A More General Framework for Understanding Atlantic Hurricane Variability and Trends

BY JAMES P. KOSSIN AND DANIEL J. VIMONT

The leading mode of coupled Atlantic variability may unify a number of previously documented hurricane–climate relationships, and offers a more complete picture of hurricane variability than SST alone.

Recent literature has been refocusing on the association between tropical North Atlantic Ocean sea surface temperature (SST) and Atlantic hurricane activity. Emanuel (2005) demonstrated this relationship using a power dissipation index (PDI), which depends on storm intensity and the lifetime of each storm over each hurricane season. Emanuel's SST time series was calculated as an average over a large region (6°–18°N, 20°–60°W) of the tropical Atlantic. He found that the Atlantic SST and PDI time series are highly correlated on decadal time scales. A similar relationship was shown by Webster et al. (2005); they found that the number and percentage of the most intense storms is well correlated with large-scale tropical Atlantic SST variability on decadal time scales. The social and economic consequences of these relationships assume a heightened urgency when recent SST increases resulting from global warming are considered. Indeed, Atlantic hurricane activity appears to be increasing in concert with the marked increases in tropical Atlantic SST over the last 30–40 yr. However, while there is both substantial evidence and fairly broad agreement that the increase of tropical Atlantic SST within the secular record is largely attributable to anthropogenic forcing (e.g., Santer et al. 2006), there is presently less agreement regarding any associated increases in hurricane activity resulting from human activity (e.g., Henderson-Sellers et al. 1998; Landsea et al. 1998; Goldenberg et al. 2001; Emanuel 2005; Webster et al. 2005; Landsea 2005; Pielke et al. 2005; Trenberth 2005; Anthes et al. 2006; Elsner 2006; Elsner and Jagger 2006; Elsner et al. 2006a,c; Pielke et al. 2006; Trenberth and Shea 2006; Holland and Webster 2007).

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Regardless of attribution (natural variability, anthropogenic forcing, or some combination of the two), there has been a remarkable increase in Atlantic hurricane activity since 1970, and although there is an active debate regarding the fidelity of the historical Atlantic hurricane records, there is objective evidence for their veracity within the present period of satellite data availability (Kossin et al. 2007).

Physical reconciliation of the relationships between SST and hurricane activity, as reported, for example, by Knutson et al. (2001), Emanuel (2005), Trenberth (2005), Webster et al. (2005), Hoyos et al. (2006), and Trenberth and Shea (2006), is generally posited using potential intensity (PI) theory (Emanuel 1988; Bister and Emanuel 1998). Stated simply, the argument is that while there is no direct contemporaneous correlation between local SST and hurricane intensity (a hurricane can routinely spend the majority of its intensity evolution over relatively constant SST), an increase of SST is generally associated with an increase in *potential* intensity, and over long enough time scales (and large enough sample sizes) this will result in a uniform increase across the intensity distribution (Emanuel 2000; Wing et al. 2007). To uncover this relationship Emanuel (2005) used a PDI, which considers the cube of the maximum wind speed and thus tends to accentuate changes in intensity, and Webster et al. (2005) looked at the frequency of the most extreme intensities (Saffir–Simpson categories 4 and 5).

Hurricane "activity" comprises three factors: the number of storms in a season (frequency), their duration (duration for an individual storm is defined as the time period that its intensity, measured as a maximum sustained surface wind speed, is greater than 17 m s^{-1}), and their intensities. The intensities either may be integrated in some form[1] over the duration of each storm (Emanuel 2005), or they may be stratified by the Saffir–Simpson category (Webster et al. 2005). Of the three factors that affect hurricane activity, however, only intensity can be directly related to PI theory. The variability of frequency and duration must be physically reconciled by other means.

A problem with reconciling the relationship between PDI (or ACE) and large-scale tropical SST with PI arguments is that the time series of the total storm periods, which is simply the product of frequency and seasonal mean duration, correlates very strongly with PDI (r = **0.87**) and ACE (r = **0.93**), so it is clear that intensity variability, which might be partly explained by PI reasoning, explains only a small part of the variability of seasonal hurricane activity as measured by PDI or ACE.[2] Furthermore, the recent increases in hurricane activity, as measured by PDI or ACE, are too large to be easily reconciled solely by the thermodynamic arguments of PI theory applied to the increases in underlying tropical Atlantic SST. Here we argue that SST variability is simply a manifestation of (and has acted as a proxy for) a more general variability of circulation patterns that affect hurricane activity through a number of factors, specifically by affecting hurricane frequency, duration, and intensity, and the regions where tropical cyclogenesis occurs. These factors are not mutually exclusive, as will be discussed below.

HURRICANE ACTIVITY AND THE ATLANTIC MERIDIONAL MODE. Vimont and Kossin (2007, hereafter VK07) showed that the relationship between SST and hurricane activity could be viewed as part of a larger relationship between hurricane activity and a dynamical mode of Atlantic variability referred to here as the Atlantic meridional mode (AMM), which is also known historically as the "gradient," "interhemispheric," or "Atlantic dipole" mode. [The structure and dynamics of the AMM is described in the sidebar to this article, and additional details and references can be found in the review by Xie and Carton (2004).] The AMM represents the leading mode of basin-wide coupled ocean–atmosphere interaction between SST and low-level winds (Chiang and Vimont 2004), and while its amplitude is maximized in boreal spring (Czaja 2004), there is also a strong signal in the Atlantic during the hurricane season, possibly due to simple persistence (Hu and Huang 2006). VK07 showed that the AMM is highly correlated with a number of local climatic factors [SST, shear, low-level vorticity and convergence, static stability, and sea level pressure (SLP)] that cooperate to either increase or decrease Atlantic hurricane activity.

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[1] When the intensity, measured as a maximum sustained wind speed, is squared and summed, the result is the accumulated cyclone energy (ACE) index (Bell and Chelliah 2006); when the intensity is cubed and integrated, the result is the PDI.

[2] Throughout this work, boldface represents statistical significance as described below in Table 1, and all time series, unless otherwise noted, are constructed from Atlantic best-track [North Atlantic Hurricane Database (HURDAT)] data (Jarvinen et al. 1984) and National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis fields (Kalnay et al. 1996) for the 1950–2005 period.

