JP3.37

AN EVALUATION OF THE LONG-TERM VARIABILITY OF TROPICAL STORM AND HURRICANE ACTIVITY IN THE ATLANTIC

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1. INTRODUCTION

Numerous studies have shown that the number of tropical storms and hurricanes developing over the Atlantic varies greatly, not only from one year to the next, but also over longer time scales (Gray 1990; Goldenberg et al. 2001; Emanuel 2005; Webster et al. 2005). Mechanisms responsible for these variations are not well understood, however. Nonetheless various oceanic, land surface and global processes, either individually or in combination, have been proposed as plausible candidates.

That tropical storm activity and sea surface temperature (SST) are closely related is a consensus view among scientists. Over the Atlantic, more than 60% of the storms develop in a narrow region, referred to as the main development region (MDR), from disturbances originating from Africa. Therefore, SST of this region is generally regarded as a crucial variable regulating the number of tropical storms. All else being equal, as SST of the MDR increases, so should the number of tropical storms. Surface waters of the entire North Atlantic exhibit multi-decadal variability (see Sutton et al. 2005 for example). Referred to as the Atlantic Multi-decadal Oscillation (AMO), this variability is also shown to influence Atlantic topical storm activity (Gray 1990; Goldenberg et al. 2001).

A recent study (Holland and Webster 2007) reported that the twentieth century Atlantic tropical storm activity was comprised of three distinct regimes, with each regime having its own characteristic SST pattern. Besides reiterating the finding reported in several other studies that an increasing trend is part of the recent Atlantic SST and tropical storm activity (Emanuel 2005; Webster et al. 2005), Holland and Webster attributed this trend to global warming. On the other hand, Landsea (2007) argues that the observed trend in tropical storm activity may not be the result of a forcing mechanism; rather, it is an artifact of improvements in storm monitoring.

It has also been shown that enhanced (suppressed) Atlantic tropical storm and hurricane activity coincide with wet (dry) spells over the Western Sahel region (Gray 1990; Landsea and Gray 1992; Landsea et al., 1992). Because more than 60% of the tropical storms of the Atlantic develop from African disturbances (Landsea et al. 1998; Goldenberg et al. 2001), an association between West African monsoon system, the chief regulator of convection over the Western Sahel region, and Atlantic hurricane activity is not entirely surprising. In this regard, Bell and Chelliah (2006) have shown that the long-term variability of upper tropospheric divergent circulation over Northwestern Africa, which is the byproduct of large-scale regional convection, is comprised of two multi-decadal modes. One of these modes evolves slowly, persists longer, and is related to the multi-decadal variability of Atlantic SST. The second mode, they argue, might be associated with land surface processes; it also appears to influence Atlantic tropical storm and hurricane formation and intensification. Interestingly, these two modes seem to exert their influence over different time periods.

Vertical wind shear of the horizontal wind and SST gradients over the tropical Atlantic also exhibit two distinct modes (Shapiro and Goldenberg 1998). Only one of which, the less dominant one, is connected to SST fluctuations in the MDR, but both modes appear to impact Atlantic tropical cyclone activity. Apparently, SST is not the sole determinant of Atlantic tropical storm and hurricane activity.

Several conclusions can be drawn from results reported in aforementioned studies and many others like them; among then are: (i) the tropical storm activity of the Atlantic undergoes systematic short-period and long-period variability; (ii) several process, either on their own accord or in conjunction with others, affect this variability; and (iii) how each individual variable influences the Atlantic topical storm activity may change with time.

In this study, a multi-pronged approach is employed to describe the long-term variability of the Atlantic tropical storm and hurricane activity and to associate this variability with SST of the MDR, the AMO, global land surface temperature anomalies (GLATA) and Western Sahel rainfall.

