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THE NON-STATIONARY CORRELATIONS BETWEEN WEST AFRICAN PRECIPITATION AND ATLANTIC HURRICANE ACTIVITY

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1. Introduction

A desire to produce long-range forecasts of seasonal Atlantic hurricane activity has motivated research into the various potential predictors for many years. Gray et al. (1993) has shown that a number of factors are useful to forecast the Atlantic tropical cyclone activity at the start of the most active period on 1 August. The nine predictors used in their seasonal forecast were related to West African rainfall, the phase of the stratospheric quasi-biennial oscillation (QBO), the phase of the El Niño-Southern Oscillation (ENSO), and sea level pressure and upper-level zonal wind anomalies in the Caribbean. In their investigation period from 1950–1990, by far the largest predictive skill was related to two measures of West African precipitation: the June-July rainfall in the West Sahel and the August–November (ASON) rainfall in the preceding year along the Guinea Coast. In another study using the same period, Gray et al. (1992) found that about 50% of the variance in several measures of Atlantic tropical cyclone activity can be predicted 6–11 months in advance by forecasting the phase of the QBO and using the observed August–September West Sahel and ASON Guinea Coast rainfall anomalies. The latter predictor showed the largest skill, again highlighting the dominant role of West African rainfall. Gray et al (1992) argued that the high year-to year persistence of the West Sahel rainfall and a positive soil moisture feedback in the Guinea Coast region on the West African monsoon rainfall in the following year are causal factors for the long-range forecast skill. The strong relation between the preceding year's ASON Guinea Coast rainfall and the concurrent June-September (JJAS) rainfall in the West Sahel to intense Atlantic hurricanes became apparent at the same time due to the work by Landsea and Gray (1992, LG92 hereafter), Landsea et al. (1992), and Gray and Landsea (1993). The latter two studies emphasized the simultaneous relation of West African rainfall and the number of intense landfalling US East Coast and Florida Peninsula hurricanes. As noted by Klotzbach and Gray (2004), the relation between West African rainfall and Atlantic tropical cyclone activity broke down rather unexpectedly in the mid-1990s for as of yet unexplored reasons. Those authors raised the questions whether this was due to a physical cause or a sampling problem affecting estimates of African rainfall from station data. In any case, that study contributed several additional predictors to the emerging statistical model but excluded consideration of monsoon precipitation in Africa.

The present study revisits the nature of the correlations between various West African rainfall indices and measures of Atlantic tropical cyclone activity for the 87-year period 1921–2007 using rainfall indices for the Western Sahel, Guinea Coast, and Central Sahel regions and some additional, recently developed measures of Atlantic tropical cyclone activity. Nicholson and Palao (1993, their Fig. 16) defined the three homogeneous rainfall regions that exhibit markedly different characteristics of rainfall variability on seasonal to multi-decadal time scales. The denomination of the regions used in this study is different to those of Nicholson and Palao (1993), but consistent with Landsea et al. (1997). The rainfall indices in this study are largely unaffected by changes in the availability of station data, especially for the recent period when the correlation between tropical cyclone activity and West African rainfall deteriorated.

2. Data and methods

a. Hurricane, re-analysis, sea-surface temperature and El Niño-Southern Oscillation data

Utilizing the re-analyzed hurricane best track data that have been downloaded from the Hurricane Research Division webpage http://www.aoml.noaa.gov/hrd/hurdat/ for the period 1851–2007, a number of indices that reflect the activity of the Atlantic hurricane season either in terms of storm number and/or intensity have been calculated. For this presentation, the only such index that is discussed is the Accumulated Cyclone Energy index (ACE, Bell et al. 2000). ACE is calculated for each six-hourly period by squaring the estimated maximum sustained wind speeds of each system of either tropical storm or hurricane intensity; these values are then summed for the season. The seasonal ACE value is a measure of the kinetic energy of the storm season. In the present study, subtropical storms have been excluded from all indices.