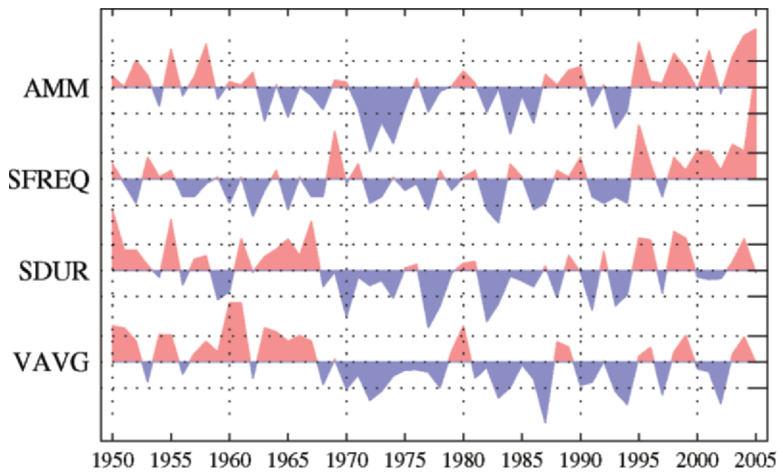

Fig. 1. Normalized time series showing decadal and interannual relationships between the AMM, seasonal mean storm frequency (SFREQ), storm duration (SDUR), and storm intensity (VAVG).

An important aspect of the AMM is that it can be physically attributed to a true dynamical mode of variability intrinsic to the tropical coupled ocean–atmosphere system (see sidebar). It is unlikely that the AMM is in an unstable state in nature, and it is thought that some sort of external stochastic forcing is required for its excitation. This forcing may be realized either through natural modes of variability or through anthropogenic pathways. VK07 provided evidence that the AMM is likely to be excited on multidecadal time scales by a local variability, now commonly referred to as the Atlantic Multidecadal Oscillation (AMO; Kerr 2000; Enfield et al. 2001). The AMO originally emerged as a mode of variability from statistical data analyses (e.g., Kushnir 1994; Mann and Park 1994: Schlesinger and Ramankutty 1994), and a posteriori efforts were subsequently made to determine physical attribution. Presently, there is controversy regarding attribution, with arguments both relating the AMO to Atlantic thermohaline circulation variability (e.g., Kushnir 1994; Delworth and Mann 2000; Goldenberg et al. 2001; Knight et al. 2005; Sutton and Hodson 2005) and relating most of the variability of the AMO to a superposition of radiative forcings (Andronova and Schlesinger 2000; Mann and Emanuel 2006). The former argues for a natural mode of variability that is internal to the coupled ocean–atmosphere system, and the latter argues that the majority of the observed variability is anthropogenically forced. Regardless of its attribution, VK07 argued that the AMO's effect on multidecadal variability of Atlantic hurricane activity (e.g., Goldenberg et al. 2001; Bell and Chelliah 2006) is manifested through its excitation of the AMM.

The relationship between the AMM and the three factors that comprise hurricane activity is shown in Fig. 1, and the correlations are shown in the first three rows of Table 1 (the other correlations in the table will be discussed later). For comparison, correlations with the AMO are also included. Here we use the AMO index as defined in VK07, which follows the definition in Goldenberg et al. (2001). In agreement with the description (and definition) of the AMO as a multidecadal phenomenon, the AMO does not correlate significantly with any measure of hurricane activity on interannual time scales. We find that frequency is significantly correlated with the AMM on both multidecadal and interannual time scales, but that the AMO is not significantly correlated with frequency. The AMM

Table 1. Correlations between the AMM, AMO, and measures of hurricane activity: seasonal mean storm frequency (SFREQ), duration (SDUR), and intensity (VAVG = seasonal mean HURDAT wind speed), and measures related to cyclogenesis: seasonal mean genesis latitude (LAT) and longitude (LON). In each column, the correlations are shown for the unfiltered/low-pass filtered/high-pass filtered time series. Low-pass filtering was performed with a 1–4–6–4–1 binomial smoother and the high-pass-filtered series are the arithmetic difference between the unfiltered and low-pass-filtered series. All time series in this work span the period 1950–2005. Significance throughout this paper is indicated by boldface, and is inferred when the T statistic of the correlation exceeds the two-tailed 95% level using the effective degrees of freedom of each series (Bretherton et al. 1999).

	AMM	AMO
SFREQ	**+0.54**/ **+0.60** / **+0.31**	+0.35 / +0.56/ –0.03
SDUR	**+0.47**/ +0.47/ **+0.54**	**+0.34**/ **+0.65**/ +0.04
VAVG	**+0.33**/ +0.44/ +0.18	+0.28/ +0.42/ +0.06
LAT	**–0.52**/ **–0.71**/ **–0.38**	**–0.48**/ **–0.71**/ –0.16
LON	**+0.30**/ +0.16/ **+0.47**	+0.10/ +0.10/ +0.17

correlates most strongly with duration on interannual time scales. The relationship between the AMM and seasonal mean intensity[3] is not very strong, but is still marginally significant in the unfiltered series, and there is no significant relationship between mean intensity and the AMO.

[3] Here we have used the uncorrected best-track intensities as they are found in the HURDAT record. Applying the pre-1970 correction suggested by Landsea (1993) and formularized by Emanuel (2005) slightly increases the correlation between VAVG and AMM from $r = \mathbf{0.33}$ to $r = \mathbf{0.35}$, and the correlations with the AMO remain insignificant. The correction decreases the amplitudes of the peaks prior to 1970 in the VAVG time series by ~5%–7%, but the series maxima in the 1960s are robust to the correction.

THE ATLANTIC MERIDIONAL MODE

The AMM is a dominant source of coupled ocean and atmosphere variability in the tropical Atlantic (Nobre and Shukla 1996; Ruiz-Barradas et al. 2000; Chiang and Vimont 2004). Research addressing the definition and specific features of the AMM spans over three decades, which precludes a summary that does justice to the rich historical development of our understanding of this phenomenon [for that, we refer the reader to the comprehensive review paper by Xie and Carton (2004, and references therein)]. Despite some disagreement about the details of the spatial structures and mechanisms responsible for AMM variability, most studies agree that the salient features of the AMM include a meridional SST gradient near the location of the thermal equator, winds that blow toward warmer water and veer to the right (left) in the Northern (Southern) Hemisphere in accord with the Coriolis force, and an associated shift in the position of the ITCZ toward the warmer hemisphere (Hastenrath and Heller 1977). Although the AMM exhibits maximum variance during boreal spring, it has also been related to rainfall variations in the Sahel region of west Africa during boreal summer (Folland et al. 1986; Hastenrath 1990) and with aspects of hurricane variability during the Atlantic hurricane season (Xie et al. 2005a,b). The spatial structure of the AMM is depicted in the composite difference between the 5 yr with the largest positive and negative AMM values in Fig. SB1. Figure SB1 illustrates many of the AMM's features described above. Details of how the AMM is calculated are provided in Chiang and Vimont (2004), and are briefly outlined below, for reference.