2. DATA & METHODOLOGY

HURDAT, the official database describing tropical storm and hurricane activity of the Atlantic basin (which includes the Gulf of Mexico and Caribbean Sea) contains yearly counts of tropical storms (NS), hurricanes (NH), major hurricanes (NMH) as well as the yearly accumulated cyclone energy (ACE)

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(www.aoml.noaa.gov/hrd/hurdat/Data_Storm.html). Yearly ACE is the sum of accumulated cyclone energies of individual storms, calculated by adding squares of maximum sustained surface wind speed, estimated at 6-hour intervals, when systems are at or above the tropical storm stage (Jarvinen et al. 1984).

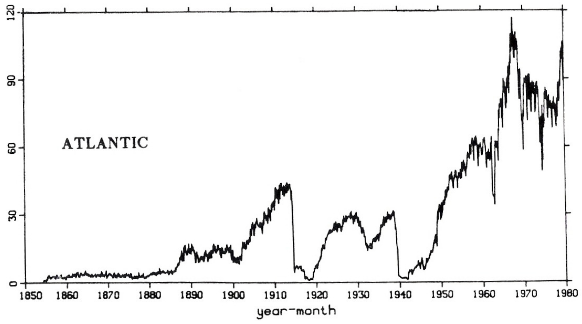

Fig. 1: Time series of number of ship observations in the Atlantic Ocean (from Sadler et al., 1987)

Prior to the launching of the first weather satellite in 1960, the formation, intensification and movement of tropical storms were monitored using ship and island weather reports. Though aircraft reconnaissance of Atlantic tropical storms commenced in 1944, only since the launching of the first weather satellite did the monitoring of storm activity reach a high level of accuracy. Ship traffic in the Atlantic through the first half of the twentieth century was sparse and was affected by the two World Wars (see Fig.1). Accordingly, the re-analysis initiative of the National Hurricanes Center that compiled the HURDAT database might not have accounted for all the storms that formed over the Atlantic during this period. This is especially true in the case of major hurricanes, which are relatively rare events, smaller tropical storms, whose effects felt only over a limited geographical area, and systems forming over eastern tropical Atlantic, a region less frequented by ships even during the middle 1900s. These shortcomings notwithstanding, HURDAT represents the only source of long-term tropical storm data from the Atlantic.

For the period from January 1854 till December 2006, monthly mean SST data from the MDR (10° to 20° N; 20° to 90° W) were extracted from NOAA's (National Oceanic and Atmospheric Administration) National Operational Model Archive and Distribution System (NOMADS). Using the data so extracted, seasonal averages were constructed for the June to October period, the period when almost all tropical storms and hurricanes form in the Atlantic. Data from the same source were used to construct annual mean SST values from a much larger area (0° to 60° N and 7.5° to 77° W) of the Atlantic and the time series containing these annual averages is used to represent the AMO.

Precipitation data from the Western Sahel dating back to the mid-nineteenth century are sparse. Only five meteorological stations, two each from Mali (Tombouctou and Keyes) and Senegal (Saint Louis and Dakar) and one from Gambia (Bathurst), have substantially long records. Monthly rainfall measurements were standardized by subtracting the long-term average of all available measurements in a month and dividing the result with the long-term standard deviation of that month. Standardized rainfall anomalies from each of the five pluvial months (June, July, August, September and October) were averaged to construct a yearly rainfall index for each station. The Western Sahel rainfall index (WSRI) used in this study is the average of the yearly rainfall indices from each of the five stations. The computational procedure used to construct WSRI is similar to what has been employed in other studies (see Landsea et al. 1992 for example). Data used to construct WSRI are available only for the 1861 to 2002 period.

Several scientific organizations have developed time series of annual global surface temperature anomalies (henceforth referred to as GLSTA) and the one used in this study is described in Jones et al. 2006, and is constructed using observations from land areas only.

Time series of NS, NH, NMH and ACE are made up of yearly aggregates, whereas the time series of SST and GLSTA are constructed by averaging several individual time series. Moreover, individual monthly SST observations are obtained by averaging all available in situ measurements in 2° x 2° latitude-longitude boxes and subjecting these averages to further data processing (Smith and Reynolds 1997). Similar spatial averaging was involved in the construction of AMO time series also. The only difference is that the area associated with the spatial averaging needed to construct the AMO time series is much larger. Such spatial averaging enhances the signal to noise ratio of long-period trend and oscillatory components in time series by reducing variance. The larger the spatial domain, the greater will be the reduction in variance.

