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Nonlocality of Atlantic tropical cyclone intensities

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[1] The assumption that tropical cyclones respond primarily to sea surface temperatures (SSTs) local to their main development regions underlies much of the concern regarding the possible impacts of anthropogenic greenhouse warming on tropical cyclone statistics. Here the observed relationship between changes in sea surface temperature and tropical cyclone intensities in the Atlantic basin is explored. Atlantic tropical cyclone intensity fluctuations and storm numbers are shown to depend not only upon SST anomalies local to the Atlantic main development region, but also in a negative sense upon the tropical mean SST. This behavior is shown in part to be consistent with changes in the tropical cyclone potential intensity that provides an upper bound on storm intensity. However, Atlantic tropical cyclone intensity fluctuations are more nonlocal than the potential intensity itself and specifically vary along with Atlantic main development region SST anomalies relative to the tropical mean SST. This suggests that there is no straightforward link between warmer SSTs in the main development region and more intense tropical cyclones.

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1. Introduction

[2] Recent studies have posited trends in various measures of tropical cyclone (TC) activity, particularly in the North Atlantic basin. *Emanuel* [2005] showed that the total power dissipation by TCs, a measure of TC intensity that scales as the cube of the maximum TC wind speed, is highly correlated with August–October sea surface temperatures (SSTs) over the North Atlantic main development region (MDR). The results of *Hoyos et al.* [2006] suggest that increases in TC intensity are closely tied to warming trends in TC main development region SSTs. This appears to open the door to the possibility that anthropogenic climate change, which almost certainly will warm tropical SSTs, might impact TC intensities, as argued for example by *Mann and Emanuel* [2006] and *Trenberth and Shea* [2006].

[3] Underlying all of these arguments is the assumption that TC intensities, and Atlantic TC intensities in particular, respond primarily to SST fluctuations in the MDR. This assumption is implicit even in studies that attempt to attribute recent changes in TC intensity not to climate change but to some other entity such as the Atlantic Multi-

