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Statistical evidence links exceptional 1995 Atlantic hurricane season to record sea warming

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Abstract. Tropical cyclones rank above earthquakes as the major geophysical cause of loss of life and property (Bryant, 1991; Houghton, 1994). In the United States alone, the damage bill from mainland landfalling hurricanes over the last 50 years averages $2.0 billion per year (Hebert et al., 1996). Years with high numbers of hurricanes provide new insight on the environmental factors influencing interannual variability; hence the interest in the exceptional 1995 Atlantic season which saw 11 hurricanes and a total of 19 tropical storms, double the 50-year average. While most environmental factors in 1995 were favourable for tropical cyclone development, we show that a factor not fully explored before, the sea surface temperature (SST) was the most significant. For the 10°-20°N, 20°-60°W region where 93% of the anomalous 1995 hurricanes developed, ~45 year statistical regressions show that SST is the dominating influence, independent of all known other factors, behind the interannual variance in Atlantic hurricance numbers. With this SST experiencing record warm levels in 1995, 0.66°C above the 1946-1995 mean, these regressions indicate that sea warming explains 61±34% of the anomalous hurricane activity in 1995 to 95% confidence.

Introduction

Only twice since 1886, when records began [*Neumann et al.*, 1993], has an Atlantic season seen either more tropical storms or more hurricanes than in 1995. Table 1 compares the 1995 activity levels with the three previous 'quiet' years 1992-1994, and with the 50-year (1946-1995) average. For each of the four measures of activity shown, 1995 was about 3σ (σ = standard deviation) more active than the 50-year mean. Indeed, in terms of each 'measure', the 1995 level has been exceeded only once since records began: 21 tropical storms (1933), 12 hurricanes (1969), 136 tropical storm days (1933) and 72 hurricane days (1893).

When and where did the 1995 anomalous (i.e. with respect to the 50-year average levels) hurricane activity form? Atlantic tropical cyclone activity peaks in the 3-month August-September-October (ASO) period when 85% of storms form (Shapiro, 1987). A similar temporal distribution occurred in 1995 with 84% of storms active during the ASO period. What is different in 1995 is the main region of storm formation. Figure 1 shows the tracks of the 19 Atlantic tropical storms in 1995. Most of the long-lived storms formed inside the region 10°-20°N, 20°-60°W which is shown shaded. The importance of this region for tropical cyclone formation in 1995 is quantified in Table 2. This Table shows that 93% of the increased (above the 50-year average) number of ASO hurricanes in 1995 formed within this region. Furthermore, 91% of the anomalous number of ASO tropical storms in 1995 also formed therein. Thus it is the extra storm formation within the region 10°-20°N, 20°-60°W which made 1995 such an active season overall. The region comprises ~60% of the 10°-20°N latitude belt stretching from the west coast of Africa to central America which has been termed the Atlantic's main tropical cyclone 'development region' [*Goldenberg and Shapiro*, 1996]. For simplicity we shall refer to our area also as the 'development region'.

SST as an Environmental Influence

What could have caused the 1995 season to be so active? The five environmental factors known to be linked to interannual variability in the ASO number of tropical cyclones are: (i) tropospheric vertical wind shear (SHEAR) [*Shapiro*, 1987; *Pasch and Avila*, 1994; *Goldenberg and Shapiro*, 1996]; (ii) the El Niño-Southern Oscillation (ENSO) [*Gray*, 1984; *Shapiro*, 1987; *Gray et al.*, 1993; *Landsea et al.*, 1994]; (iii) the stratospheric Quasi-Biennial Oscillation (QBO) [*Gray*, 1984; *Shapiro*, 1989; *Gray et al.*, 1993; *Landsea et al.*, 1994]; (iv) monsoon rainfall in the African west Sahel (SAHEL) [*Landsea and Gray*, 1992; *Landsea et al.*, 1994]; and (v) the Caribbean basin sea level pressure anomaly (SLPA) [*Ray*, 1935; *Shapiro*, 1982; *Gray et al.*, 1993; *Landsea et al.*, 1994]. A thorough study comparing the importance of each for concurrent (i.e. taking place at the same time), as opposed to predictive, Atlantic tropical storm activity has not been made. However, it is generally believed that tropospheric vertical wind shear, influenced by ENSO, has the strongest direct control. Low values of vertical shear ($<5ms^{-1}$ shear between 1km and 12km altitude [*Goldenberg and Shapiro*, 1996] favour tropical cyclone development as high wind shear prevents a vertically coherent vortex from developing.