The first generation of the National Centers for Environmental Prediction (NCEP-1) re-analyses (Kalnay et al. 1996) at T62 spectral resolution available on a 2.5° x 2.5° latitude–longitude mesh were employed to calculate monthly values of the 200-850-hPa vector wind shear and the 700-hPa relative vorticity for the period 1958–2007. Prior to 1958, the lack of quality controlled, electronically available upper-air data casts doubt on the quality of the NCAR/NCEP reanalyses (Kistler et al. 2001; Stickler et al. 2010). The latter authors, for example, point to a specific deficiency of the NCAR/NCEP reanalysis in the representation of the West African monsoon circulation before 1958. Kossin and Vimont (2007) note a significant bias in plots of vertical shear prior to 1957 over the North Atlantic tropical cyclone basin. Monthly sea-surface temperature (SST) data for the 1921–2007 period were taken from the HADISST data set (Rayner et al. 2003). The values of the Southern Oscillation Index (SOI) have been computed by the NCAR Climate and Global Dynamics (CGD) Climate Analysis Section (CAS) and were downloaded from http://www.cgd.ucar.edu/cas/catalog/climind/soi.html.

b. West African rainfall indices

Constrained by the availability of monthly rainfall data on the Global Telecommunication System (GTS), Landsea et al. (1998) used a reduced sample of seven stations in the Western Sahel to assess the role of the concurrent JJAS Western Sahel rainy season for the very active 1995 hurricane season. For similar reasons, Landsea et al. (1997) chose 10 (14) stations to gauge the quality of the rainy seasons in the Guinea Coast (Central Sahel) with respect to the 1950–1990 base period. These stations were located in the three rainfall regions depicted in Fig. 16 of Nicholson and Palao (1993). The rainfall indices for the period 1950–1998 and the JJAS 1950–1990 mean rainfall for each of the 31 stations were furnished for this study by Christopher Landsea. For the present work, the monthly rainfall data have been updated and extended into the past by using the Global Historical Climatological Network (GHCN) version 1 and 2 data sets (Vose et al. 1992, Peterson et al. 1997) and the NCDC Monthly Climatic Data of the World (MCDW) available at http://www5.ncdc.noaa.gov/pubs/publications.html to cover the period 1921–2007. Significant data gaps in these resources – particularly in the observations necessary to calculate the August–November (ASON) indices along the Guinea Coast – were remedied through the collaboration with the African Centre of Meteorological Applications for Development (ACMAD) and the Service Météorologique National (SMN) in Benin under the African Monsoon-Multidisciplinary Analysis (AMMA) and Integrated Approach to the Efficient Management of Scarce Water Resources in West Africa (IMPETUS) projects.

Additionally, the number of stations in the Guinea Coast region has increased in the present study by six in Ghana and Nigeria to cover the Guinea Coast region more evenly (Fig. 1). The additional monthly station data for the period ASON 1921-2007 were provided to us by the Ghanaian and Nigerian Meteorological Agencies. Note that the period used in the correlation analyses ends one year earlier due to the one-year lagged relationship between Guinea Coast rainfall and Atlantic hurricane activity. The linear correlation coefficient between the ASON Guinea Coast rainfall index time series based on 10 and 16 stations is 0.97. Furthermore, as expected, the index time series for the larger station sample is smoother (not shown).

The calculation of rainfall indices based on these precipitation data is given in a forthcoming paper that has been submitted to the *Journal of Climate* (Fink et al., 2011).

3. Modulating factors of the correlation between West African rainfall and Atlantic hurricane activity

In this section, a statistical methodology is used to explore some of the ways in which changes in the large scale environment can modulate the character of the relationship between parameters such as West African rainfall indices and ACE. The hypothesis is that there are subsets or subsamples of observations in which the correlations between the predictor and predictand are stronger than in others. These subsamples are not, in general, composed of consecutive annual observations, as implicitly assumed in the calculations shown in the previous section, but rather are lists of years stratified with respect to some third independent variable. For example, one could hypothesize that an index of annual West African rainfall could be more highly correlated with Atlantic hurricane activity in El Niño years than in La Niña years. In that scenario, the subset of years defined as having El Niño conditions, as defined by an independent variable such as the Southern Oscillation Index, would demonstrate a different correlation coefficient than in the subset of years defined as having La Niña conditions. Documented nonlinearities in teleconnections established in cold and warm events (e.g., Hoerling et al. 1997) may enhance or reduce this difference. In any case, it would also need to be shown that the difference between these correlations is statistically significant, using the test outlined in Fink et al. (2011). Finally, it should be noted that some of these stratifications variables (such as SST, midtropospheric relative vorticity, and vertical wind shear) can be highly correlated themselves.