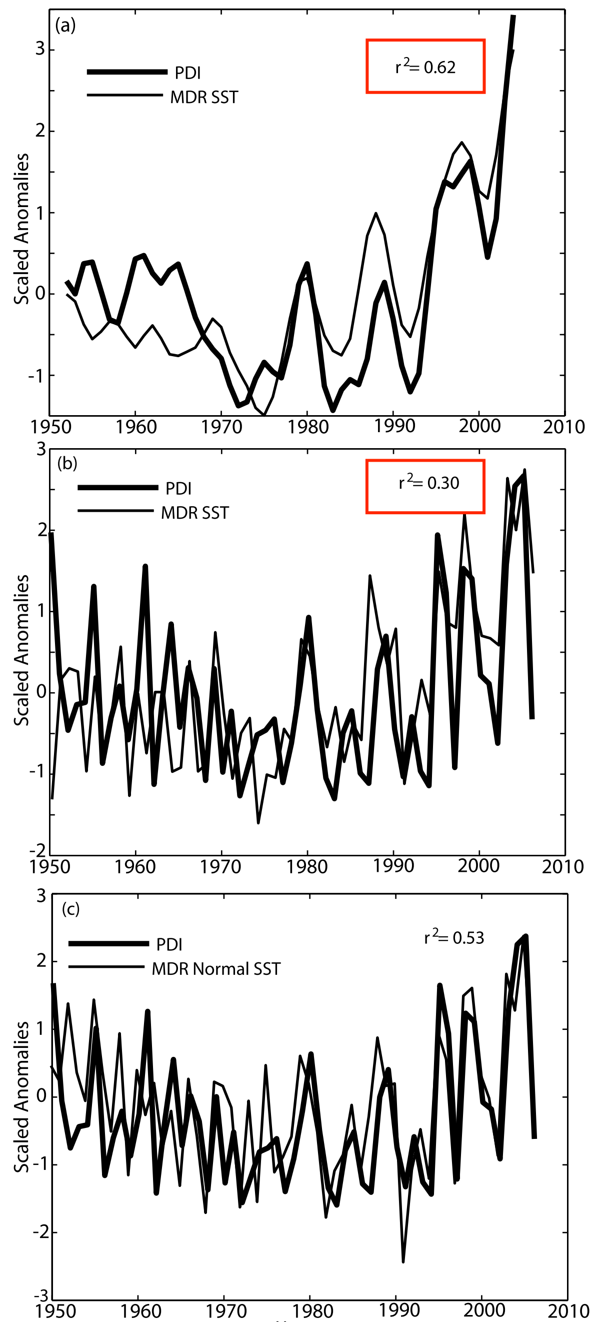

Figure 1. (a) Smoothed normalized anomalies in PDI and MDR SST for the North Atlantic. (b) As in Figure 1a but with no interannual smoothing. (c) As in Figure 1b but with MDR SST anomalies relative to the tropical mean (MDRN SST anomalies).

decadal Oscillation (AMO) [*Goldenberg et al.*, 2001]. Within the context of potential intensity (PI) theory [*Emanuel*, 1988; *Bister and Emanuel*, 1998], all other factors being equal a local increase in SST will destabilize the atmosphere and result in more intense TCs. However, nonlocality enters into this apparently straightforward relationship between local SST and TC intensities, as atmospheric temperature in the tropical upper troposphere is in general set not by the local SST but rather by the tropical mean SST [*Sobel et al.*, 2002]. Anomalously warm tropical mean SST increases upper tropospheric temperatures, stabilizing the atmosphere, and hence should lead to weaker tropical cyclones [*Tang and Neelin*, 2004; *Shen et al.*, 2000]. *Elsner et al.* [2006] highlight such suppression of Atlantic TC intensities by remote factors, as they show that in the Atlantic basin global mean temperature acts as a negative predictor of TC intensity when the local impact of MDR SST is removed. Indeed, the fact that global tropical SST trends might have a smaller effect on tropical cyclone intensities than regional fluctuations in MDR SST relative to that global mean was explicitly recognized by *Emanuel* [2005].

[4] Given this state of affairs, it is vital to understand whether local or nonlocal influences dominate TC intensities in the North Atlantic hurricane basin. The degree of localization examined here shades from totally local control, where SST anomalies within the Atlantic MDR dominate observed fluctuations in TC intensity, to nonlocal control, where fluctuations in TC intensity depend solely upon the MDR SST relative to the tropical mean SST. Note that nonlocal control defined in this manner will be more or less independent of global warming, as it depends upon the relative regional distribution of SST anomalies rather than a basin-independent increase in SST.

[5] Within this context, we show that Atlantic TC intensities are nonlocal in the sense that intensity fluctuations and storm numbers depend much more sensitively on MDR SST anomalies relative to the tropical mean than on the MDR SST anomalies themselves. The implication of this behavior is that Atlantic TCs are intrinsically nonlocal, and specifically that the increase in Atlantic TC intensities since roughly 1980 cannot be attributed to a global increase in SST.

2. SST and Hurricane Intensity Fluctuations

[6] We examine TC winds for the period 1950–2006 in the North Atlantic basin based upon Tropical Prediction Center best track reanalysis, with intensity corrections for the pre-1975 part of the record following *Emanuel* [2005]. The SST

fields used are from the extended reconstruction of global SST based on the COADS data as documented by *Smith and Reynolds* [2004], as archived at NOAA's National Climatic Data Center. The emphasis is on the Atlantic main development region (MDR), which is defined here as 6–18°N, 20–60°W. In addition, we consider the tropical mean SST, defined as the SST averaged over 0–15°N. This averaging is appropriate for the Northern Hemisphere fall season (ASO), when the warmest SSTs are generally located north of the equator.

