The Atlantic Meridional Mode and hurricane activity

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[1] Connections between the Atlantic Meridional Mode (AMM) and seasonal hurricane activity are investigated. The AMM, a dynamical "mode" of variability intrinsic to the tropical coupled ocean-atmosphere system, is strongly related to seasonal hurricane activity on both decadal and interannual time scales. The connection arises due to the AMM's relationship with a number of local climatic conditions that all cooperate in their influence on hurricane activity. Further analysis indicates that the Atlantic Multi-decadal Oscillation (AMO) can excite the AMM on decadal time scales. As such, it is suggested that the AMO's influence on seasonal hurricane activity manifests itself through the AMM. This relationship between the AMM, AMO, and seasonal hurricane activity refocuses our understanding of how climate variations relate to seasonal hurricane activity in the Atlantic, and offers an improved framework beyond purely thermodynamic arguments that relates hurricanes to large-scale climate variations. **Citation:** Vimont, D. J., and J. P. Kossin (2007), The Atlantic Meridional Mode and hurricane activity, *Geophys. Res. Lett.*, *34*, L07709, doi:10.1029/2007GL029683.

1. Introduction

[2] The recent upswing in the number and intensity of Atlantic tropical cyclones since 1995 has spurred renewed interest in understanding how local climatic conditions, and known "modes" of climate variability, may impact seasonal hurricane activity. It has been shown that Atlantic hurricanes are sensitive to a number of local large-scale climatic conditions such as sea surface temperature (SST), sea level pressure (SLP), vertical wind shear (SHR), low-level vorticity (VOR) and convergence (CON), and vertical (static) stability ($\Delta\theta_e$). Atlantic hurricanes have also been shown to be remotely influenced by teleconnections to concurrent El Niño-Southern Oscillation (ENSO) variations [*Gray*, 1984; *Goldenberg and Shapiro*, 1996].

[3] Pronounced coupled ocean-atmosphere variability in the Tropical Atlantic is generated by fluctuations in the Atlantic Meridional Mode (AMM) [*Servain et al.*, 1999; *Xie and Carton*, 2004; *Chiang and Vimont*, 2004]. The AMM is characterized by a meridional SST gradient near the location of the climatological inter-tropical convergence zone (ITCZ); boundary layer winds that flow toward the anomalously warmer water and veer to the right (left) in the northern (southern) hemisphere, in accord with the Coriolis force; and a meridional displacement of the ITCZ toward the warmer hemisphere. Although AMM variance maximizes in boreal spring, it also exhibits variability during the Atlantic hurricane season. Variations in the AMM have been shown to be related to principal variations in hurricane tracks over the North Atlantic [*Xie et al.*, 2005].

[4] The AMM is part of a broader class of "meridional modes" that emerge as true dynamical modes of variability, intrinsic to the tropical coupled ocean-atmosphere system [*Xie*, 1999; *Xie and Carton*, 2004]. These meridional modes involve a positive feedback between surface winds, evaporation, and SST (the so-called WES feedback) [*Xie and Philander*, 1994; *Chang et al.*, 1997]. Although the WES feedback destabilizes the meridional mode, it is not likely that the AMM is in a linearly unstable state in nature. Rather, it is thought that some sort of stochastic or external forcing is required for its excitation (here, "external" refers to processes external to the coupled dynamical system within which meridional modes exist.) In particular, it has been shown that the AMM can be excited by variations in the North Atlantic Oscillation (NAO) and ENSO [*Chiang et al.*, 2002; *Czaja et al.*, 2002, and references therein].

[5] Another candidate that we consider here for the excitation of decadal AMM variability is the Atlantic Multi-decadal Oscillation (AMO) [*Delworth and Mann*, 2000; *Kerr*, 2000]. Like the AMM, the AMO is related to an anomalous meridional SST gradient in the tropics, cross equatorial flow, and a meridional shift in the ITCZ location. The AMO is strongly related to decadal fluctuations in tropical cyclone activity [*Goldenberg et al.*, 2001]. Currently the physical mechanism that generates AMO variability or its relationship with tropical cyclones is not known, though it's low-frequency time scale implicates variations in the thermohaline circulation and/or anthropogenic forcing [*Kerr*, 2000; *Goldenberg et al.*, 2001; *Mann and Emanuel*, 2006]. Similarities between the AMM and AMO motivate an examination of how the two phenomena relate to each other, and to seasonal hurricane activity in the Atlantic. We will demonstrate that the AMO and AMM are not simply *ad hoc* manifestations of the same physical phenomenon, but have significantly different behaviors on multiple time scales.