A parameter whose influence has not been fully explored on the interannual variability in Atlantic tropical storm numbers is sea surface temperature (SST). Positive correlations involving

Table 1. Tropical Storm and Hurricane Activity in the North Atlantic During 1995 Compared with that in Adjacent Years and with the Previous 50-Year Average.

	1995	1994	1993	1992	1946-1995 mean ± σ
Tropical Storms*	19	7	8	6	9.4 ± 3.2
Hurricanes*	11	3	4	4	5.8 ± 2.3
Tropical Storm Days†	121	28	30	38	47.8 ± 22.2
Hurricane Days†	62	7	10	16	24.0 ± 14.3

* A tropical storm (hurricane) is defined as having a maximum 1-minute sustained wind speed above $17ms^{-1}$ ($32ms^{-1}$).

† A tropical storm (hurricane) day is defined as four 6-hour periods during which a tropical cyclone sustains tropical storm (hurricane) intensity wind status.

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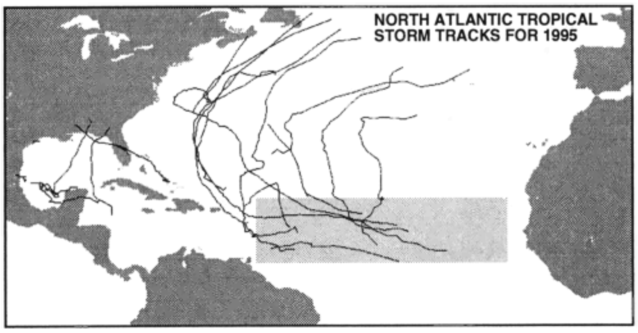

Figure 1. Tracks of the 19 North Atlantic named tropical storms and hurricanes in 1995. The region shown shaded (10°-20°N, 20°-60°W) is the main region of tropical cyclone development.

SST have been reported [*Carlson*, 1971; *Shapiro*, 1982; *Raper*, 1990], but these studies are limited by not correlating SSTs with concurrent tropical storm activity [*Shapiro*, 1982; *Raper*, 1990] and by examining only 5 years [*Carlson*, 1971].

How large and exceptional was the 'development region' SST in 1995? Figure 2 displays this region's monthly mean SSTs for the years and climatology given in Table 1. These SSTs come from the Meteorological Office Historical Sea Surface Temperature data set version 6 (MOHSST6) [*Parker et al.*, 1995]. MOHSST6 SSTs are a bulk temperature retrieval between 1m and 10m depth, and contain the best available quality controls and bias corrections. The random error in the monthly mean values in Figure 2 is < 0.1°C [*Parker et al.*, 1995]. For the ASO peak in activity, the 1995 mean SST, at 28.03°C, is 0.66°C (2.1σ) warmer than the 50-year MOHSST6 climatology. This is the warmest the 'development region' SST has been since records began in 1865.

Regression Analysis: the Dominant Effect of SST

Comparison of Figure 2 with the tropical cyclone activity statistics in Table 1 indicates a positive correlation with the mean SST. But how significant is this SST influence compared to that of the five other environmental parameters (SHEAR, ENSO, QBO, SAHEL rainfall, and Caribbean SLPA) also linked to interannual changes in Atlantic tropical cyclone numbers? Figure 3 makes this comparison in terms of the reduction in the interannual variance, r^2 (r is the linear correlation coefficient), in the ASO number of hurricanes (NH) originating within the 'development region'. Our data spans 17 years for SHEAR and ~45 years for the other factors. Variances are calculated for each of the 12 months to examine both concurrent and lagged controls. Partial correlations [*Kleinbaum et al.*, 1986] are used to isolate the SST influence which is independent of the other parameters (panels labelled SST/SHEAR, SST/NINO 3, SST/QBO, SST/SAHEL and SST/SLPA respectively). The horizontal dashed lines indicate the 95% significance level.