a. Samples stratified by SST or phase of ENSO

Figure 2 presents maps of the difference in correlation between indices of Sahelian precipitation and ACE. At each location on these maps, a time series of 87 years of SST values for August through October was used to determine the 29 warmest years (namely, one third of the available data) and the 29 coldest years. The August through October period was chosen because it spans the height of the Atlantic hurricane season. The correlation between Sahelian rainfall and ACE was computed for each of these two subsamples of years, and the difference between the two correlations is plotted. The null hypothesis is that the correlation coefficients of the two subsamples are statistically indistinguishable. This hypothesis is rejected if the absolute value of the difference in correlation exceeds the thresholds established in Fink et al. (2011), meaning that we can state at the given confidence level that the correlation between Sahel precipitation and ACE was different in

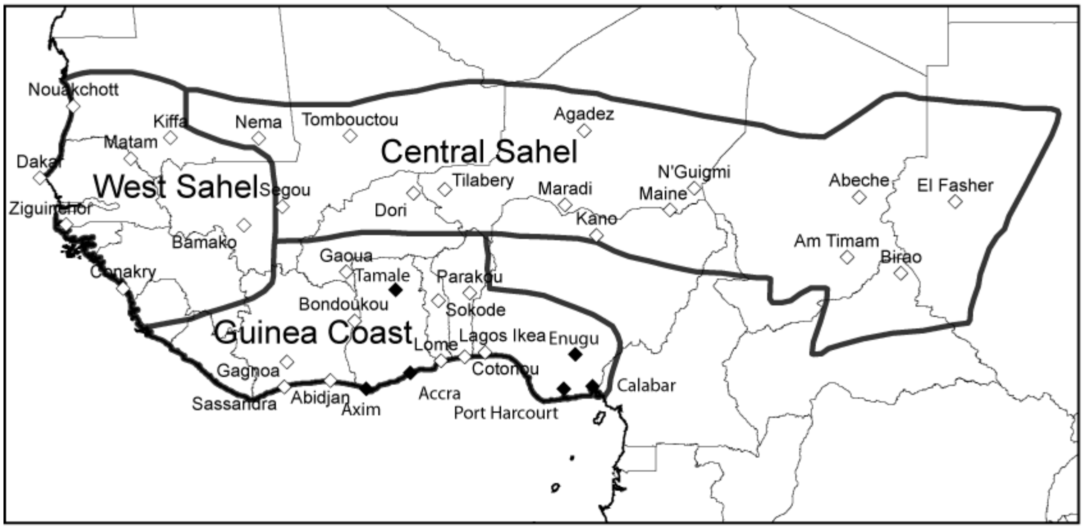

Figure 1. Definition of regions and stations employed in this study. The six stations with bold markers in the Guinea Coast region have been added to the original set of stations obtained from Christopher Landsea.

the two subsamples that had been picked as a function of SST at the given location.

As can be inferred from the contour lines in Fig. 2a, in the tropical North Atlantic's warm years the correlations are near 0.0 for the Western Sahel rainfall index whereas in the cold years the correlations were in the range of 0.5 to 0.7. Therefore, the difference in correlation across this domain is approximately -0.6, as evident from the green shading in Fig. 2a. At many grid points in this region, the differences in correlation exceeded the 95% confidence level determined by the Monte Carlo method described in Fink et al. (2011). The insignificant correlation between the Western Sahel rainfall index and ACE in the warm years is likely to be due to the local forcing of ACE by the underlying warm SSTs; that is, the status of precipitation in the Western Sahel does not influence ACE when the waters in the MDR are exceptionally warm. In contrast, the fairly high correlation in the cold years in the tropical North Atlantic demonstrates that the precipitation in the Western Sahel is a strong predictor of ACE when the SST conditions are generally less favorable for tropical cyclogenesis. The results for the Central Sahel rainfall index in the Atlantic Basin are similar (Fig. 2b).

In Fig. 2c, it can be seen that the known correlation between Atlantic tropical cyclone activity and the ASON Guinea Coast rainfall index in the preceding year is not meaningfully modulated by the water temperatures in the tropical Atlantic. The positive differences in correlation on either coast of Central America indicate that this correlation may be somewhat weaker in the years when these domains are unusually cold, but the differences in correlation do not reach the 95% confidence level determined by the method described in Fink et al. (2011).