A persistent long-term movement or trend appears to be a common characteristic of all time series used in this study (see Fig. 2). Not surprisingly, due to spatial averaging, this signal is most conspicuous in the time series of AMO, GSTA and SST. By contrast, NS, NH and NMH time series exhibit large year-to-year fluctuations. But these time series are also marked by frequent occurrences of larger values. Consequently, variances of these time series are elevated. Even so, it is not difficult to identify the long-term systematic changes in them. That said, given the paucity of observing platforms during the second half of the 19th and first half of the 20th centuries, observations in these time series may be biased, and the bias itself might be a function of the number of ships traversing the Atlantic. A case in point: During the 80-year period between 1861 and 1940, when the number of ships reporting weather observations were markedly low, no major hurricanes were recorded to have formed in 26 different years. Is this an artifact of sampling or a real signal? While the odds are good that some of the major hurricanes that formed during this period eluded detection, the overall decrease in hurricane activity seen prior to the 1920s is most likely a real signal, as SST of the MDR was at its lowest during this period. In other words, despite the inadequacy of sampling, it is still possible to tease out valuable information from the HURDAT database.

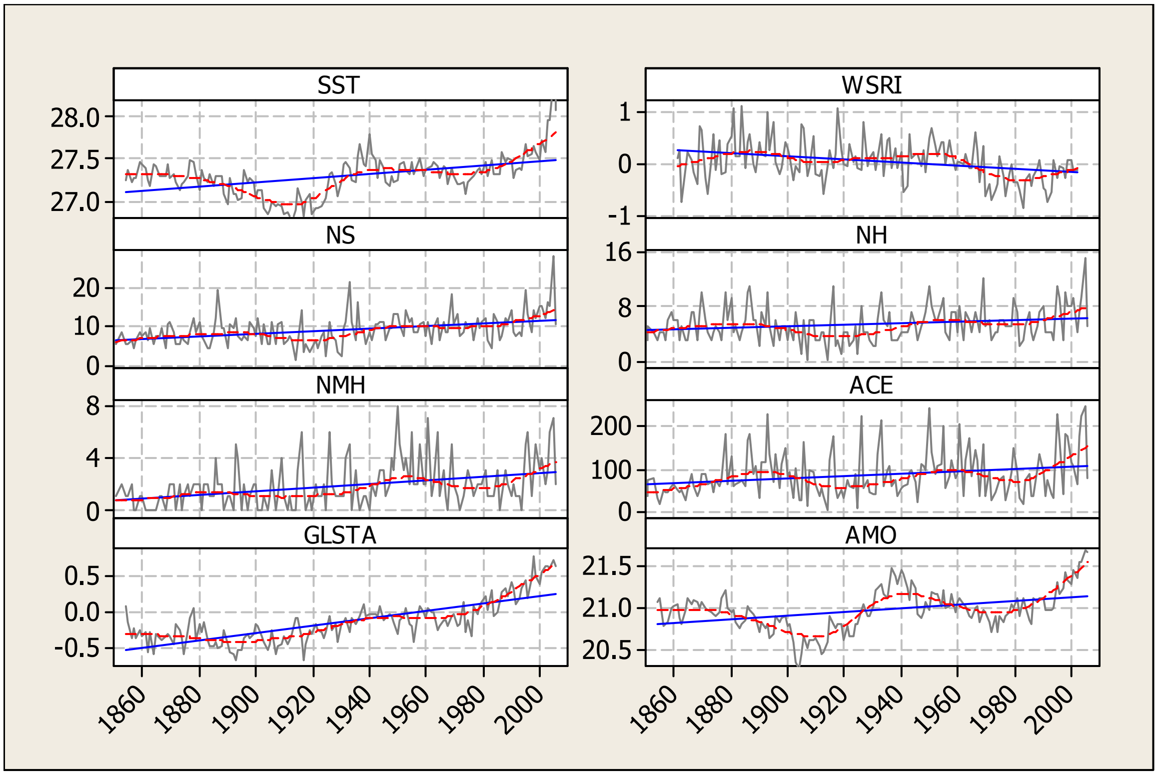

Fig. 2: Time series plots of SST from MDR, yearly counts of tropical storms (NS), hurricanes (NH) and major hurricanes (NMH), global surface temperature anomalies (GLSTA), Western Sahel rainfall index (WSRI), accumulated cyclone energy and Atlantic multi-decadal oscillation (AMO) (light gray lines). Black lines represent linear (deterministic) estimate and dashed lines represent stochastic trend estimates.

Without sufficient phenomenological justification, trends seen in SST and other time series are often modeled as deterministic and constrain them to be nonrandom functions of time. Slopes of simple linear regression equations fitted to time series data, by treating time as the independent variable, are then used to describe the nature of the temporal change.

More appropriately, these trends should be treated as stochastic, as their evolution appears to be non-deterministic in time. Most climatological studies employ moving average filters, also known as low-pass filters, to infer the shape of the function representing the stochastic trend (Trenberth and Shea 2006, Emanuel 2005, Webster et al. 2005). These filters impose a window on each times series, compute the average of time series observations within the imposed window and use the computed average as the estimate of the value of the trend function at the middle point of the window. By moving the window from the beginning of the time series to the end, one time step at a time, and the smooth functions representing the trend are determined. As the size of the window is increased, the degree of smoothness of the curve representing the trend increases. This approach has at least two drawbacks. First, trend estimates are influenced by the presence of outliers, and second, trend estimates are not available at either ends of the time series.