Figure 3 shows: (a) the SST influence is largely concurrent, peaking from July to November, (b) the SST influence changes with time, being twice as strong for 1979-1995 as for 1951-1995 (confirmed by a sliding 17-year correlation not shown), (c) the SST influence exceeds the lagged or concurrent influences of the other environmental parameters by factors of 1.9 (SHEAR), 5.0 (ENSO), 1.4 (QBO), 2.6 (SAHEL) and 3.0 (SLPA) for August to October, and (d) the SST influence is largely independent of the other environmental parameters. The latter is clear from the partial correlations which show percentage reductions in the August to October SST r^2 value of just 28% (SHEAR), 4% (ENSO), 16% (QBO), 12% (SAHEL) and 6% (SLPA). Similar results are obtained using ASO mean values for each environmental factor rather than taking the average of monthly r^2 values as above. Second-order partial correlations [*Kleinbaum et al.*, 1986] give the contributions of SST, SHEAR and SAHEL which are independent of each of the two other major factors as r^2 = 0.42 (SST), 0.20 (SHEAR) and 0.01 (SAHEL) for 1979-1995. For the 1951-1995 period, using QBO as a proxy for SHEAR, these become r^2 = 0.20 (SST), 0.15 (QBO) and 0.16 (SAHEL). In summary, SST is the most important environmental parameter, independent of all known others, in affecting seasonal hurricane numbers in the 'development region'. SST directly influences at least 42% (1979-1995) or 20% (1951-1995) of the interannual variance in these numbers.

The influence in 1995 of SST compared to the other environmental factors is shown in Table 3 based on the above regressions and the size of the different environmental anomalies in 1995. ΔNTS and ΔNH give the percentages of the 1995 ASO anomalous tropical storms (NTS) and hurricanes starting development within 10°-20°N, 20°-60°W which may be explained by linear regression and the 1995 anomaly.

Table 2. Comparison of Atlantic Tropical Storm and Hurricane Numbers for Events Starting Inside and Outside the 10°-20°N, 20°-60°W 'Development Region' During the 3-Month August-September-October Peak in Activity.

	Tropical Storms		Hurricanes	
Formation Region	1946-1995 mean ± σ	1995 anomaly	1946-1995 mean ± σ	1995 anomaly
10°-20°N, 20°-60°W	3.1 ± 2.2	+ 2.7 σ	2.1 ± 1.8	+ 2.2 σ
Elsewhere	4.4 ± 2.2	+ 0.3 σ	2.7 ± 1.5	+ 0.2 σ

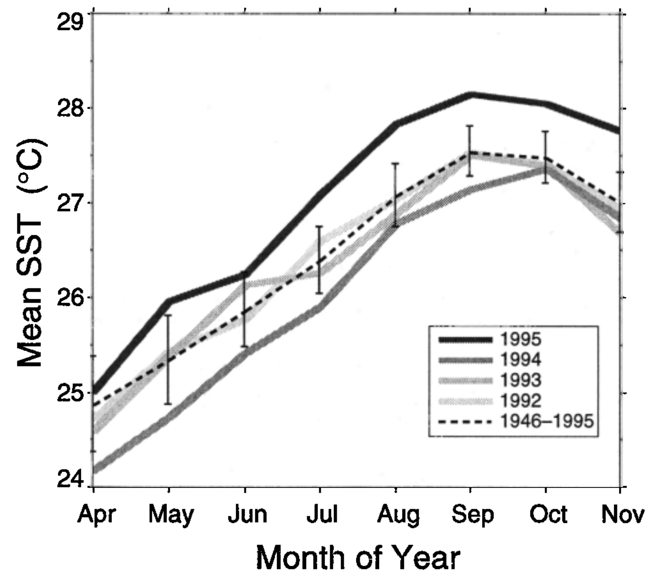

Figure 2. Mean monthly sea surface temperature (SST) for the tropical cyclone development region in Figure 1. The months April to November are displayed, these spanning the 3-month ASO peak in tropical cyclone activity. Values are plotted for 1992 to 1995, and for a 50-year (1946-1995) climatology [*Parker et al.*, 1995]. The latter is shown as a mean ± standard deviation (σ). The Figure shows that unusually high SSTs prevail during 1995. For the ASO peak in activity, the 1995 mean SST, at 28.03°C, is 0.66°C (2.1σ) warmer than the 50-year climatology.