Figure 3a and 3b display the difference in correlations between Sahel rainfall and ACE for warm and cold SST years in the western tropical Pacific. Between 150°E and the International Date Line (IDL), the difference in correlation shows large negative values. In years with high SSTs in this region, correlations between the indices of the Sahelian precipitation and ACE are close to zero or negative. These correlations are fairly weak for Western Sahel rainfall anomalies, but in the case of the Central Sahel they are below -0.3. In the cold years in

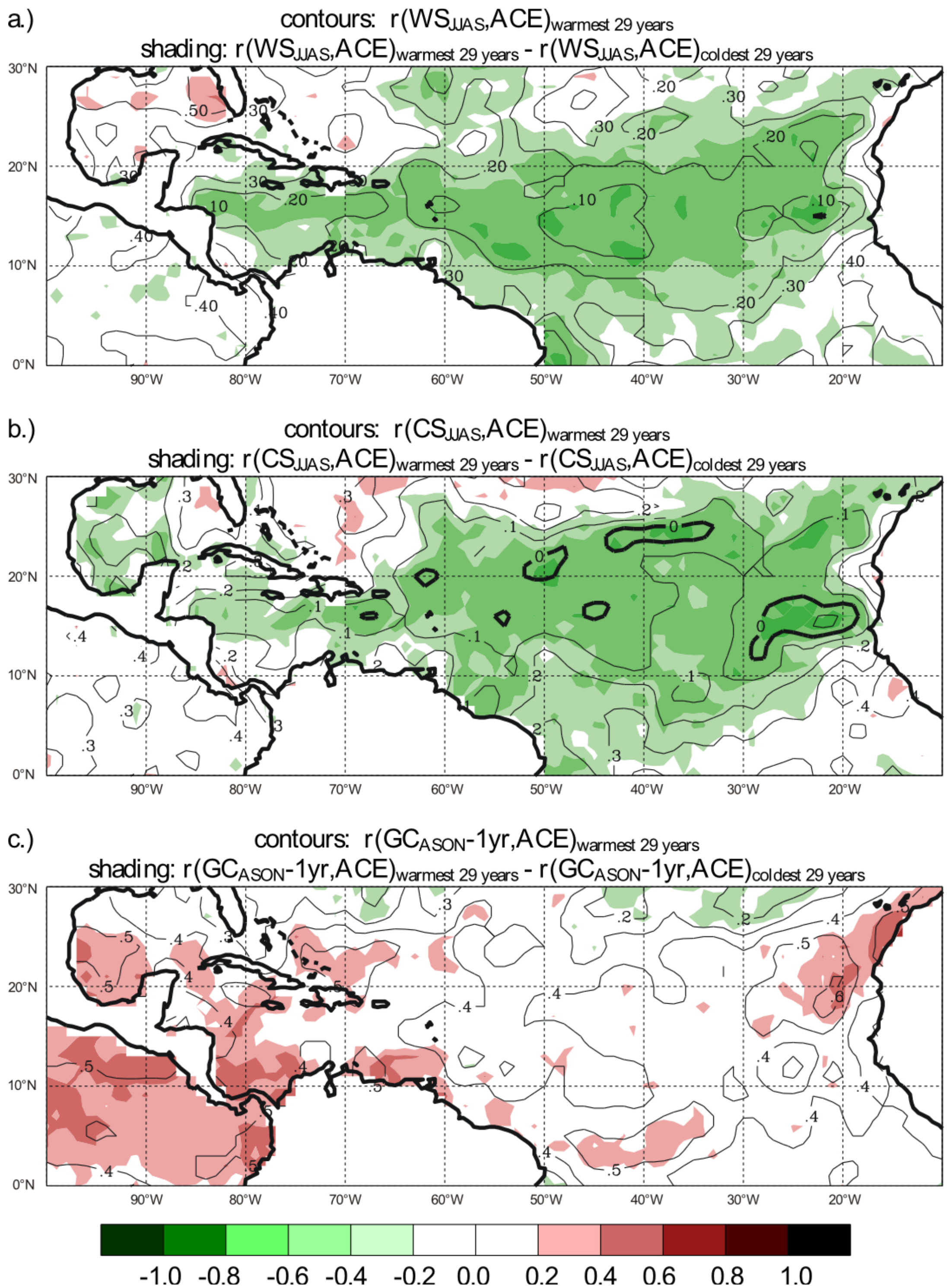

Figure 2. (a) Shading depicts the difference in the linear correlation coefficients between pairs of ACE and the JJAS West Sahel rainfall index in two subsamples, one being the 29 years with the highest SST at a given grid point and the other being the 29 years with the lowest SST at the same grid point. Black contour lines show the correlations in just the warmest 29 years, with the zero contour being thicker. (b) As in (a), but for the JJAS Central Sahel rainfall index. (c) As in (a), but for the ASON Guinea Coast rainfall index in the preceding year.