Nonparametric regression (Cleveland 1979), which also uses a window and treats time as the independent variable, may be used to obtain a robust estimate of the stochastic trend, even at the end points. The width of the window is specified as a fraction of the number of observations in the time series and the window itself may be centered at any desired value of the independent variable. As with moving average smoothers, wider windows produce smoother estimates. Each value of the dependent variable within the imposed window is assigned a weight. Weights are determined based on how far are the corresponding independent variables from the center of the window. Weighted dependent and corresponding independent variables are used to fit a weighted linear regression equation. This equation is then used to compute the fitted value of the regression at the center of the window, which serves as the value of the trend function. By placing the window at any desired value of the independent variable, which is time, from the beginning of the time series till the end, the shape of the function representing of the trend can be obtained. Not only does the nonparametric regression used in this study minimize the effect of outliers with the help of a recursive procedure, it also provides trend estimates at end points. Like all statistical estimates, however, computing the stochastic trend using nonparametric regression involves bias-variance tradeoff. Larger windows reduce variance at the expense of bias and vice versa. For this reason, sizes of windows were determined using trial and error.

The suggestion in Holland and Webster (2007) that increasing trends in SST and hurricane activity in the Atlantic are due to global warming creates a methodological problem, when one tries to assess the relationship between hurricane activity and mechanisms regulating it. This is because global warming affects hurricane activity as well as mechanisms regulating this activity, namely SST, AMO and WSRI etc. In an attempt to overcome this difficulty, the aforementioned nonparametric regression procedure was used to control for the effects of global warming on other time series. A two-step process, involving fitting smooth functions representing relationships between GLSTA and each of the other variables and subtracting fitted functions from each of the time series, was used to achieve this.

In order to determine whether or not the relationship between tropical cyclone activity and each of the independent variables is changing with time, Pearson's correlation coefficients were computed in a manner analogous to computing moving averages, using 30-year moving windows. Pairs of observations from the first possible 30-year period, 1861 to 1890, were used to calculate the first correlation coefficient. By moving the window one time step at a time and computing the correlation coefficient each time, 30-year running correlation coefficients were estimated until all available 30-year time periods were exhausted. Nonparametric regression, described earlier, is then used to estimate smooth curves representing the temporal evolution of bivariate relationships.