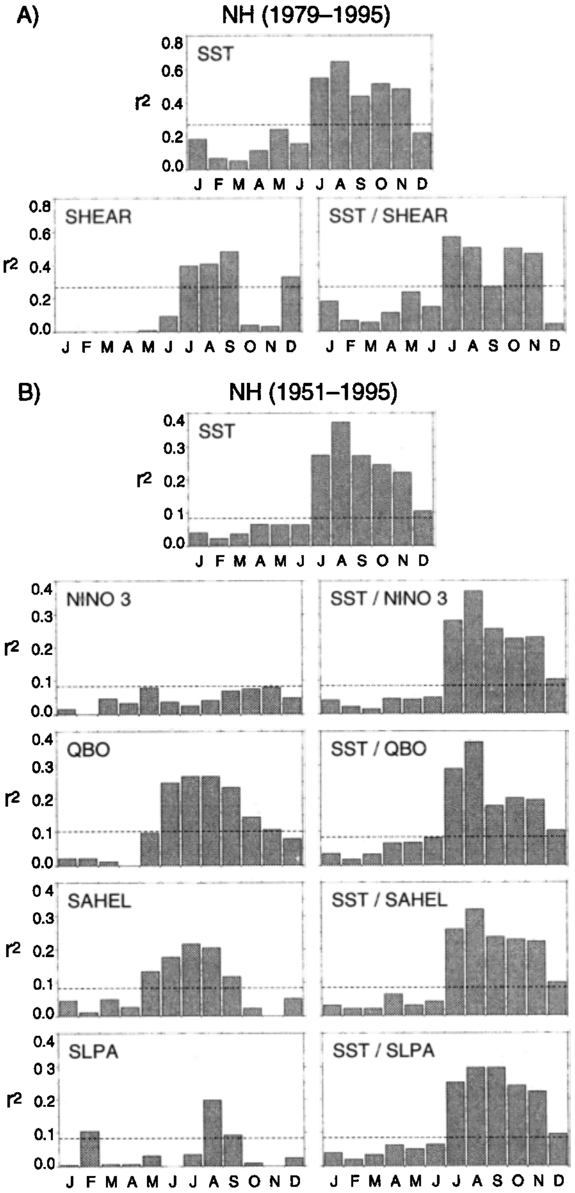

Figure 3. Comparison of the effect of SST and five other environmental factors in reducing the interannual variance, r^2, in the ASO number of hurricanes starting development within 10°-20°N, 20°-60°W. (A) spans the period 1979-1995. (B) covers the period 1951-1995. Dashed lines mark the 95% significance level. The monthly data sets employed are the mean SST for 10°-20°N, 20°-60°W (labelled SST), the mean vertical wind shear, defined as |V(200mb) - V(850mb)|, for 10°-20°N, 20°-60°W (marked SHEAR), the El Niño Niño 3 index (labelled NINO 3), the Singapore stratospheric 50mb zonal wind record (marked QBO) which spans 1954-1995, the west Sahel rainfall index (marked SAHEL), and the Caribbean plus Gulf of Mexico (10°-25°N, 70°-90°W) sea level pressure anomaly (labelled SLPA). The SST records come from the MOHSST6 data set [*Parker et al.*, 1995]. The vertical wind shears are obtained from the National Center for Environmental Prediction (NCEP) / National Center for Atmospheric Research (NCAR) Reanalysis Project fields [*Kalnay et al.*, 1996]. The Niño 3 SST and Singapore 50mb zonal wind anomaly values come from the National Oceanic and Atmospheric Administration's Climate Prediction Center. The SLPA values are derived from a blended analysis of the U.K. Meteorological Office (UKMO), NCAR, and the Scripps Institute of Oceanography [*Parker et al.*, 1994]. The monthly Sahel rainfall index is obtained from a blended analysis of UKMO and P. J. Lamb (University of Oklahoma) station data. The data spatial resolution of the SST and SHEAR records is 5° x 5° in latitude and longitude, while the SLPA data are of 5° x 10° resolution. Our use of the period 1979-1995 stems from the NCEP/NCAR reanalysis data being available, at the time of writing, only back to 1979. Our choice of the Niño 3 (5°N-5°S, 90°W-150°W) index follows that of recent studies by Gray and co-workers, while the area chosen for SLPA ensures maximisation of r^2 The top center panel in (A) and (B) gives the monthly r^2 value for SST. The panels centered below and to the left of the SST panels give the r^2 values for SHEAR, NINO 3, QBO, SAHEL and SLPA. The panels to the right of these give the partial variance correlations with the variability linked to SHEAR, NINO 3, QBO, SAHEL and SLPA removed from the SST r^2 values. The Figure shows that for the 10°-20°N, 20°-60°W development region, the SST influence on Atlantic hurricane numbers exceeds, and is largely independent of, the concurrent and lagged correlations of vertical wind shear, El Niño, QBO, west Sahel rainfall, and Caribbean SLPA.