An important characteristic of the AMM is that it may be identified not only through statistical analysis of observations, but also as a class of true dynamical modes of variability in coupled ocean–atmosphere models (e.g., Chang et al. 1997; Xie 1999). As an example, Fig. SB2 shows the least-damped normal mode of a simple coupled tropical system, consisting of a 1.5-layer reduced gravity shallow-water model on an equatorial beta plane (representative of the sub-trade-inversion tropical boundary layer; Battisti et al. 1999), thermodynamically coupled to a motionless "slab" ocean:

$$\frac{\partial \mathbf{u}}{\partial t} = \beta y \mathbf{k} \times \mathbf{u} - \nabla(\phi - \Gamma\kappa T) - \varepsilon_u \mathbf{u},$$
$$\frac{\partial \phi}{\partial t} = -c^2_{\mathrm{RG}} \nabla \times \mathbf{u} - \varepsilon_\phi(y)\phi, \qquad \text{(SB1)}$$
$$\frac{\partial T}{\partial t} = \alpha_{\mathrm{WES}}(y)u - \left(\varepsilon_T - \gamma\nabla^2\right)T.$$

The atmosphere is coupled to the ocean temperature via a hydrostatic pressure perturbation induced by a surface temperature–dependent equilibrated heat flux into the atmospheric boundary layer $-\Gamma\kappa T$. Here c_{RG} is the reduced gravity wave speed (about 25 m s^{-1}), γ is a harmonic damping coefficient, ε_U and ε_T are linear damping coefficients, and ε_φ is a linear damping coefficient that physically represents the time scale for the development of convection in regions of mean moisture convergence [ε_φ = (8 hr)$^{-1}$] or mean moisture divergence [$\varepsilon_\varphi = \varepsilon_U$ = (48 h)$^{-1}$; Battisti et al. (1999)]; other variables assume their standard definitions. The ocean, in turn, is influenced by changes in evaporation that result from variations in the lower-level zonal wind field, as given by $\alpha_{\mathrm{WES}}(y)u$. Note that a positive $\alpha_{\mathrm{WES}}(y)$ results from a

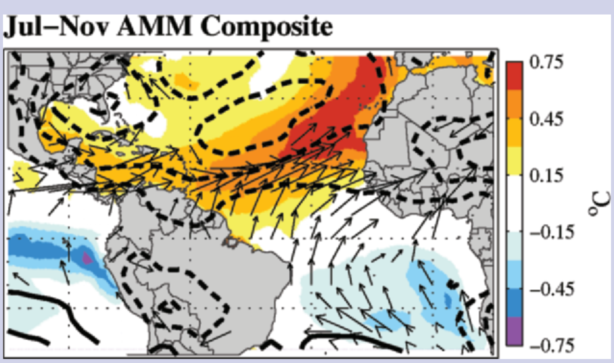

Fig. SB1. SST (shaded), 925-mb height (contour, 2 m), and 925-mb wind (vectors) composite anomalies around the 5 yr with the largest positive AMM index, minus the composite anomalies around the 5 yr with the largest negative AMM index. For 925-mb height, solid contours denote positive anomalies, dashed contours denote negative anomalies, and the zero contour has been omitted. Vectors are shown only where the composite difference is significant at the 90% level.

To summarize: unlike the AMO, the AMM is physically reconcilable in a simple dynamical framework, and correlates significantly with overall hurricane activity on interannual, as well as decadal-to-multidecadal, time scales. The coherent relationships between the AMM and a broad spectrum of local climatic factors that influence hurricane activity, combined with the finding that the multidecadal variability of the AMM is likely to be excited by the AMO, offers a more complete and general link between climate and hurricanes than arguments based solely on Atlantic basin SST anomalies.

THE ATLANTIC MERIDIONAL MODE AND REGIONS OF TROPICAL CYCLOGENESIS.

The PI theory, as mentioned above, offers a mechanism

mean easterly wind, because a westerly wind anomaly will reduce evaporation through reducing the total wind speed. Further details of this sort of model and the parameter definitions involved can be found in either Xie (1999) or Battisti et al. (1999). The linear model is discretized in the meridional direction and decomposed into a single harmonic in the zonal direction, and normal modes are obtained via eigenanalysis of the resulting linear matrix.

The least stable normal mode of the above linear system is depicted in Fig. SB2. Note the similar features of the observed AMM—an anomalous meridional SST gradient, cross-equatorial winds that blow toward lower pressure (which, by definition through the coupling, is located over warmer water) and veer in accord with the Coriolis force, and a shift in surface convergence (analogous to an ITCZ shift) toward the warmer hemisphere. Figure SB2 and Eq. (SB1) also demonstrate the destabilizing effect of the WES feedback. It can be shown (Xie 1999) that the WES feedback is positive when surface temperature and zonal wind variations are in phase [i.e., westerly (easterly) wind anomalies overlie warm (cold) SST anomalies]. This phasing leads to reduced (enhanced) evaporation over warmer (colder) water, a positive feedback to the surface temperature anomalies. Although this positive feedback is probably not strong enough to generate linearly unstable meridional mode variability in nature (especially when considering surface temperature damping), it is likely important for enhancing meridional mode persistence and variance. Finally, we note that the WES feedback in nature may involve a number of different physical processes; our intent here is merely to illustrate a basic dynamical origin of meridional mode variations and to highlight the associated important coupled feedbacks.

In the present analysis, we define the AMM in exactly the same manner as in Chiang and Vimont (2004), except over the time period 1948–2005. Maximum covariance analysis (MCA) is applied to SST and lower-level winds (taken from the NCEP reanalysis; Kalnay et al. 1996) defined over the time period of 1948–2005, and the region 21°S–32°N, 74°W to the west African coastline. Data are detrended, and temporally and spatially smoothed, and an index of ENSO variability is linearly removed. MCA is then applied to the monthly data, and the July–November-averaged SST expansion coefficient is used to represent the hurricane season AMM in the present analysis for the period of 1950–2005 (shown, in normalized form, in Fig. 1. To test the robustness of our results, we also constructed an AMM index by projecting raw SST (i.e., not detrended and without ENSO removed) onto the spatial AMM pattern. The resulting time series is nearly identical to the time series used in our analyses (***r* = 0.96**), and the use of either index produces very similar results. For simplicity, and consistency with earlier work, we used the index as defined in Chiang and Vimont (2004) in this work.