When two or more mechanisms are known to influence a process, partial correlation may be used quantify the relationship between the process in question and a specific mechanism by controlling for the effects of other mechanisms. Given the distinct possibility that the relationship between Atlantic tropical storm activity and mechanisms regulating it might change with time, computing 30-year running partial correlations is not only the prudent thing to do, it is also an imperative. Time-varying nature of the underlying relationship is explored with the help of smooth curves fitted to correlation coefficients plotted against time. Curves themselves are fitted using the same nonparametric regression procedure used to describe stochastic trends and time varying patterns of correlation structure.

3. RESULTS

Deterministic trend estimates (Fig. 2) suggest that all time series variables, save WSRI, have increased in magnitude with time. These estimates do not adequately describe the temporal evolution of the variables, however. Stochastic trend estimates (Fig.2), by contrast, trace the long-term movement of all time series variables very effectively; most effectively in the case of SST from the MDR and AMO. In the case the SST time series, the stochastic trend accounts for 56% of the variance. By contrast, only 18% of the variance of the WSRI time series is accounted for by the stochastic trend component. Similar percentage for NS, NH NMH and ACE are 23%, 14%, 16% and 16%, respectively.

Without a doubt, between 1851 and 2006, tropical storm activity in the Atlantic Ocean appears to have waxed and waned, though not in a strict periodic manner. During the first 100 years of the study period, when storm detection relied heavily on ship weather reports, the number of ships traversing the Atlantic increased steadily, which, no doubt, affected storm detection. A bias, therefore, might be present in the data. The number of storms detected prior to the satellite monitoring era might be proportional to the number of ships traversing the Atlantic Ocean. However, upon closer scrutiny, it also becomes clear that the temporal variability in NS, NH, NMH and ACE can not be explained in terms of the number of ships traversing the Atlantic alone. One may, therefore, surmise that features revealed by the stochastic trend estimates are not mere artifacts of sampling; instead, they are more or less true representations of changes that occurred during the last 150 years. Even so, the probability that yearly storm counts, compiled using ship and island weather reports, underestimated what actually occurred is not zero. Therefore, it is better to focus on the waxing and waning pattern seen in trend estimates, than on the actual storm counts themselves.

Yearly storm count increased gradually from 1851 to 1890, a period when the number of ships traversing the Atlantic remained more or less the same, except for the last 5 or so years of the period. At the same time, within the MDR, SST appears to have decreased gradually. Ordinarily, one would expect the number of tropical storms to decrease as SST decreases. But observations from this time period suggests otherwise. Interestingly, there is no such discord between trends in NS and WSRI. Increasing rainfall in Western Sahel was associated to an increase in the number of tropical storms. From the mid 1880s onward, the number of storms forming in the Atlantic decreased, reaching a minimum around 1920. Trend components of NH, NMH and ACE also exhibit a similar pattern, which is better defined in the case of the NMH and ACE. Notice also that while the minimum in SST precedes the minima in NS, NH, MNH and ACE, there is a batter correspondence between these minima and the minimum in WSRI.

Coinciding with the First World War, ship traffic in the Atlantic decreased precipitously, but the decade prior to World War I was marked by a great surge in ship traffic. A less dramatic increase in ship traffic occurred between 1885 and 1900 as well. But tropical storm and hurricane activity decreased around the same time. Hence, this decrease is most likely a real signal.

Tropical storm and hurricane activity began to increase in the early 1920s, a trend that continued for the next 30 years, eventually reaching a maximum, though not a very prominent one, in the mid 1950s. Correspondingly, WSRI also registered its maximum. Prior to the 1920s, SST of the MDR began increasing and this increase was most dramatic till 1940, as were increases in NS and NH. However, SST increase peaked well before NS, NH, NMH and ACE registered their peaks. Though peaks in NS, NH, NMH and ACE did not coincide with the SST peak, the heightened storm activity occurred when SST was relatively high.