2. Data and Analysis

[6] Hurricane activity is described here by time series of accumulated cyclone energy (ACE), a measure of seasonally integrated hurricane activity that depends on the number of storms, their duration, and their intensity over their lifetime [*Bell and Chelliah*, 2006]. We use the traditional "best track" estimate over the time period 1950–2005. The quality (and temporal consistency) of the data is high for the 1983–2005 record [*Kossin et al.*, 2007], and is

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Table 1. Correlations Between Hurricane Activity and Large-Scale Climatic Indices[a]

	Large-Scale Local Conditions						Climatic Indices			
	SST	SLP	VOR	SHR	CON	$\Delta\theta_e$	ACE	AMM	AMO	N34
	Correlations Between Unfiltered Time Series									
ACE	**0.45**	**−0.64**	**0.52**	**−0.33**	**0.54**	(−0.14)	1	0.64	0.44	−0.31
AMM	**0.79**	**−0.46**	**0.33**	**−0.43**	**0.32**	(−0.37)	0.64	1	0.60	(−0.14)
AMO	**0.63**	(−0.41)	**0.42**	(−0.33)	(0.14)	(−0.24)	0.44	0.60	1	(−0.06)
	Correlations Between Lowpass-Filtered Time Series									
ACE	**0.79**	**−0.65**	**0.71**	**−0.58**	(0.12)	(−0.12)	1	0.75	0.80	(−0.03)
AMM	**0.90**	(−0.43)	**0.55**	**−0.62**	(0.00)	(−0.24)	0.75	1	0.82	(0.17)
AMO	**0.83**	(−0.51)	**0.63**	**−0.60**	(−0.04)	(−0.25)	0.80	0.82	1	(0.06)
	Correlations Between Highpass-Filtered Time Series									
ACE	(0.21)	**−0.62**	**0.37**	(0.00)	**0.61**	(−0.22)	1	0.49	(0.01)	−0.44
AMM	**0.69**	**−0.47**	(0.06)	(−0.18)	**0.46**	**−0.63**	0.49	1	(0.23)	−0.39
AMO	(0.22)	(−0.20)	(0.16)	(0.07)	(0.13)	(0.08)	(0.01)	(0.23)	1	−0.33

[a]Correlations that are expected, via physical arguments, to contribute to an increase in hurricane activity are listed in bold and underlined. Statistical significance is inferred when the correlation's T-statistic exceeds the one-tailed (for ACE) or two-tailed (for the AMM and AMO indices) 95% significance level, using the effective number of degrees of freedom [*Bretherton et al.*, 1999]. Correlations that are not statistically significant are listed in parentheses – all other correlations are statistically significant.

expected to be acceptable for the longer period of record, which spans the aircraft reconnaissance and satellite eras.

[7] Large-scale climatic indices are constructed for comparison with the ACE estimates. The large-scale local climatic conditions include the HadISST SST data [*Rayner et al.*, 2003]; and SLP, SHR, VOR, CON, and $\Delta\theta_e$ from the NCEP reanalysis [*Kalnay et al.*, 1996]. Physical arguments suggest that increased activity — due to increased frequency, duration, or intensity — should be associated with high SST, VOR, and CON; and low SLP, SHR and $\Delta\theta_e$. All indices are spatially averaged over the region 90°W–20°W, 5°N–25°N corresponding to the main development (MDR) region for Atlantic hurricanes; and temporally averaged (hence annually resolved) from July-November, from 1950–2005. We note that although an influence of hurricane activity on climate has been shown on short time scales [e.g., *Sobel and Camargo*, 2005], we do not expect our results to be unduly influenced by hurricane activity due to our longer averaging period (our results also suggest that this influence is not strong, e.g. in the positive correlation between ACE and SST, or the negative correlation between ACE and SHR).