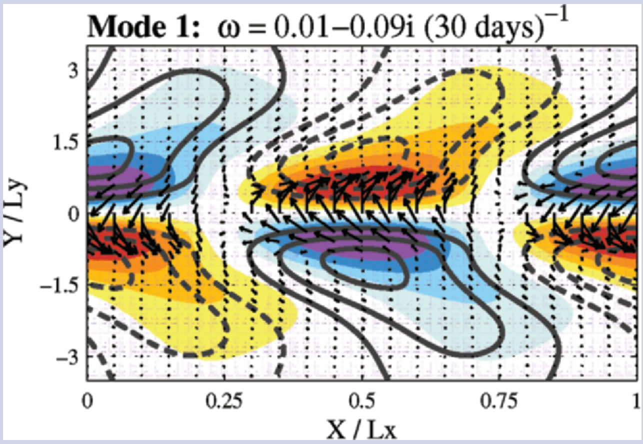

Fig. SB2. Least stable eigenvector of the linear model in Eq. (SB1), for a zonal wavelength (L_x) of 120°, and a radius of deformation (L_y) of about 8.5°. In this model, both the WES parameter $\alpha_{WES}(y)$ and the adjustment time for convection $\varepsilon_\varphi(y)^{-1}$ are assigned symmetric meridional structures that are representative of the tropical Atlantic basin. Shading denotes SST, contours denote equivalent geopotential perturbations ($\Phi_{RG} = g'h - \Gamma\kappa T$), and vectors denote integrated flow in the boundary layer. For geopotential perturbations, solid contours denote positive anomalies, dashed contours denote negative anomalies, and the zero contour has been omitted. Solutions evolve as $exp(-i\omega)$, indicating that this mode is nearly stationary and weakly damped.

that links intensity to local SST variability. To move beyond the limitations of PI theory and better reconcile the variability of seasonal hurricane frequency and duration, we considered the relationship between the AMM and the variability of Atlantic tropical cyclogenesis locations. Figure 2 and the bottom two rows of Table 1 show that AMM variability is significantly related to a northwest–southeast shifting of the seasonal mean cyclogenesis locations [defined as the points at which each storm first reaches tropical storm status (maximum sustained surface winds exceeding 17 m s^{-1})]. Of particular interest, we find that during positive AMM phases, the mean genesis location moves eastward and toward the equator. The relationship between the AMM and mean genesis location is significant on interannual and decadal time scales (Table 1). The north–south shifts (cf. Hess and Elsner 1994; Kimberlain and Elsner 1998; Landsea et al. 1999) are more strongly modulated on decadal time scales. The east–west shifts, however, are more strongly modulated by the AMM on interannual time scales, and the AMO is not correlated with mean genesis longitude on any time scale. These results agree with and extend the results of Xie et al. (2005a,b), which focus on unfiltered correlations between the Atlantic SST dipole mode (defined as the leading empirical orthogonal function of Atlantic SST) and hurricane frequency and tracks.

The relationship between the AMM and genesis longitude offers a climatic feature that can contribute to the observed variability of hurricane activity in the eastern tropical Atlantic. There is presently some uncertainty regarding attribution for this variability, namely, that in addition to possible climatic influences, pre–satellite era observations may be more rarified in the easternmost parts of the Atlantic compared with the western regions. This is likely to lead to an underrepresentation of actual activity during the earlier parts of the historical best-track records (Landsea 2007). The relative contributions of data fidelity issues versus physically reconcilable climatic modulation to eastern Atlantic hurricane variability is presently an open question, but the AMM offers a physical mechanism for the latter.

Recall that the positive phase of the AMM is related to an increase in storm duration (Fig. 1). This is physically congruent with storms that form farther eastward and equatorward, because storms in the Atlantic generally track westward (and to a lesser extent, northward) along the southern flank of the Atlantic subtropical high. The southeast shift moves the genesis location farther away from land, allowing storms to persist longer before making landfall or curving northward around the western edge of the subtropical high and into the hostile environment of the midlatitudes. This is dramatically demonstrated in Fig. 3, which shows the genesis locations composited by the five strongest and five weakest AMM years. During negative phases of the AMM, cyclogenesis occurs more often along the east coast of the United States, very near land, and often in the extratropics where nearby cold SST and strong midlatitude vertical wind shear create an environment that is highly unfavorable for either storm persistence or intensification. In comparison, during positive phases of the AMM, genesis takes place more often in the "main development region" ("MDR"; e.g., Goldenberg et al. 2001) that spans the basin between 10° and 20°N. This region is relatively free of large landmasses, is generally described by warmer SST and lower shear than the extratropics, and is usually conducive to hurricane persistence and intensification.

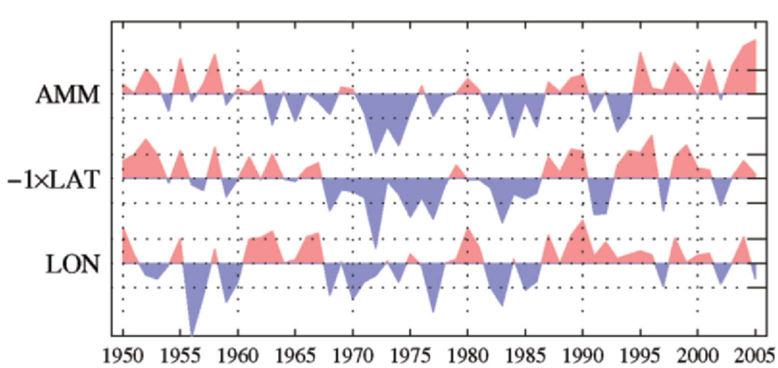

FIG. 2. Same as Fig. 1, but for seasonal mean values of the latitude and longitude of the cyclogenesis points [defined as storm location when the intensity first reaches tropical (named) storm strength (17 m s^{-1})], as determined from the HURDAT record. The mean genesis latitude is multiplied by −1 for display purposes.