Ship traffic again dwindled during the Second World War, rebounded after the war and reached pre-war levels by about 1950 (Fig. 1). The number of tropical storms and hurricanes detected during this period were high, notwithstanding the possibility that decreased ship traffic might have caused the measuring system to underestimate the tropical storm and hurricane activity during a shot period.

Trend components of NS and NH exhibited a minor decrease from the mid 1950s till about 1980, as did the trend component of SST, with the minimum in SST occurring first. Not only is this decrease more vivid in the case of NMH and ACE, it is also matched by an equally vivid decrease is WSRI.

A sharp, but not necessarily an unprecedented, increase in tropical storm activity is seen since 1980. But is this increase due to global warming? An attempt is made to answer this question later in the following paragraph.

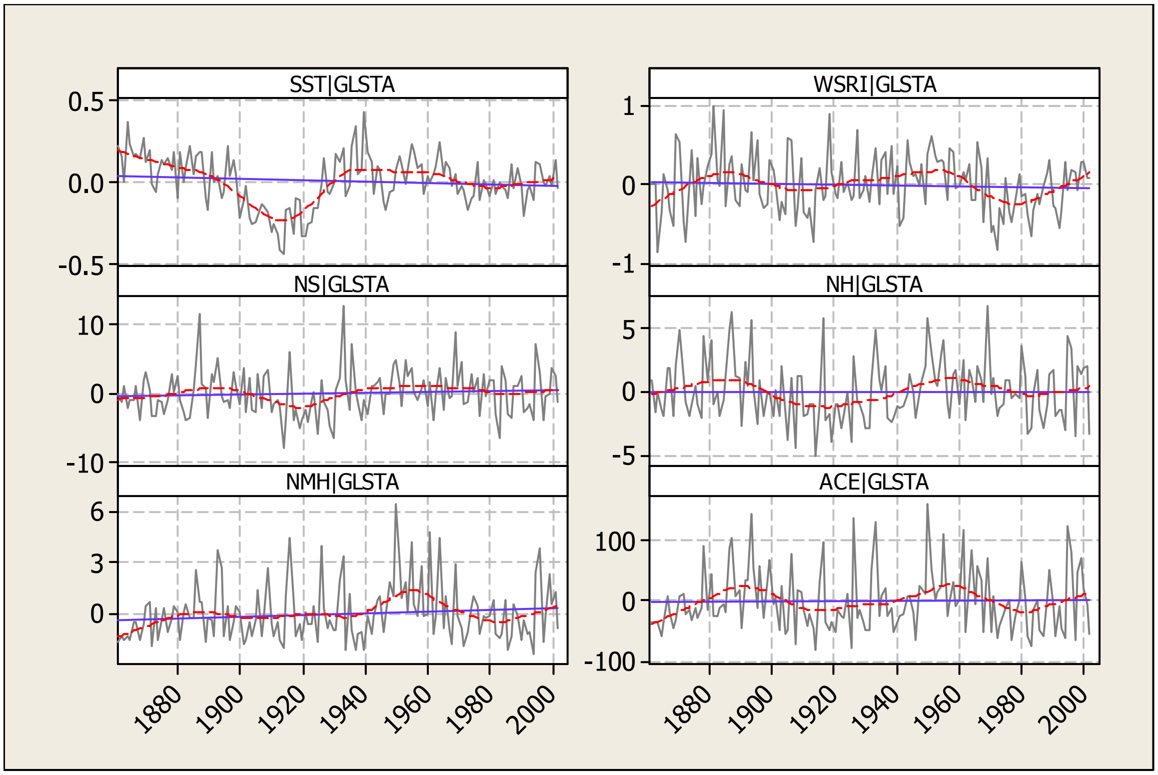

Fig. 3: Time series plots of SST, NS, NH, NMH, ACE and WSRI after controlling (see text for details) for the effects of global warming (gray lines). Blue and red lines represent linear trend and stochastic trend estimates, respectively.