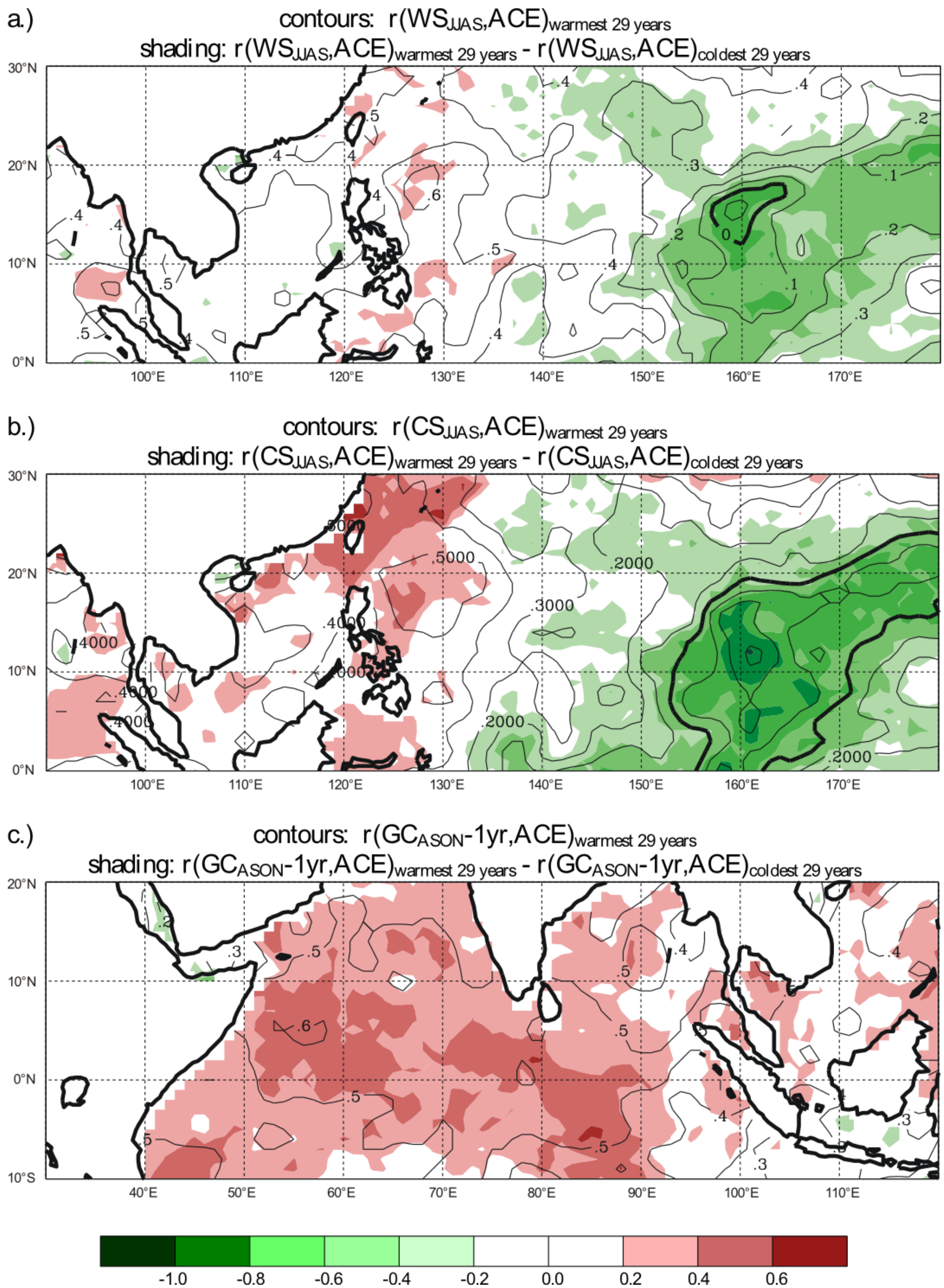

Figure 3. As in Figure 2, but for selected remote domains.

the Western Pacific, however, correlations between West African precipitation and ACE are very high, ranging from 0.5 to higher than 0.7. The resulting differences in correlation, shown in Figs. 3a and 3b are statistically significant at the 99% confidence level.