Figure 3 also shows marked variability in the frequency and spatial distribution of "major hurricanes" (Saffir–Simpson category 3 or greater), in relation to AMM phase. During strong negative phases, very few tropical storms form and only a small percentage intensify into major hurricanes, while during strong positive phases, more storms form and many become major hurricanes. In our composites shown in Fig. 3, the five positive AMM years had 84 storms, 51 of which became hurricanes, and 29 of which became major hurricanes. In the five negative AMM years, there were 45 storms,

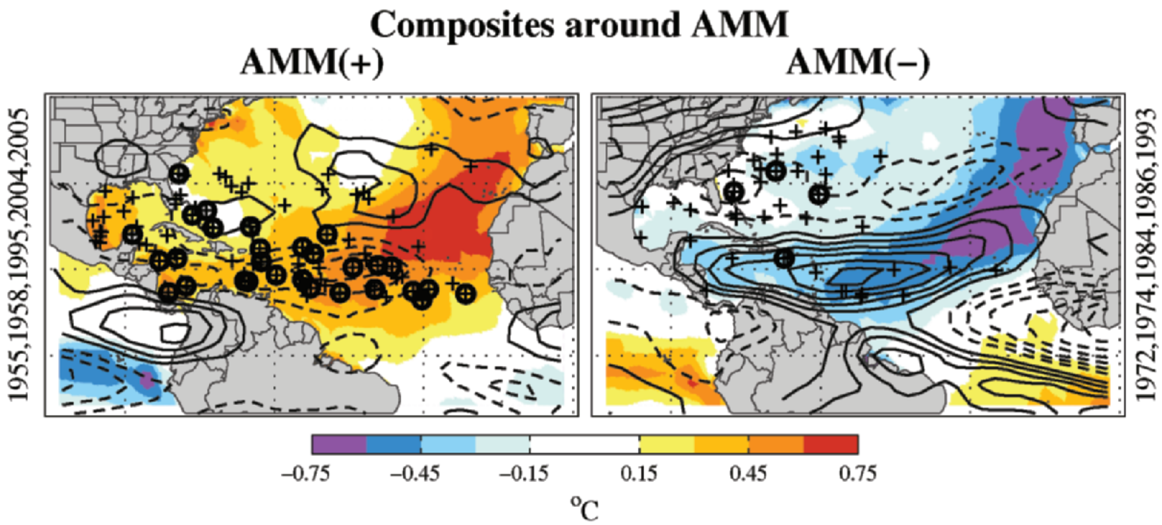

Fig. 3. Tropical cyclogenesis points for the five strongest and five weakest AMM years, superimposed on composites of SST (shaded) and shear (contours) anomalies. Crosses show the genesis points for all storms that reached tropical storm strength. Storms that reached "major hurricane" strength (maximum sustained surface wind speed >49 m s^{-1}) also have a circle around their genesis point. Solid (dashed) shear contours denote positive (negative) values. The contour interval is 0.25 m s^{-1}, and the zero contour has been omitted. Shear was calculated every 6 h as the amplitude of the vector difference between the layer mean winds in the 300–150- and 925–700-hPa layers, and means were formed around the hurricane season from monthly means.

20 of which became hurricanes, and only 4 of which became major hurricanes. This agrees well with Gray (1990), who uncovered strong statistical relationships between interhemispheric SST differences in the Atlantic, rainfall in the Sahel region of Africa (cf. Folland et al. 1986), and the frequency of intense hurricanes.

The composite differences of SST and vertical wind shear shown in Fig. 3 provide causal evidence for the observed shift of the genesis locations. During positive AMM phases, anomalously low shear and high SST are found in the MDR. During negative phases these anomalies reverse sign in the MDR, creating an anomalously hostile environment for hurricane genesis and intensification, while the subtropical region becomes anomalously benign.

Various local mechanisms, beyond remote effects from El Niño–Southern Oscillation (ENSO) (e.g., Gray 1984; Shapiro 1987; Goldenberg and Shapiro 1996), have been posited to explain the variability of tropical Atlantic shear. Landsea et al. (1999) suggest that decreased SLP in the MDR reduces the low-level easterlies by weakening the meridional pressure gradient between the MDR and equator. Knaff (1997) suggests a feedback mechanism between SLP, subsidence, midlevel drying, and radiational cooling that modulates the strength and location of the upper-level trough and ultimately modulates shear by changing upper-level flow patterns. Prior to the formal description of the wind–evaporation–SST (WES) feedback mechanism by Xie and Philander (1994), Gray et al. (1993) suggested that the variability of tropical Atlantic shear, low-level vorticity, and SLP is related to meridional shifts of the ITCZ, although no formal mechanism was suggested. In VK07, it was found that the relationship between the AMM and shear in the tropical Atlantic was dominated by variability of the flow at upper levels. In addition to the modulation of upper-level flow through the enhancement of local baroclinicity (Knaff 1997), we suggest here that the northward (southward) shift of the ITCZ associated with positive (negative) phases of the AMM may also reduce (increase) shear in the MDR by moving the ascending branch of the Hadley circulation to the north (south), which reduces (increases) upper-level westerlies through simple angular momentum arguments.

As noted above, the shift in the mean cyclogenesis regions offers an explanation for the observed variability in storm duration, but this relationship can also explain at least part of the variability of intensity. There is a strong relationship between storm duration and intensity (r = **0.56, 0.65, 0.39** for the unfiltered and low-, and high-pass-filtered series). This relationship can be couched in terms of PI theory because longer-lived storms have more opportunity to achieve their PI. Emanuel (2005) also noted the relationship between duration and intensity, but suggested that this was due to stronger storms taking longer to decay. In terms of cause and effect, our results suggest that it is the shifting of the mean genesis region and associated increased duration that allows storms to achieve greater intensities, and not that stronger storms simply last longer.

Our results also align well with the results of Webster et al. (2005) and Kossin et al. (2007) for the Atlantic basin; that is, the shifting of the mean Atlantic genesis region to the southeast allows greater opportunity for storms to intensify toward their PI for a long enough period of time to reach Saffir–Simpson category 4 or 5. Moreover, the climatological PI in the MDR is greater than in the mean genesis region associated with negative phases of the AMM. Recalling that hurricanes typically track from west to northwestward along the southern flank of the subtropical high (i.e., in the MDR), storms during positive AMM phases have a greater PI *and* a greater opportunity to reach it.

We find, then, that intensity and duration are linked in a way that causes a compounded increase in hurricane activity, and both can be at least partly explained in terms of the variability of genesis regions. This result can also be compared with Emanuel (2000), who suggested that western North Pacific storms become more intense, on average, than their Atlantic counterparts because they have longer tracks, on average, over warm water. When the additional relationship between hurricane frequency and the AMM is also considered, the influence on overall hurricane activity is compounded even further; during positive AMM phases 1) there are more storms, 2) they form in and track through regions of anomalously high PI (and a suite of other anomalously favorable environmental conditions), and 3) they have a longer time to intensify toward their PI. In light of these compounding factors, it is clear that PI theory is an important factor in the physical explanation of observed hurricane activity variability, but is insufficient by itself to accurately describe or predict how long-term SST trends will affect hurricane activity.