[7] An apparent local relationship between SST and hurricane intensity is readily shown using this data set. Figure 1a reproduces the result of *Emanuel* [2005] for the data here, showing the remarkably similar time traces for SST in the Atlantic MDR and the power dissipation index (PDI) that is proportional to the cube of the wind speed for these storms in the Atlantic basin. Both quantities are filtered using a 1-3-4-3-1 filter. The apparent covariability of these two quantities is striking; while filtering reduces the number of degrees of freedom to roughly 15, the null hypothesis that there is no relationship between the MDR SST and PDI can be rejected with $p < 0.0001$ ($t = 5.8$) via a two-tailed Student's t test.

[8] However, it is important to note that this agreement does not prove locality. All that has been shown is that there is a relationship between MDR SST anomalies and PDI. Specifically, the PDI might depend not only upon the local value of MDR SST, but some other unspecified global quantity. Figure 1b shows that the unfiltered data has substantial interannual variability about the direct PDI/MDR SST relationship, but the two quantities are still strongly linked ($r = 0.53$; $t = 4.6$; $p < 0.0001$). It is tempting to view this interannual variability as simply "noise" around the MDR SST "signal"; this ultimately is the motivation underlying the filtering applied by *Emanuel* [2005] as reproduced in Figure 1a. This interpretation is incorrect, as the unfiltered PDI is related to the tropical mean SST component normal to the Atlantic MDR SST at a level ($r = -0.49$; $t = 4.2$; $p < 0.0001$) nearly as strong as the PDI and Atlantic MDR SST itself. The inescapable implication of this is that SST anomalies remote from the Atlantic MDR are as important as SST anomalies within the MDR in determining Atlantic TC intensities.

[9] This nonlocality of Atlantic PDI is more than simply a reflection of the El Niño–Southern Oscillation (ENSO) signal in Atlantic basin TC intensities [*Gray*, 1984; *Pielke and Landsea*, 1999; *Elsner et al.*, 2001]. By itself, the Nino 3 index explains only 8% of the PDI variance ($r = 0.29$; $t = 2.3$; $p < 0.03$), substantially less than the approximately 25% captured by the tropical mean SST anomaly normal to the Atlantic MDR SST. This suggests a larger dynamic encompassing the entire tropics underlies Atlantic TC intensity fluctuations. Any anomalies in deep convection will be communicated rapidly throughout the tropics because of the smallness of the Coriolis parameter, so in this sense there should be nothing special about convective anomalies arising from the ENSO cycle. This should also apply to anomalous convection over land surfaces as well. However, because of equinoctial conditions, tropical land surfaces in the Northern Hemisphere in general will not be warmer than nearby oceans, so one expects any signal due to anomalous convection over land to be small.

[10] Figure 1c shows the Atlantic PDI and the MDR SST component normal to the tropical mean SST (hereafter the MDRN SST), where this normal component is calculated using a Gramm-Schmidt orthogonalization. The MDRN SST is quite close to the Atlantic MDR SST anomaly relative to the tropical mean SST, having the specific form

$$[\text{Atlantic MDRN SST}] \simeq [\text{Atlantic MDR SST}] - 0.8 \times [\text{Tropical Mean SST}]. \quad (1)$$

These two time series are more closely related ($r = 0.73$; $t = 7.7$; $p < 0.0001$) than the Atlantic PDI and MDR SST shown in Figure 1b. The agreement over the modern (post-1975) era is even more spectacular, with the MDR normal SST explaining roughly 75% of the interannual variance in the unfiltered PDI time series. Indeed, over this latter period these two quantities are so strongly linked on interannual time scales that it seems reasonable to hypothesize that the MDRN SST determines the PDI. It also holds when low-pass filtering these quantities; the 1-3-4-3-1 low-pass filtered MDRN SST anomaly time series explains roughly 10% more low-pass PDI variance than the low-pass MDR SST shown in Figure 1a. Similar results are found for the accumulated cyclone energy metric of integrated TC intensity as well.