It is tempting to interpret this interesting signal as a manifestation of El Niño's known impact on tropical cyclogenesis in the Atlantic basin. In this reading, cold water in the western equatorial Pacific is associated with El Niño conditions in the eastern Pacific and, therefore, suppressed tropical cyclogenesis; once again, the hypothesis that West African precipitation is a good predictor of tropical cyclone activity only when other conditions are unfavorable is invoked. However, the strongest correlations between West African precipitation indices and ACE were found in the years when SSTs were cold between 150°E and the IDL, a region where the SST anomalies associated with El Niño change sign and are therefore small (cp. Fink and Speth 1997). In the tropical Pacific between 150°E and the IDL, the lists of the 29 coldest years contained a mix of both El Niño and La Niña years. Furthermore, if ENSO were the primary process modulating the character of the relationship between Sahelian rainfall indices and Atlantic hurricane activity, one would expect to find strong differences in the correlations between these parameters when the subsamples were stratified with respect to SSTs in the eastern tropical Pacific, where the ENSO signal is typically much more robust; in practice, the differences in correlations corresponding to that region are statistically insignificant (not shown). This is consistent, too, with the results depicted in Figs. 4a and 4b, which illustrate the correlations between Sahelian rainfall indices and ACE for subsamples stratified by the magnitude of the SOI. While there is some modest suggestion that the Sahelian rainfall indices are better predictors of Atlantic hurricane activity in El Niño than in La Niña years, this difference never rises to a meaningful significance level as defined by the

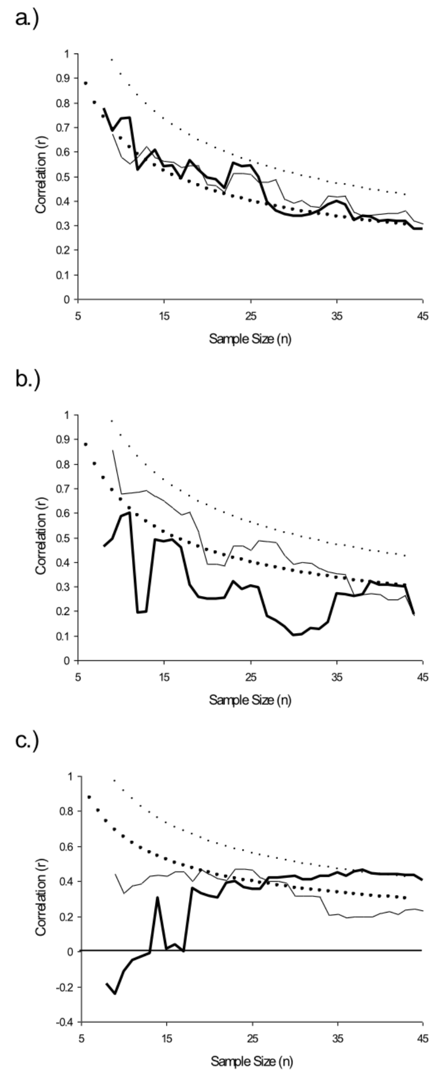

Fig. 4: Correlations between Accumulated Cyclone Energy (ACE) and the June September Western Sahel rainfall index in subsamples of observations. The subsamples are comprised of the years with the highest (thin solid) and lowest (thick solid) values of the Southern Oscillation Index (SOI) in August-October, where the size of the subsample is shown on the abscissa. (b) As in (a), but for the Central Sahel rainfall index. (c) As in (a), but for the preceding year's August November Guinea Coast rainfall index. The 95% and 99% confidence levels for correlations are shown using large and small dots, respectively. (The differences in correlation between the high and low SOI samples do not exceed the 95% confidence interval given in Fink et al. 2011.)

Monte Carlo techniques explained in Fink et al. (2011).

