to be random samples from two distinct distributions: one approximately uniform for low-v_{max} values <145 km/h, and the other more skewed and approximately gamma-distributed for high-v_{max} values ≥145 km/h (Fig. 5, left). Among all low-v_{max} storms (~62% of all storms attaining tropical or greater status), the magnitudes of v_{max} were found to be nearly uniformly distributed, consistent with similar observations made in previous studies (Emanuel, 2000, 2004).

The second part of our analysis demonstrated how extreme-value theory, combined with the average value and historical range of the fraction of NAO storms falling into each of the two v_{max} categories identified (Fig. 5, left), can be used to make predictions concerning $Max(v_{max})$ likely to be delivered by a single hurricane over a specified future period (Fig. 5, right). For example, the model we describe (Eq. 3) predicts that, during the present century, a NAO storm with v_{max} as great as 400 km/h may occur with non-negligible likelihood, and a storm with v_{max} ≥ 330 km/h should be expected.

Results obtained using this model are similar to those we reported previously (Bogen et al., 2007) for storms classified by Power Dissipation Index (PDI, or integrated 3rd power of wind speed), rather than by the $Max(v_{max})$ metric used in the present study. Our earlier analysis examined intra-annual variation in storm-specific PDI, and inter-annual variation in annual accumulated PDI (APDI), as another way to investigate another version of the SST hypothesis, positing that the clearly positive trend in NAO sea surface temperature (SST) since 1970 has caused and will continue to cause increased hurricane destructive potential as measured by PDI and APDI. In that study, we applied a combination of statistical and probabilistic methods to the same sets of National Hurricane Center HURDAT best-track data on NAO hurricanes during 1880–2002, and corresponding NOAA Extended Reconstruction SST estimates, as those used for the present study, to compare hurricane behavior and corresponding hurricane-specific (i.e., spatiotemporally linked) SST. In contrast, previous similar comparisons considered only SST averaged over large NAO regions. Contrary to the SST hypothesis, we found that SST varied in a monthly pattern inconsistent with that of corresponding PDI or APDI, and was at best weakly associated with PDI or APDI, despite a strong correlation with corresponding mean latitude (R^2 = 0.55), and with combined mean location and a ~90-year periodic tend (R^2 = 0.70) (Bogen et al., 2007; cf. the ~80-year oscillatory period shown in Fig. 4-left above). Over the last century, the lower 75% of APDI values achieved appear to have been sampled randomly from a nearly uniform distribution, and the upper 25% of APDI values from a nearly lognormal distribution (Bogen et al., 2007). From the latter distribution, we derived a baseline (SST-independent) stochastic model predicting that over the next half century, APDI will not likely exceed its maximum value over the last half century by more than a factor of 1.5. This factor increased to 2 using a baseline model modified to assume SST-dependence conditioned on an upper bound of the increasing NAO SST trend observed since 1970 (Bogen et al., 2007). An additional model was developed that predicts PDI statistics conditional on APDI (Bogen et al., 2007). These PDI and APDI models can be used to estimate upper bounds on indices of hurricane power likely to be realized over the next century, under divergent assumptions regarding SST influence, analogous to the model (Eq. 3) predicting v_{max} extremes developed in the present study.

Applications of stochastic modeling approaches described here must consider the fact that the relation between v_{max} and seasonal destructive potential is weakened by stochastic

variation of landfall likelihood, conditional on hurricane activity (Elsner & Bossak, 2004), as well as by other critical factors such as population density and state of economic development of affected coastal areas (Pielke & Landsea, 1998; Pielke & Sarewitz, 2005). Such estimates can be refined to focus on realized damage by expanding predictive models to incorporate landfall likelihoods and associated potential loss in relation to trends in coastal economic development.

5. Conclusions

Historical data, physical theories, and modeling have been used to claim that increased sea-surface temperature (SST) causes increased cyclone activity, intensity, or potential destructiveness in the North Atlantic Ocean (NAO) and other ocean basins (the "SST hypothesis"). Other studies, including this one, support an alternative, "extreme-value hypothesis," that recent strong hurricanes like Katrina are simply extreme samples from an essentially stationary intensity distribution that has not increased appreciably over at least the last half century. The SST hypothesis was tested using historical data on changes (Δv_{max}) in NAO hurricane intensity and corresponding changes (ΔSST) in estimates of local SST along tracks of individual hurricanes lasting ≥36 h, over equal time intervals set at a value between 6 and 24 h. The SST hypothesis requires a positive correlation between Δv_{max} and ΔSST. In contrast, tracking records during 1880–2002 indicate that, as hurricanes intensified, those that migrated into *colder* waters tended to experience significantly *greater* intensification regardless of absolute position within the NAO basin, and this trend was more pronounced for hurricanes of greater intensity. Consequently, although effects of global warming on hurricanes may be plausible theoretically, directly relevant historical data exhibit no evidence that increases in SST tend to induce increased hurricane intensities.

To bound possible future trends in maximum intensity (v_{max}, km/h) of hurricane seasons, we performed stochastic and extreme-value analysis of National Hurricane Center HURDAT best-track data on hurricanes during 1880–2002, combined with NOAA Extended Reconstruction SST estimates. In contrast with a recent positive trend in NAO SST since about 1970, we detected no historical trend for v_{max}. Storm-specific SST was predicted fairly well from corresponding data on storm latitude, longitude, and year of occurrence, whereas v_{max} has had little or no direct association with SST or other local variables. Estimated v_{max} since 1910 appears to be randomly sampled from two distinct distributions: one (for v_{max} < 145 km/h) approximately uniformly distributed, and the other (v_{max} ≥ 145 km/h) approximately gamma-distributed. A corresponding extreme-value model developed in this study predicts Max(v_{max}) for any single hurricane over time. In particular, this model predicts that, during this century, a storm with v_{max} up to 400 km/h may occur with non-negligible likelihood, and a storm with v_{max} ≥ 330 km/h should be expected. Cautious interpretation of these modeling results is warranted, in view of uncertainty about the accuracy of reconstructed historical SST maps and best-track hurricane records used.

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This book represents recent research on tropical cyclones and their impact, and a wide range of topics are covered. An updated global climatology is presented, including the global occurrence of tropical cyclones and the terrestrial factors that may contribute to the variability and long-term trends in their occurrence. Research also examines long term trends in tropical cyclone occurrences and intensity as related to solar activity, while other research discusses the impact climate change may have on these storms. The dynamics and structure of tropical cyclones are studied, with traditional diagnostics employed to examine these as well as more modern approaches in examining their thermodynamics. The book aptly demonstrates how new research into short-range forecasting of tropical cyclone tracks and intensities using satellite information has led to significant improvements. In looking at societal and ecological risks, and damage assessment, authors investigate the use of technology for anticipating, and later evaluating, the amount of damage that is done to human society, watersheds, and forests by land-falling storms. The economic and ecological vulnerability of coastal regions are also studied and are supported by case studies which examine the potential hazards related to the evacuation of populated areas, including medical facilities. These studies provide decision makers with a potential basis for developing improved evacuation techniques.

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