[8] We calculate large-scale climatic indices that represent the AMM, the AMO (defined, following *Goldenberg et al.* [2001], as SST averaged over the region 60°W–20°W, 45°N–65°N), and ENSO (represented by the Niño 3.4 index; N34). The AMM is calculated in the same manner as used by *Chiang and Vimont* [2004]: (*i*) SST and lower level winds over the Atlantic (75°W–15°E, 20°S–30°N) are obtained from 1950–2005, (*ii*) data are detrended and smoothed using a 3-month running mean (*iii*) an index of ENSO variability is removed from the data via linear regression, and (*iv*) Maximum Covariance Analysis (MCA) is applied to the temporal covariance matrix between the resulting two fields. We use the SST expansion coefficient from the MCA. The AMO index of *Sutton and Hodson* [2005] (SST averaged over the entire Atlantic north of the equator) is correlated with our AMO index at $r = 0.82$ for the raw (yearly) indices, and at $r = 0.92$ for the lowpass-filtered indices. We use the North Atlantic-based AMO index to remove geographic overlap between

our AMM index (defined over the Tropical Atlantic, to 32°N) and the all-Atlantic AMO index. In the analyses below, lowpass-filtered data are constructed by applying a 1-4-6-4-1 filter to the time series, which roughly retains variance at decadal and longer time scales; highpass-filtered data is constructed by subtracting the lowpass-filtered data from the raw data.

3. Large-Scale Climate and Atlantic Hurricanes

[9] The relationship between ACE and large-scale climatic conditions in the MDR is shown via their correlation in Table 1. Table 1 shows that higher ACE is associated with higher SST, VOR and CON, and reduced SLP and SHR, as expected from physical arguments. We note that this relationship is not guaranteed – similar analysis of tropical cyclone activity outside of the North Atlantic (not shown) produces very different relationships, probably due, in part, to the more dominating influence of ENSO on both storms and large-scale climate in the Pacific and Indian Ocean basins. Table 1 also shows that ACE is significantly correlated with both the AMM and the AMO. An important finding is that the AMM explains twice as much variance of ACE as does SST in the MDR ($r^2 = 0.64^2$ vs. $r^2 = 0.45^2$, respectively). This indicates that the AMM's spatial structure — and ultimately the coupled mode of variability represented by that spatial structure — is more useful for explaining hurricane/climate relationships than SST alone. On decadal timescales, SST and the AMM explain equal amounts of variance of ACE ($\sim$60%), but the AMM offers a more physically reconcilable association and relates locally to ACE on shorter time-scales as well.

[10] Why is ACE so strongly related to the AMM? To address this question, we considered the correlation between the AMM and the same large-scale conditions in the Atlantic MDR for the time period 1950–2005 (Table 1). Like ACE, the AMM is positively correlated with SST, VOR and CON, and negatively correlated with SLP and SHR. These correlations highlight a major finding of this study: *the AMM is associated with climatic conditions in the Atlantic that all cooperate in their influence on seasonal hurricane activity.* Naturally, the AMM is not perfectly

Table 2. Correlations Between the AMM and Tropical Cyclone Metrics[a]

	ACE	MKE	VAV	N	DUR	NCAT345
AMM	0.64	0.36	0.33	0.54	0.47	0.61

[a]New variables include: mean kinetic energy (MKE; defined by squaring the maximum wind speed for each observation and averaging over each season — this is identical to ACE divided by the number of storm periods), averaged maximum wind speed (VAV; defined by averaging the maximum wind speed over each season), the number of named storms (N), the average duration of storms (DUR; defined by averaging the duration of each storm in a season), and the number of intense hurricanes (NCAT345; defined as the number of category 3, 4, or 5 hurricanes). All correlations are statistically significant, using the same methodology as Table 1.

correlated with ACE in the Atlantic due to unrelated fluctuations in both climatic variability and hurricane activity. For example, it is known that a part of any season's integrated hurricane activity will be determined by the internal dynamics of individual hurricanes, which may have little relationship with the large-scale climatic conditions. Table 1 indicates that the AMM is also significantly correlated with the AMO; the AMO/AMM relationship is discussed below.