Returning to Figure 3, the lowest panel shows the differences in correlation for ACE and the ASON Guinea Coast rainfall index of the preceding year; as before, here the subsamples of years were chosen based on the 29 years with the highest and lowest SSTs at each grid point. Although the differences in correlation do not quite rise to the 95% confidence level, the results shown in Fig. 3c may suggest that the nature of this relationship is modulated by water temperatures in the tropical Indian Ocean. When SSTs were high in this region, the correlation was statistically significant, whereas that correlation slips to insignificant values during the colder years. As much of West African rainfall is thought to be negatively impacted by high SSTs in the Indian Ocean (e.g., Bader and Latif 2003; Lu and Delworth 2005), it is possible that this result suggests an exploitable connection between global SST patterns and Atlantic tropical cyclone activity. Our analyses suggest that during years with increased Indian Ocean SSTs which occurred frequently in the recent decades due to a warming trend in this ocean basin, the preceding year Guinea Coast rainfall impacts in a statistical sense on Atlantic hurricane activity. It remains unclear if this impact is due to the soil moisture feedback, as suggested by LG92.

b. Samples stratified by tropospheric wind shear

The 200-hPa zonal wind anomaly over the Caribbean has been shown to be a useful predictor of seasonal tropical cyclone activity in the Atlantic (e.g., Gray et al. 1993). Positive (i.e. westerly) anomalies are associated with suppressed activity. At 850 hPa, easterly trades dominate the region, suggesting that enhanced wind shear is partly responsible for the decrease in tropical cyclone activity over the Caribbean. In the present study, the authors have used tropospheric vector wind shear as a proxy for this parameter. In general, years with larger values of wind shear are known to demonstrate less overall hurricane activity, with more active years having generally weaker wind shear (cf. Goldenberg and Shapiro 1996). For this study, the seasonal measure of wind shear at each point was the magnitude of the vector difference between the August – October winds at 200 hPa and 850 hPa in the NCAR/NCEP reanalyses. Note that the period for which results are shown is restricted to the 50-year period 1958–2007 due to the doubtful reanalysis quality before 1957. As depicted by the black contours in Figs. 5a and 5b, linear correlations between ACE and the Sahelian precipitation indices are quite strong and statistically significant in the 17 years with the most wind shear, particularly in the Caribbean and south of 10°N across the northern MDR. The differences in correlation, as indicated by the colored shading in Figs. 5a and 5b, reveal that the correlations are much lower and statistically insignificant in the years with the least wind shear. The signal in the eastern Atlantic for the Guinea Coast rainfall, as depicted by linear correlation coefficients in excess of 0.5 in Fig. 5c, can be interpreted in a statistical sense in that for high shear years the rainfall in the second rainy season along the Guinea coast of the previous year seems to have an impact on Atlantic tropical cyclone activity. The local tropospheric wind shear across the Atlantic, therefore, is another example of a variable that modulates the nature of the relationship between West African precipitation and Atlantic hurricane activity, with African precipitation being less (more) important in influencing the amount of ACE in years when the overall environment is more (less) favorable for tropical cyclogenesis. Figure 5 was also calculated for the longer NCEP reanalysis period 1948–2007 and for the ECMWF Re-Analysis (ERA-40; Uppala et al. 2005) period 1958–2001 for both data sets. Though some changes were found, the general conclusion drawn from Fig. 5 is robust against different periods and reanalysis data sets (not shown).

Since El Nino impacts Atlantic hurricane activity by modifying the shear environment, it may