3. Nonlocality

[11] The above result suggests that MDR SSTs and tropical mean SST are of roughly equal importance

PDI Power Dissipation Index
PI Potential Intensity
ACE Accumulated Cyclone Energy

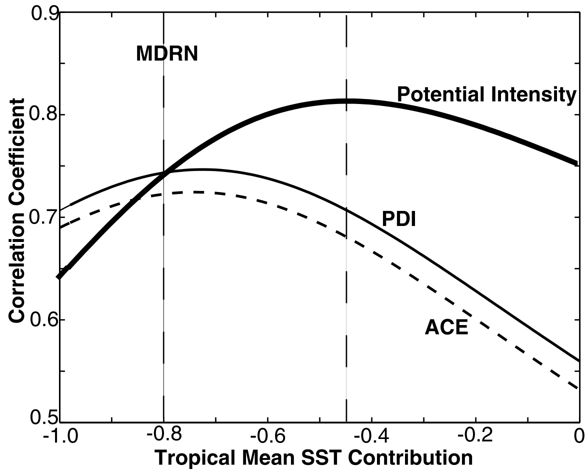

Figure 2. Correlation as a function of locality for the potential intensity, PDI, and the accumulated cyclone energy (ACE) index. A tropical mean SST contribution of zero is purely local, i.e., is the MDR SST in isolation, while a tropical mean SST contribution of (−1) is the MDR SST relative to the tropical mean. The MDRN SST (−0.8) on this scale is shown for comparison.

in determining TC intensities in the North Atlantic. However, it is important to note that this behavior is not necessarily inconsistent with potential intensity (PI) theory. PI theory uses an atmospheric temperature profile, along with sea level pressure and boundary layer moisture content, to provide an upper bound for TC intensities [*Emanuel*, 1988; *Bister and Emanuel*, 1998]. However, because of the small magnitude of the Coriolis parameter in the tropics, upper tropospheric temperatures are not set locally but rather by the tropical mean SST [*Sobel et al.*, 2002]. Hence, the nonlocality above could well be consistent with PI theory. Indeed, the PI has been shown to capture aspects of TC intensity in the Atlantic basin [*Wing et al.*, 2007], and also appears to reflect the likelihood of TC development [*Emanuel and Nolan*, 2004; *Carmargo et al.*, 2007].

[12] To examine whether the nonlocal aspects of TC intensity are consistent with PI theory, we construct the PI for a representative sounding for the Atlantic MDR using the NCEP reanalysis over the period 1950–2006. This representative sounding is calculated by averaging the temperature profiles, sea level pressure, and boundary layer moisture content over the MDR for the months ASO in any given year. The PI is then calculated following *Bister and Emanuel* [1998], with corrections prior to 1980 following *Emanuel* [2007]. Note that PI appears to be linear in the sense that calculating the PI for all locations within the MDR and then averaging yields basically the same result as calculating the PI for a representative sounding as done here (G. A. Vecchi, personal communication, 2007).

[13] Figure 2 shows the correlation between the PI and a hypothetical SST anomaly of the form

$$\Delta\text{SST} = [\text{Atlantic MDR SST}] + \alpha[\text{Tropical Mean SST}] \quad (2)$$

as a function of the parameter α, where $\alpha \in [-1, 0]$, consistent with the expectation from the previous section that positive tropical mean SST anomalies act contrary to TC intensity in the Atlantic basin. It is apparent that PI in the Atlantic MDR is more local than either PDI or ACE, as its correlation is maximum when $\alpha \simeq -0.5$, compared to $\alpha \simeq -0.8$ (i.e., MDRN SST) for PDI or ACE. Two questions immediately arise from this result. First, is this degree of locality generic to the entire Atlantic basin, or is the basin on the whole more nonlocal? Second, why are TC intensities more nonlocal than the PDI?