[11] The relationship between the AMM and ACE in Table 1 can be further fleshed out by considering the correlation between the AMM and the individual components that comprise ACE: intensity (measured as a maximum wind speed), frequency (number of storms that form in a season), and the duration of the storms. Table 2 indicates that the AMM has more influence on the number (N) and duration (DUR) of storms than on their intensity. The small positive correlation between the AMM and the hurricane intensity metrics (e.g. MKE or VAV) may reflect the relationship between SST and intensity as expected by maximum potential intensity (MPI) theory [*Emanuel*, 1987]: that is, in a large enough sample an increase in MPI (due to a local increase of MDR SST) will be

discernable as an increase of the greatest measured intensities. On interannual timescales, however, it is more likely that the correlation is due to the relationship between mean intensity and duration: longer-lived storms tend, on average, to become stronger.

[12] The spatial structure of variability associated with the AMM is shown in Figure 1. Despite the AMM's maximum variance during boreal Spring, the SST and lower-level wind fields reproduce salient features of the AMM during boreal Summer and Fall: an anomalous meridional SST gradient and lower-level winds that flow toward anomalously warmer water and veer to the right (left) in the northern (southern) hemisphere. Climatic conditions in the Atlantic MDR reproduce the expected relationships from Table 1, with increased SST and CON, and reduced SLP, SHR, and $\Delta\theta_e$. Despite insignificant relationships with $\Delta\theta_e$ in Table 1, the spatial map indicates a large region of reduced static stability in the eastern MDR. Also shown in Figure 1b is the regression map of latent heat flux onto the AMM index which indicates an anomalous downward flux along about 15°N despite warmer SSTs in that region. Upon closer inspection, it is seen that the downward latent heat flux anomalies are collocated with westerly lower-level wind anomalies along the southern flank of an anomalously weak subtropical high (Figure 1a). This relationship could be caused by independent atmospheric circulation anomalies, or it could reflect the coupled WES feedback associated with meridional mode dynamics. In either case, the downward heat flux (in an area of increased SST) highlights the role of ocean-atmosphere interactions in generating MDR SST anomalies associated with the AMM.

[13] The strong correlation between the AMM and AMO, combined with the similar spatial structure of SST anomalies associated with the two time series (compare Figure 1a with Figure 2 of *Goldenberg et al.* [2001]) indicates a close relationship between the AMM and AMO. The strong correlation between the two indices suggests that either (a) the AMM and AMO are the same phenomenon, or,
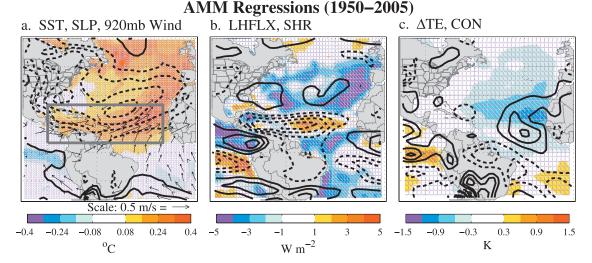
AMM Regressions (1950–2005)

Figure 1. Regression maps of various data (Jul−Nov mean) onto the AMM index: (a) SST (shaded), SLP (contour 0.1 mb), and 925mb winds (vectors); (b) Latent Heat Flux (shaded), SHR (contour 0.25 m s^{-1}); (c) $\Delta\theta_e$ (shaded), CON (contour 4×10^{-8} s^{-1}). For all panels, solid contours denote positive values, dashed contours denote negative values, and the zero contour has been omitted. Regression slope coefficients are obtained with the standardized AMM time series, so values indicate variations in each respective field per standard deviation of the AMM time series.
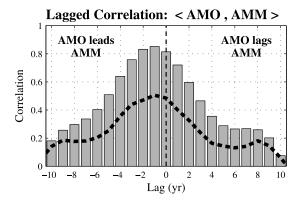
Lagged Correlation: < AMO , AMM >

Figure 2. Cross correlation between the raw (dashed line) and lowpass-filtered (bars) AMO and AMM time series. The raw cross-correlation function has been smoothed with a 1-2-1 filter.