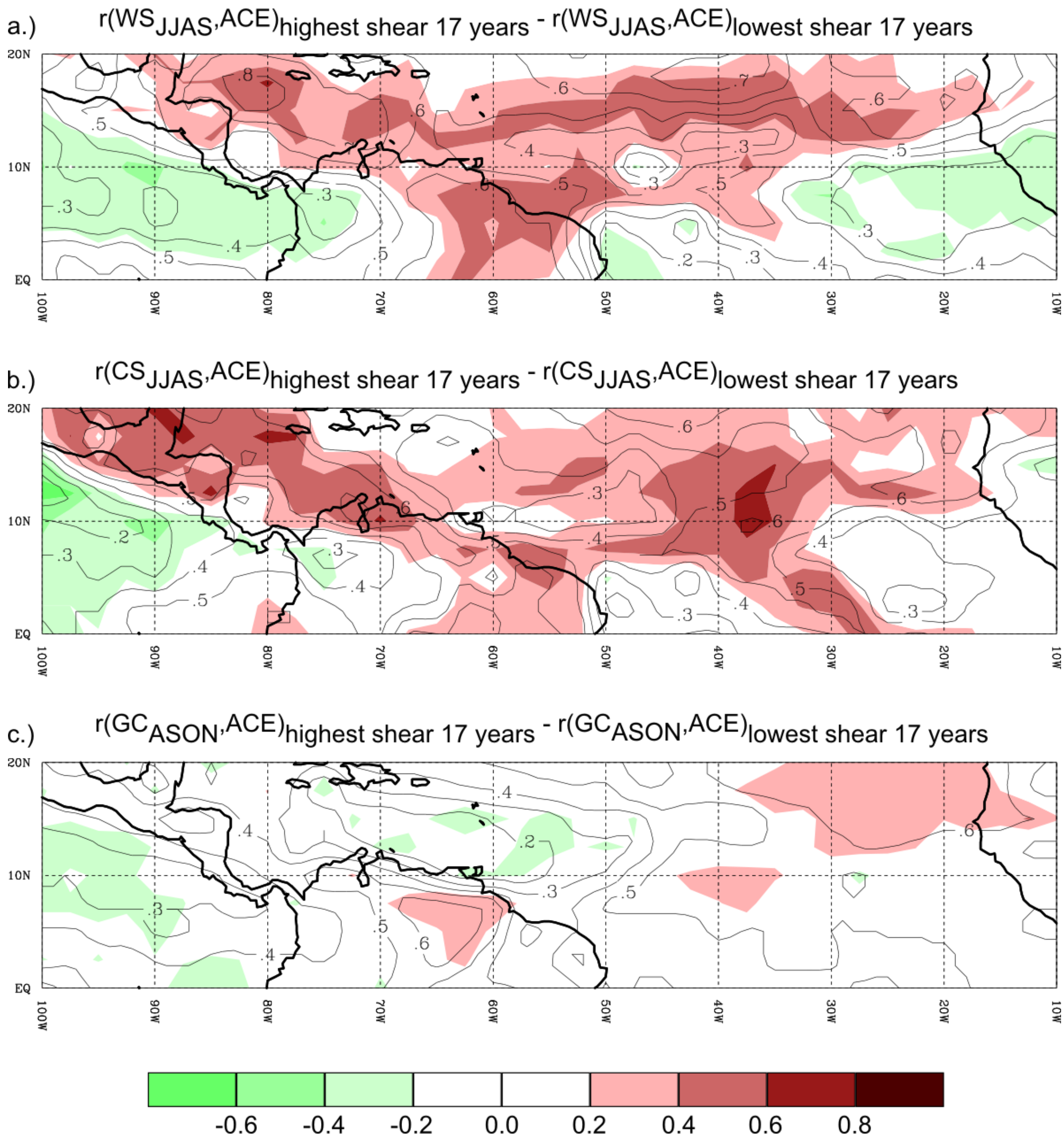

Figure 5. (a) Shading depicts the difference in the linear correlation coefficients between pairs of ACE and the JJAS West Sahel rainfall index in two subsamples, one being the 17 years with the highest 200-850-hPa wind shear at a given grid point and the other being the 17 years with the least wind shear at the same grid point. Determination of lists of years with the greatest and least wind shear is based on NCAR/NCEP reanalysis values for the August–October 1958 2007 period. Black contours show the correlations in just the 17 years with the greatest amount of shear. (b) As in (a), but for the JJAS Central Sahel rainfall index. (c) As in (a), but for the ASON Guinea Coast rainfall index in the preceding year.

seem surprising that stratification of the years with respect to wind shear revealed significant differences in the correlations between indices of African rainfall and ACE when a stratification with respect to the SOI did not. An examination of the correlations between 200-hPa zonal winds in July-September and the SOI (not shown) suggested that El Nino's greatest impact on the upper-tropospheric winds in the tropical Atlantic is centered on the equator. The correlations between SOI and 200mb zonal winds were actually quite low at the latitudes with the most significant values seen in Fig. 5. It may be that the role of West African precipitation as a predictor of Atlantic hurricane activity is simply less sensitive to the impacts of ENSO than it is to lower-latitude shear. These results are consistent with the results discussed in Goldenberg and Shapiro (1996). In their study period (1968–1992), no additional variance in major hurricane activity could be explained compared to a linear correlation with West Sahel rainfall when an ENSO index was added in a partial correlation analyses; during ENSO warm years, the wind shear anomaly was mostly restricted to the equatorial Atlantic Ocean whereas African rainfall was correlated to the shear in the MDR.

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