Thus far we have addressed relationships involving hurricane intensity and duration, and the significant shift of the mean cyclogenesis regions offers a simple explanation for their observed variability. The third factor of hurricane activity (frequency) poses a greater challenge to identifying a causal mechanism because the process of cyclogenesis, which is notoriously poorly understood, directly modulates it. We presently have little physical guidance with which to explain the observed interannual frequency variability (cf. Trenberth 2005), and much of the dynamics of cyclogenesis is likely to be stochastically forced (e.g., Ritchie and Holland 1999; Simpson et al. 1997). Still, there are environmental thresholds that control genesis and might shed some light on the problem. For example, genesis typically does not occur where SST < 26.5°C (Gray 1968), so variations in the areal extent of the Atlantic warm pool (e.g., Wang et al. 2006) could affect the probability of the random organization of incipient storms. More research is needed, and efforts toward improving the physical understanding of cyclogenesis and its potential modulation of climate change are underway.

The AMM is, of course, not the only mode of interest when considering hurricane variability, and there are clearly additional factors, beyond those that can be related to the AMM, that modulate hurricane activity (e.g., Gray et al. 1993; Landsea et al. 1998). For example, it appears that any relationship that we might expect between the decadal variability of mean genesis longitude and the AMM is being dominated and masked by other factors. It is unclear at this time exactly how the AMM works in concert with other modes of variability to modulate hurricanes, but this is presently an active topic of inquiry. By construction, the AMM is largely independent of ENSO (see sidebar), but there are interbasin feedbacks between the two and it has been shown that Pacific ENSO variations can contribute directly to the excitation of AMM variability through teleconnection patterns (e.g., Covey and Hastenrath 1978; Enfield and Mayer 1997). The AMM and the North Atlantic Oscillation (NAO) are contemporaneously independent during the hurricane season (Xie et al. 2005b), but it has also been shown that the AMM can be excited by variations in the NAO (Xie and Tanimoto 1998; Czaja et al. 2002). The goal of the present work is not to suggest the AMM as the only mode of variability relevant to hurricanes, but to suggest the AMM as a framework that unifies a number of features that have been previously shown to affect hurricanes, and that can be reconciled, to some extent, in terms of a simple dynamical model.

PREDICTABILITY OF THE ATLANTIC MERIDIONAL MODE.

Figure 2 suggests that the AMM, like the AMO, has been strongly positive since 1995, which also marks the start of the present period of increased hurricane activity (Landsea et al. 1998; Elsner et al. 2000; Goldenberg et al. 2001). It is not clear that this recent period constitutes a new norm, and a similarly enhanced AMM is also seen in the 1950s. Still, the strength of the AMM in the past few years is unprecedented within the record we are considering. To provide a sense of the longer-term behavior of the AMM, we constructed an extended AMM index by projecting the Hadley Centre Sea Ice and SST dataset version 1 (HadISST1) product (Rayner et al. 2003) over the period of 1900–2006 onto the spatial AMM pattern from Chiang and Vimont (2004).[4] This time series is shown in Fig. 4 along with the time series of seasonal mean storm frequency for that period. The pre-1950 SST, and particularly the HURDAT data, should be considered with caution (e.g., Landsea 2007), but it is still instructive to do so. Within this record, the correlation between the AMM and storm frequency is r = **0.50, 0.54,** and **0.38** for the raw, low-pass, and high-pass time series. The AMM achieved its maximum in 2005, with a value 2.3 standard deviations above the long-term mean. In 2006, the AMM was still anomalously high, but dropped measurably to 1.6 standard deviations above the mean. This aligns to some degree with the decrease in 2006 activity, which comprised a roughly average hurricane season after the record-high activity of the 2005 season.

Because a positive AMM is strongly related to an increase of hurricane activity on *interannual* time scales, a persistently elevated AMM may not bode well for the immediate future. We have found, however, that the AMM does exhibit measurable predictability and this might be exploited toward improving seasonal forecasting. Here we investigate the predictability of the AMM using linear inverse modeling (LIM), a statistical technique that is commonly used for SST predictions in the Tropics and midlatitudes [a more thorough description and examination of this method is found in Penland and Magorian (1993), Penland and Sardeshmukh (1995), and Alexander et al. (2007)]. It has been previously shown by Penland and Matrosova (1998) that LIM can forecast various features of the AMM, but their study did not include an analysis of seasonal forecast skill.

LIM assumes that the state of a system at any time, represented by $\mathbf{x}(t)$, can be represented by a multivariate Markov model,

$$\frac{d\mathbf{x}(t)}{dt} = \mathbf{M}\mathbf{x}(t) + \xi(t). \quad (1)$$

Here, $\mathbf{M}$ is the linear approximation to the dynamical system and $\xi(t)$ is assumed to be white noise stochastic forcing. The best prediction of the system is obtained by solving the homogeneous form of (1), which gives

$$\mathbf{x}(t + \tau) = \exp(\mathbf{M}\tau)\mathbf{x}(t) = \mathbf{G}(\tau)\mathbf{x}(t), \quad (2)$$

where the Green function $\mathbf{G}(\tau)$ is obtained via the covariance and lagged covariance matrices of the state vector with itself,

$$\mathbf{G}(\tau) = \langle \mathbf{x}(t + \tau), \mathbf{x}(t) \rangle \langle \mathbf{x}(t), \mathbf{x}(t) \rangle^{-1}. \quad (3)$$

To evaluate the hurricane season AMM forecast skill, we developed predictions of the AMM using a jackknifed cross-validation technique. Here we used monthly SST data from 1950 to 2006 over the region 120°E–15°W (incorporating both the Pacific and Atlantic Oceans), and 21°S–62°N. After removing the annual cycle, the data were spatially averaged over every two latitudinal and longitudinal points, and lightly temporally smoothed using a 3-month running mean. Principal component (PC) analysis was applied to the data, and a state vector $\mathbf{x}(t)$ was defined as the first 16–18 PCs (enough to account for about 85% of the total SST variance in each jackknifed time period). The jackknife procedure involves removing the first 10 yr from the 1950–99 period; constructing a set of Green functions for lags out to 2 yr, using the remaining 40-yr training period; using those Green functions to predict SST over the independent decade, and over the entire spatial domain (after transforming back to physical space from the spectral space of the PC

[4] We performed this calculation using detrended SST with ENSO removed, and also with the raw SST data. The two AMM index time series are essentially identical (r = **0.94**). For consistency, here we use the detrended data with ENSO removed.