given that the AMM is thought to require some sort of external excitation, (b) the AMO excites the AMM. To illuminate the difference between the AMO and the AMM, we show the relationship between the AMO or AMM, and large-scale climatic conditions (including ACE) on decadal and interannual time scales in Table 1. On decadal time scales, the AMM and the AMO exhibit the same relationship with large-scale climatic conditions, including increases in SST, VOR, and ACE, and decreases in SHR. On interannual time scales, however, our highpass-filtered AMO index is uncorrelated with hurricane activity and large-scale climatic conditions in the MDR. This is not surprising, as the AMO is not expected to operate on interannual time scales in any physically meaningful way. However, the application of a highpass-filter to the AMM index is well justified as the AMM is a known dynamical mode that operates on both interannual and decadal time scales — and, the resulting correlations indicate decidedly different relationships. In particular, the AMM is found to be significantly correlated with ACE and large-scale climatic conditions in the MDR. (The reduced correlation with SHR is due to spatial averaging over the MDR; regression maps of highpass-filtered variability onto the AMM (as in Figure 1; not shown) show large regions of reduced SHR over the region. The highpass-filtered relationship between hurricane activity and local SST or SHR is generally consistent with results of *Elsner et al.* [2006]). A second major finding of this study is: *the AMM and AMO both correlate strongly with Atlantic hurricane activity on a decadal time scale, but the AMM also correlates strongly on interannual time scales.*

[14] We speculate from the above analysis that the strong relationship between the AMM and AMO exists because the AMO excites the tropical AMM. As a first step toward testing this hypothesis, we plot the lagged correlation between the lowpass-filtered and raw AMO and AMM time series in Figure 2. The lagged correlation shows a clear asymmetry with the AMO *leading* the AMM. This asymmetry is evident for both lowpass-filtered and raw lagged correlations, and leads to the third major finding of this research: *the AMO excites the AMM.* This is not surprising, as it appears that the AMM can be excited by a number of physical processes (e.g. heat fluxes induced by past ice-sheet variations [*Chiang and Bitz*, 2005], or stationary wave

induced variations in subtropical trade winds). However, the consequent interpretation that the influence of the AMO on seasonal hurricane activity is manifest through the AMM, constitutes a significant reinterpretation of our understanding of relationships between hurricanes and climate in the Atlantic. The cause of the lagged correlation in Figure 2 is not currently known, and is an area of present research.

4.   Conclusions and Discussion

[15] This manuscript examines the relationship between seasonal hurricane activity and large-scale climatic variability in the Atlantic. It is found that seasonal hurricane activity is strongly related to the Atlantic meridional mode (AMM) and the Atlantic multi-decadal oscillation (AMO). Further analysis identifies the following major findings:

[16] 1. The AMM is associated with a number of large-scale climatic conditions in the Atlantic that, based on physical arguments, all cooperate in their influence on seasonal hurricane activity. (This is markedly different than the inter-relationships between these variables in other basins, which points to the Atlantic as a basin that is particularly prone to strong connections between hurricane activity and climate variability.)

[17] 2. Seasonal hurricane activity in the Atlantic is strongly related to the AMM on interannual and decadal time scales, but is related to the AMO only on decadal time scales.

[18] 3. The AMO appears to be an effective means of exciting the AMM on decadal time scales.

[19] Combined, these findings suggest that the AMO's influence on seasonal hurricane activity manifests itself through the AMM.

[20] The findings from this paper refocus our understanding of the relationship between climate variability and seasonal hurricane activity. In particular, the AMM is a dynamical mode of variability, which suggests that the relationships expressed in Table 1 arise due to dynamical interactions in the tropics. This constitutes an advancement over traditional, thermodynamic arguments of hurricane-climate interactions. In particular, it indicates that seasonal hurricane activity strongly relates to SST in the Atlantic MDR because SST is strongly related to the AMM, which in turn generates a number of large-scale climatic conditions that all cooperate in their influence on seasonal hurricane activity.

[21] We note that further analysis is needed to identify the physical mechanisms that underlie AMO variations, and link the AMO and AMM (e.g. we expect that the tropical meridional SST gradient common to both phenomena plays an important role). The notion that the AMO is anthropogenically forced [*Mann and Emanuel*, 2006] presents the intriguing possibility that the AMM will be affected by anthropogenic climate change.

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