Many aspects of the long-period variability of Atlantic tropical storm and hurricane activity, including increases in the numbers of tropical storms, hurricanes, and major hurricanes that began around 1980, remain intact even after controlling for the effects of global warming (see Fig. 3). At best, the recent global warming trend accentuated the increase in tropical storm activity that commenced around 1980. Moreover, the correspondence among tropical storm activity, SST of the MDR and WSRI vis-à-vis their long-period variability appears to be unaffected by the global warming signal. In other words, attempts to interpret the recent surge in Atlantic tropical storm and hurricane activity in terms of a single mechanism, namely global warming, lack empirical support.

Previous studies (Elsner at al. 2006, for example) have employed correlation and partial correlation analyses to explain how different variables/mechanisms influence tropical storm and hurricane activity in the Atlantic. Systematic long-term variability brings forth persistence in data and when persistence is present, the magnitude of the correlation coefficient is inflated, making it difficult to ascertain its statistical significance. Moreover, relationship between each dependent variable representing various aspects of tropical storm and hurricane activity (NS, NH, NMH and ACE) and the independent variables (SST and WSRI) impacting each of them may change with time. Keeping these issues in mind, a heuristic approach is adopted to study correlation structure among variables. It involves computing 30-year moving partial correlations coefficients and using the nonparametric regression to probe whether or not relationships among variables change with time.