PDI or PI?

[14] Regarding the first question, extending the PI analysis beyond the MDR suggests that this degree of locality is particular to the MDR, as PI in the Caribbean and Gulf of Mexico are both more strongly correlated with the MDR relative SST (α = −1) rather than the α = −0.5 value characteristic of the MDR PI itself. Moreover, this degree of locality is not found in the 21st century projections of PI examined by *Vecchi and Soden* [2007b], as they consistently find α = −1 provides the best description of projected changes in PI over the Atlantic basin.

[15] Regarding why TC intensities might be more nonlocal than the PI itself, there appear to be three possibilities, namely storm intensity scaling, storm numbers, and storm duration. Let us consider scaling first. Complementary cumulative distribution functions (CDFs) provide a succinct means by which to examine whether it is changes in the transitions between different categories of TCs, i.e., their scaling behavior with respect to intensity as they evolve from tropical storm strength to major hurricane strength, or whether it is changes in the maximum potential intensity of hurricanes that govern fluctuations in intensity [*Emanuel*, 2000; *Swanson*, 2007]. The focus is on CDFs for storms that originate in the Atlantic MDR, as such storms comprise the bulk of intense storms in the North Atlantic Basin.

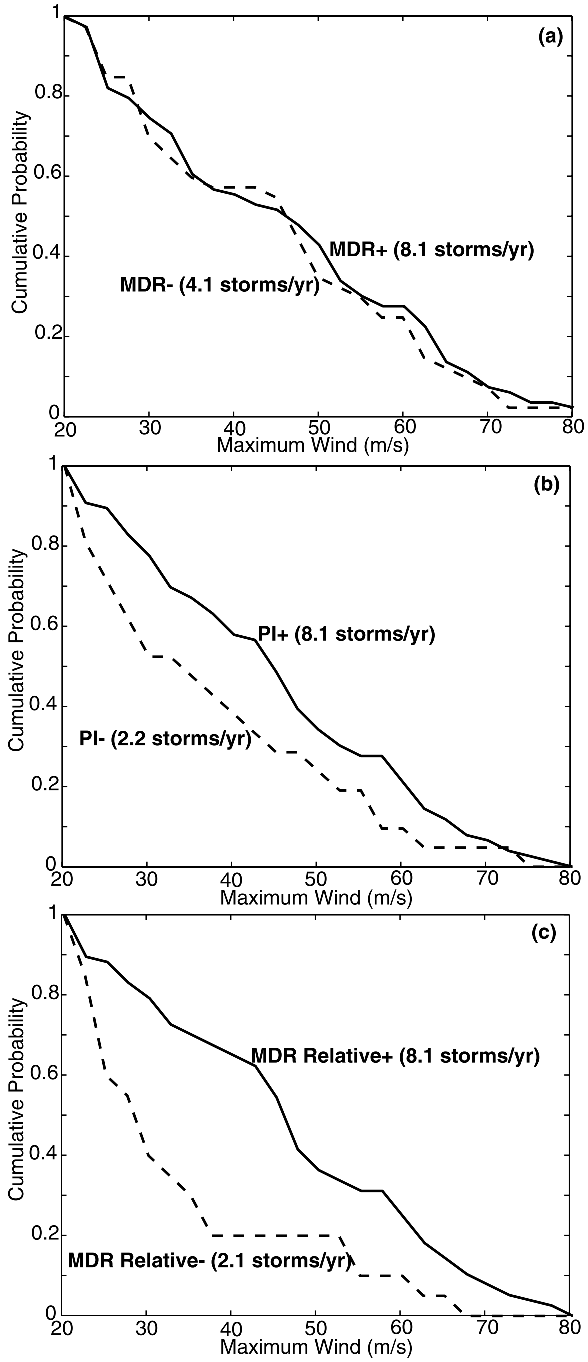

Figure 3. Complementary cumulative distribution functions for storms originating in the Atlantic MDR. (a) Storms originating during MDR+ and MDR− years. (b) Storms originating during PI+ and PI− years. (c) Storms originating during MDR relative+ and MDR relative− years.