'Anomalous' again means the number above the 50-year average values of 3.1 (NTS) and 2.1 (NH) (see Table 2). Errors are expressed to 95% confidence. All environmental factors, with the exception of SAHEL whose effect was neutral, had a positive influence on the 1995 anomalous activity. However, SST with its largest anomaly (Table 3) and strongest correlation (Figure 3), contributes the highest ΔNTS and ΔNH, albeit subject to error levels. This is true even allowing for 29% (39%) of the SST influence being correlated with SHEAR and SAHEL based on 1979-1995 (1951-1995) statistics. ΔNTS (ΔNH) percentage values of 41±26% (61±34%) correspond to 2.4±1.5 (2.4±1.3) anomalous tropical storms (hurricanes).

Discussion

Our regression analysis provides a compelling statistical case for sea temperature having the dominant environmental effect on hurricane formation within the 10°-20°N, 20°-60°W region. A physical mechanism for this association is suggested below. Tropical cyclones forming within the development region all originate from easterly wave disturbances coming off north

Table 3. Influence in 1995 of the Different Environmental Factors Linked to Interannual Variability in the ASO Number of Atlantic Tropical Cyclones Forming Within the 'Development Region'.

Environmental Factor	ASO Mean ± σ	1995 Anomaly	1995 ΔNTS	1995 ΔNH
1979-1995				
SST	27.45 ± 0.29 °C	2.00 σ	59 ± 46 %	75 ± 58 %
SHEAR	11.93 ± 1.40 ms⁻¹	-1.48 σ	24 ± 38 %	32 ± 48 %
1951-1995				
SST	27.38 ± 0.27 °C	2.41 σ	41 ± 26 %	61 ± 34 %
NIÑO 3	24.76 ± 0.84 °C	-0.79 σ	8 ± 13 %	9 ± 17 %
QBO*†	0.00 ± 13.95 ms⁻¹	0.79 σ	12 ± 15 %	17 ± 19 %
SAHEL†	0.00 ± 0.68	-0.12 σ	-2 ± 10 %	-3 ± 14 %
SLPA†	0.00 ± 0.58 hPa	-2.18 σ	25 ± 25 %	34 ± 33 %

*1954-1995 only; †anomaly

Africa. Easterly waves are convectively active troughs in the lower troposphere which track westward across the Atlantic in the tradewind flow between 10° and 20°N. Each year between May and November about 60 such waves cross this region, an average of one every 3 or 4 days [*Pasch and Avila*, 1994]. In 1995, more easterly waves developed into tropical cyclones within the 'development region' than in other years. Tropical storms are fuelled by the transfer of latent and sensible heat from the ocean. Through the Clausius-Clapeyron relation the latent heat content of air at constant relative humidity increases exponentially with SST, nearly doubling with SST rise from 20°C to 30°C. However, observations and theory indicate that tropical cyclone development and intensification is most sensitive to small increases in SST between 26-29°C [*Emanuel*, 1991; *DeMaria and Kaplan*, 1994; *Holland*, 1997]. For the Atlantic, the sensitivity to SST over this temperature range is due to the concomitant ability for cumulus clouds to start penetrating the trade-wind temperature inversion at 1-2km altitude [*Emanuel*, 1986], thereby leading to the onset of deep convection and the development of a warm core above ~10km altitude [*Holland*, 1997]. Penetration of the trade-inversion arises from the increased sensible and latent heat warming of boundary layer air as it moves over higher SST water. This warming leads to shallow cumulus convection which mixes the moist surface air with dry air above the inversion The convection also mixes dry air towards the surface which further increases evaporation from the ocean into the boundary layer [*Wells*, 1986)] Thus the higher the SST, the deeper the boundary layer, and the more favourable conditions are for easterly waves to develop into tropical storms.

While our analysis emphasises the role of local SST in influencing Atlantic hurricane formation, it is likely that remote SSTs also play a role. Remote SSTs would influence hurricane formation through the trade-wind advection of heat and moisture. Recent modelling work on the Asian summer monsoon shows the relationship between convection and SST is complex with contributions from both local and remote SSTs [*Soman and Slingo*, 1997]. We note in 1995 that the SST anomalies adjacent to the south east trade-wind flow off northwest Africa actually exceeded those in the hurricane development region.

Conclusions

The 1995 Atlantic tropical cyclone season was exceptionally active with double the 50-year average number of hurricanes and tropical storms. More than 90% of this anomalous activity began development inside the region 10°-20°N, 20°-60°W. While all known environmental factors apart from Sahel rainfall were favourable for hurricane development in 1995, we find that a record sea surface temperature warming within the development region had statistically the dominant influence. This result is based on the regression analysis of ~45 years of data.

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