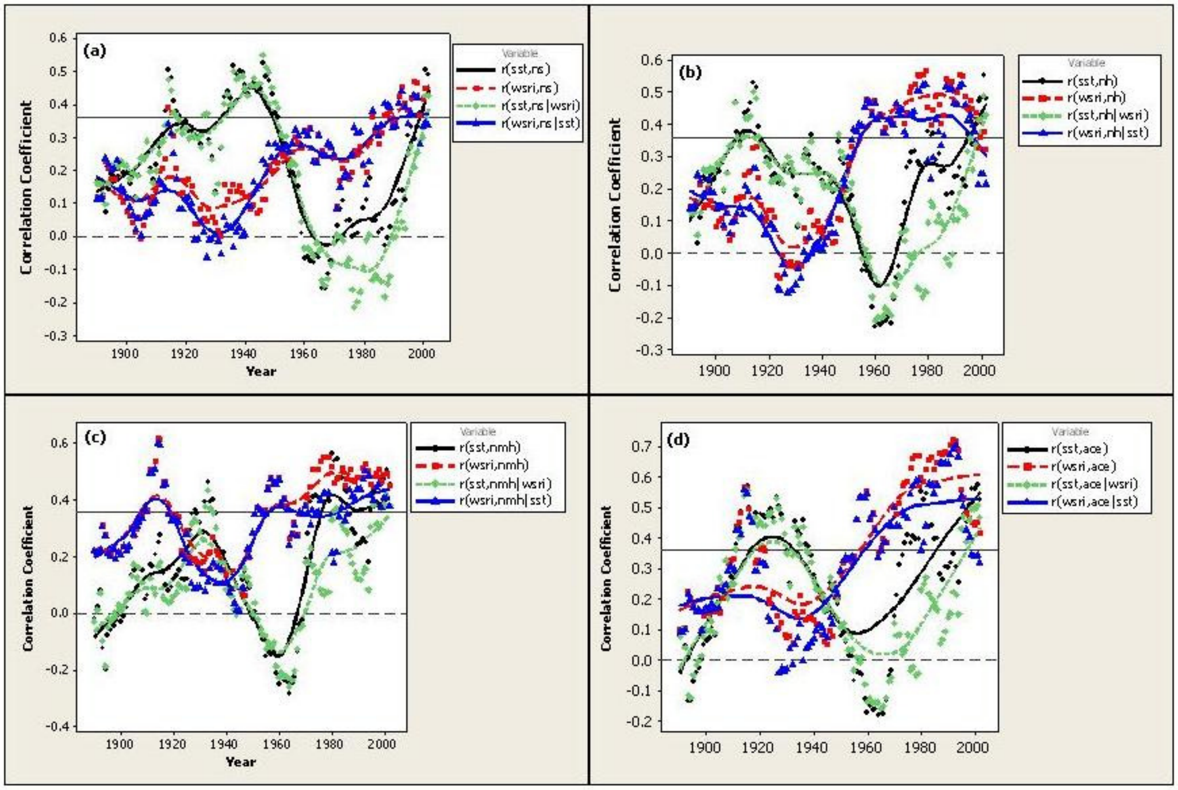

Fig. 4: 30-year running correlation (black and red symbols and lines) and partial correlation coefficients (blue and green symbols and lines) among (a) SST, NS and WSRI, (b) SST, NH and WSRI, (c) SST, NMH, and WSRI, and (d) SST, ACE and WSRI. Note that notations, sst,ns|wsri (green symbols and lines) and wsri,ns|sst (blue symbols and lines), stand, respectively, for partial correlation coefficients between SST and NS when effects of WSRI are controlled and partial correlation coefficients between WSRI and NS when effects of SST are controlled. The correlation and partial coefficients plotted against 1890 are computed using 30-year data from 1861 to 1890. Nonparametric regression curves, estimated separately for each pair, are also shown.

A cursory examination is sufficient to recognize several interesting aspects exhibited in these graphs. First, the relationship among dependent and independent variables change with time, though magnitudes of correlation coefficients themselves are relatively small. As a point of reference, it is useful to note that for the correlation coefficient to be statistically significant at the 95% level, its value must be 0.316 or above, when the number of observations is 30. Second, a see-saw-type pattern is seen in the magnitudes of correlation coefficients between storm activity and each of the two independent variables, SST and WSRI. For example, during the first half of the 20th century, when correlations coefficients between SST and NS are near or above 0.316, correlation coefficients between NS and WSRI are near zero. The relationship between the number of storms and WSRI began to strengthen during the second half of the 20th century. Correspondingly, the association between NS and SST started to decline. In recent decades, strengths of relationships between tropical storm activity and the two independent variables considered in this study have been increasing. Compared to SST, magnitudes of correlation coefficients between various aspects of tropical storm activity and WSRI are higher, however. Third, controlling for the effects of one of the independent variables does not reduce the magnitude of the correlation coefficient between the other independent variable and various measures of tropical storm activity. The inescapable conclusion is that how each of the two independent variables considered in this study regulates the Atlantic tropical storm activity is only weakly mediated by the other. Since the reduction in the magnitudes of partial correlation coefficient is greater when controlled for WSRI than SST, processes regulating Western Sahel rainfall might have a strong mediating effect on Atlantic tropical storm activity.

4. CONCLUSIONS

Stochastic trends of various aspects of Atlantic tropical storm activity–numbers of storms, hurricanes, major hurricanes and accumulated cyclone energy–and two variables believed to be regulating this activity, estimated using nonparametric regression, allow one to draw the following inferences. All aspects of Atlantic tropical storm activity have changed systematically in the last century and half. Changes occurred since the 1980s are most conspicuous and they are marked by an increasing trend. This trend, however, does not appear to be unprecedented, as its extent is comparable to what occurred between 1920 and 1940. Similar changes are seen in the time series of SST and WSRI, with the pattern in WSRI matching more closely with storm activity. Patterns revealed by stochastic trend estimates can not explained in terms of changes in the observing system alone.

To examine, whether or not the recent increases in Atlantic tropical storm activity are due to global warming, effects of the latter were statistically controlled in all time series. Controlling for the effects of global warming diminished the extent of the most recent increase in storm activity. But the residual time series still exhibits a diminished increasing trend. One may, therefore, surmise that if global warming played any role in impacting recent increases in Atlantic tropical storm activity, it was to accentuate a change that has been mediated by other processes.

Time-varying correlation analysis between various aspects of tropical storm activity and the two independent variables leads one to construe that how one process impacts tropical storm activity is not mediated by the other process.

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