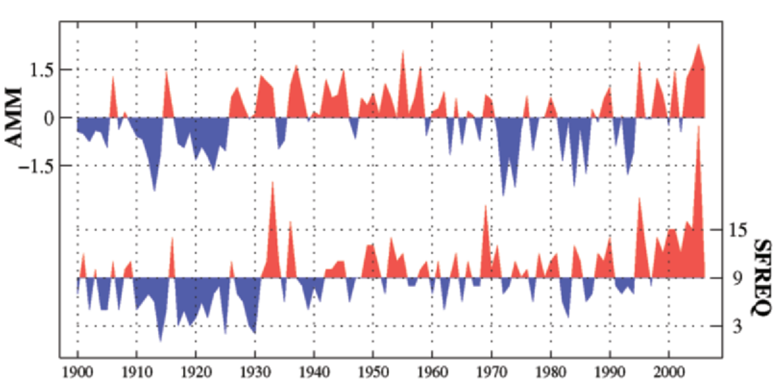

Fig. 4. Time series of the AMM and storm frequency for the period 1900–2006. The AMM time series is standardized. The long-term mean of the SFREQ series is 9 and the standard deviation is 4, so the grid lines represent 1.5 standard deviations from the mean, as in the AMM plot. Values prior to 1948 should not be considered too strictly because of the higher potential for data issues in that period.

analysis); and projecting the spatial structure of the AMM onto the independent SST predictions to obtain cross-validated AMM predictions. Finally, the entire procedure was repeated over the entire 1950–99 record to predict the remaining 2000–07 AMM values.

The predicted values of the hurricane season AMM from the end of the previous hurricane season (an October-centered initial condition, which, given the 3-month running mean, implies a 1 December real-time prediction) are plotted in Fig. 5a. The forecast values explain a remarkable 40% of the actual AMM variance of the following hurricane season. The correlation at any given lag is compared to the skill of a persistence forecast in Fig. 5b. At short lead times (less than about 7 months, or a February-centered initial condition), the LIM does no better than persistence, which suggests that for these shorter lead times, the nonnormal growth given by the LIM (see, e.g., Farrell and Ioannou 1996) does not contribute significantly to the prediction amplitude. However, beyond about 7 months, the LIM exhibits significantly more skill than a persistence forecast. Interestingly, the 1-yr prediction skill is higher than the 6-month prediction skill. Further analysis is underway to investigate the source of the forecast skill seen in Fig. 5b.

It is also worth noting that the NAO, like the AMM, has been shown to modulate the hurricane

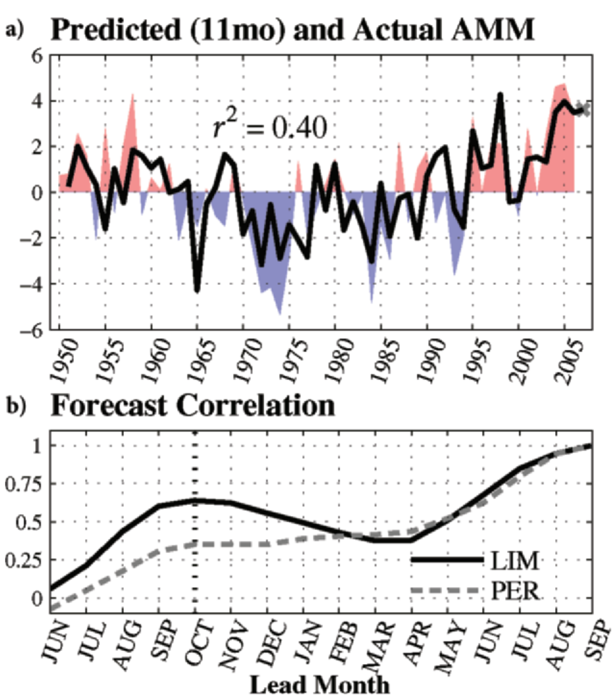

Fig. 5. (a) Comparison of predicted (bold black curve) and actual (color shading) AMM during the hurricane season. (b) Predictive skill of the LIM as a function of forecast lead time (solid) and persistence (dashed).

track and to exhibit interannual predictability, and these features of the NAO have been exploited toward seasonal landfall prediction (Elsner 2003; Elsner and Jagger 2006; Elsner et al. 2006b). In particular, Elsner et al. (2006b) found that the boreal fall and winter mean NAO contains predictive information about storm tracks in the following hurricane season. There is no contemporaneous correlation between the NAO and AMM during the hurricane season (cf. Xie et al. 2005b), but wintertime NAO does correlate with springtime AMM, maximizing with $r = -0.4$ for January NAO and March AMM. A detailed description of this mode of AMM excitation is given in Czaja et al. (2002). It is still unclear through what mechanism the wintertime NAO affects Atlantic storm tracks in the following hurricane season, but the excitation of the springtime AMM, which has been previously shown to persist into the hurricane season and we have shown to affect storm tracks, provides a plausible candidate.

COMPARISONS AND ANALOGIES WITH ENSO. The AMM is a leading mode of coupled ocean–atmosphere variability in the Atlantic. In the western North Pacific, ENSO assumes this role and, analogous to the relationship between the AMM and seasonal mean cyclogenesis regions, ENSO is strongly correlated with the western North Pacific tropical cyclogenesis regions (Lander 1994; Chen et al. 1998; Chia and Ropelewski 2002; Wang and Chan 2002; Wu et al. 2004), as well as mean storm track, duration, and intensity (Camargo and Sobel 2005; Camargo et al. 2007a,b). Similar relationships have also been documented in the South Pacific (e.g., Basher and Zheng 1995).

Both ENSO and the AMM are understood to manifest via coupled feedback mechanisms (the so-called Bjerknes and WES feedbacks, respectively). Although zonal modes (such as ENSO) and meridional modes exist in both the Atlantic and Pacific basins (Ruiz-Barradas et al. 2000; Chiang and Vimont 2004), the differing mean state and basin geometry in the Atlantic reduces the maximum amplitude that Atlantic El Niño events achieve (Battisti and Hirst 1989; Zebiak 1993). This allows the emergence of the AMM as the leading coupled mode and the primary modulator of Atlantic hurricane variability [with secondary nonlocal contributions from Pacific ENSO variability (Gray 1984; Shapiro 1987; Goldenberg and Shapiro 1996; Bove et al. 1998)].

The evolution of the AMM (e.g., Fig. 1) suggests that it is presently in a long-term positive regime and contains a significant trend, since 1970, superimposed on interannual variability. Such a marked increase is not clearly evident within the interannual variability of ENSO indices (e.g., Wolter and Timlin 1998), and observational analyses and numerical integrations yield conflicting results as to whether ENSO variability may be influenced by global warming (Trenberth and Hoar 1997; Cane et al. 1997; Timmermann 1999; Karl and Trenberth 2003; Zelle et al. 2005; Merryfield 2006). The fact that the observed increases in the AMM since 1970 are more easily extracted from the interannual variability than contemporaneous increases in ENSO may offer some elucidation for recent findings regarding the basin dependence of trends in hurricane activity: the upward Atlantic trends since 1970 appear to be significant and robust to reanalysis of the data records, but recently documented trends in the records for the Pacific basins are not as easily corroborated under reanalysis (e.g., Wu et al. 2006; Kossin et al. 2007), despite similar upward tropical SST trends in all basins.

We now consider the comparative contributions of ENSO and the AMM to the variability of Atlantic hurricane activity. Figure 6 shows regression maps of vertical wind shear (calculated as described in Fig. 3) onto the standardized AMM and Niño-3.4 indices.[5] The numeric values superimposed on the shear plots show the correlations between the AMM and Niño-3.4 indices and storm activity in varying regions of the tropical Atlantic. (In this case, storm activity is measured simply by the number of storm days, because pre-1950 intensity values in the HURDAT record are more suspect than frequency and duration. As noted above, activity metrics such as ACE or PDI are very strongly correlated with number of storm days.) Figure 6 shows that the influence of the AMM is significant everywhere, while ENSO's influence is only significant in the western portion of the basin. The collocation of the shear maxima and regions of maximum correlation confirms that the influence of the AMM and ENSO on Atlantic storm activity is realized, in part, through modulation of the regional shear patterns. This is also evident in the western Caribbean where both ENSO- and AMM-related shear are large and both equally modulate storm activity. Contrarily, the shear signature in the MDR is largely dominated by the AMM, particularly in regions east of 60°W longitude.

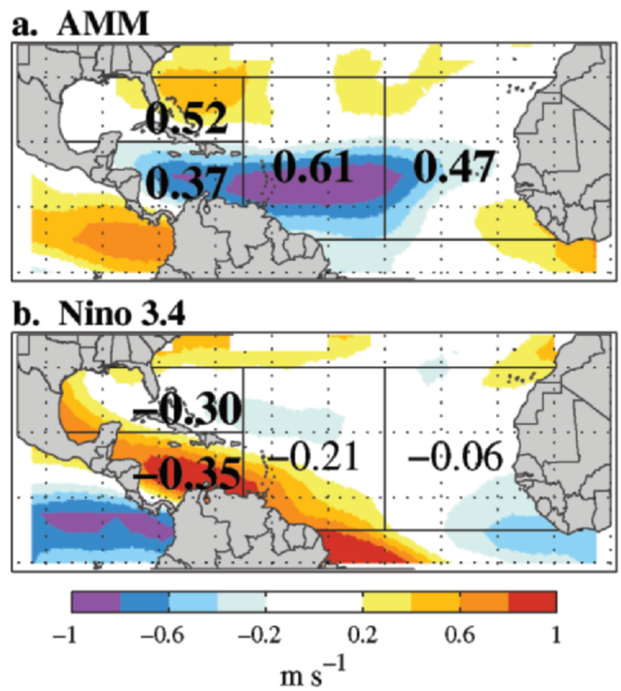

FIG. 6. Regression maps of mean vertical wind shear onto the standardized (a) AMM index and (b) Niño-3.4 index. Units: m s^{-1} per standard deviation of the respective time series, so amplitudes may be directly compared. Also listed is the correlation between the number of storm days within each region and the respective index. Statistically significant correlations are listed in boldface.

DISCUSSION. The AMM represents the leading mode of coupled ocean–atmosphere variability in the Atlantic and has been discussed in the literature, in one form or another, for over 30 yr (e.g. Hastenrath and Heller 1977). It is somewhat surprising then that this mode of Atlantic variability has rarely been *explicitly* considered in analyses of Atlantic hurricane variability, particularly when compared with the number of studies relating ENSO variability to Pacific tropical cyclones [recent exceptions are Xie et al. (2005a,b)]. However, the relationships between hurricane variability and various isolated proxy features implicit in the AMM have been well documented. These isolated proxies include patterns of SST, shear, SLP, vorticity, upper- and lower-level flow, static stability, and the position of the ITCZ, among others (e.g., Gray 1990; Gray et al. 1993, 1994; Goldenberg and Shapiro 1996; Knaff 1997; Landsea et al. 1999). One issue with considering only isolated proxies for the AMM is demonstrated in the relationship between African Sahel rainfall and hurricane activity (Gray 1990; Gray and Landsea 1992; Landsea and Gray 1992; Landsea et al. 1992). The relationship

[5] Here we considered the period 1958–2005, which comprises the well-sampled radiosonde era. Our results do not change appreciably if 1950–2005 is used, but plots of vertical wind shear suggest that significant bias exists in the earlier part of the reanalysis record. This bias has no significant effect on the shear composites shown in Fig. 3.

between the AMM and Sahel rainfall is well known (Folland et al. 1986; Breugem et al. 2006) and Sahel rainfall can be considered, to some degree, as a proxy for the AMM. The relationship between hurricane and Sahel rainfall variability was strong and robust through the period of 1950–95, but has significantly degraded in the period from 1995 to the present. Fink and Schrage (2007) showed this degradation in terms of the relationship between ACE and a west Sahel rainfall index. However, the relationship between the AMM and ACE is strong and robust throughout the entire period from 1950 to the present. The consideration of a more general mechanism that unifies many of the isolated features considered in past studies thus has the potential to mitigate potential nonstationarity issues associated with these isolated features.

Atlantic hurricane variability can be considered in terms of intensity, frequency, duration, and position/track. Basin-wide thermodynamic and kinematic fields are the primary modulators of all of these factors, and the direct relationship between *local* SST and hurricane intensity appears to play a relatively small role. The AMM may provide more general relationships with hurricane activity because SST gradients are more fundamentally linked to local circulation patterns than SST in an absolute sense (Lindzen and Nigam 1987; Shapiro and Goldenberg 1998). It could be argued that tropical Atlantic SST affects hurricane intensity via local thermodynamics, while SST gradients affect overall activity by modulating the local large-scale circulation.

The persistently warm (positive) phase of the AMM that the Atlantic is experiencing at present, and the significant upward trend of the AMM since 1970, supports the idea that hurricane activity is in a long-term active phase (Elsner et al. 2000; Goldenberg et al. 2001). But, it is unclear at present whether this will continue indefinitely or whether hurricane activity will return to a more quiescent period similar to the 1970s and 1980s. Much of the uncertainty lies in the larger uncertainties regarding how anthropogenically forced tropical Atlantic SST increases will project onto future hurricane variability. The AMM does not answer this question, but it does provide an additional framework for furthering our understanding of the physical mechanisms driving these relationships.

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