[16] Figure 3a shows the complementary cumulative distribution function (CDF) for years with the 10 largest and smallest Atlantic MDR SST anomalies. There is a significant difference in storms/year between anomalously warm (MDR+) and cold (MDR−) conditions, as during MDR+ years 8.1 storms/year form while MDR− years only see 4.1 storms/year forming. However, there is no apparent difference in the CDFs between these anomalously warm and cold conditions. In both situations, the CDFs are approximately linear ($r^2 > 0.99$); the least squares best linear fit decreases from unity at the tropical storm level to intersect the x axis at roughly 75 m s^{-1} for both MDR+ and MDR− years.

[17] Markedly different scaling behavior is observed for the 10 largest and smallest MDR PI years (Figure 3b). The number of storms originating in the MDR varies much more strongly as a function of PI than for the MDR SST in isolation, as PI+ years experience 8.1 storms/year versus 2.3 storms/year for PI− years. Curiously, the scaling does not vary to the same extent as storm numbers. The CDF for PI− years is no longer linear, as the scaling transition between tropical storm-like and hurricane-like scaling discussed at length by *Swanson* [2007] emerges and influences the number of TCs that become intense. Roughly 35% of TCs originating in the Atlantic MDR achieve category 2 strength (>43 m s^{-1}) during PI− years, compared to 60% during PI+ years. This change in storm scaling is exacerbated for MDR relative SSTs. Figure 3c shows that only 20% of tropical storm-strength systems make the transition to category 2 hurricanes is when MDR relative SSTs are anomalously small.

[18] These changes in scaling behavior provide some insight into why TC intensities are more local than the MDR PI itself, as anomalously cold MDR relative SST anomalies strongly suppresses TC intensification, particularly for tropical storm strength systems. However, it is useful to enlarge the perspective to include the entire Atlantic basin. Moving from local to nonlocal, Table 1 outlines the number of storms for the decades with respectively the largest/smallest MDR SST anomalies, PI anomalies, MDRN SST anomalies, and MDR relative SST anomalies. At the tropical storm level, there is not a significant difference between event numbers among these measures, as roughly half as many events are found during negative anomaly years compared to positive anomaly years regardless of the underlying measure. Anomalous MDR relative SSTs yield the largest fractional difference between extreme positive and negative years, while anomalous MDR SSTs yield the smallest fractional difference. However, a statistically significant dis-

Table 1. Upper/Lower Quintile Events/Year, Ranging From Local (MDR SST) to Nonlocal ($MDR_{relative}$)[a]

Intensity	MDR	PI	MDR_{normal}	$MDR_{relative}$	PI $\perp$ $MDR_{relative}$	$MDR_{relative} \perp$ PI
$\geq$17 m s^{-1}	13.0/8.9	**15.5**/8.7	12.9/**7.3**	14.4/**7.3**	13.5/9.6	11.2/8.6
$\geq$33 m s^{-1}	7.3/4.3	**8.9**/4.5	8.0/3.3	**8.9**/**3.3**	7.1/6.5	7.6/3.9
$\geq$50 m s^{-1}	3.1/1.8	4.1/1.5	3.7/**0.8**	**4.5**/**0.8**	3.1/2.7	3.4/1.2

[a] Extreme values for each row are in bold.

tinction emerges for more intense events. Intense TCs (max wind $\geq$ 50 m s^{-1}) are 6 times more likely to occur during extreme positive MDR relative SST years compared to extreme negative years, 3 times as likely during PI+ years compared to PI− years, and less than twice as likely when MDR+ years are compared to MDR− years. Figure 4 shows tracks for these intense TCs for extreme positive/negative PI and MDR relative SST years; the reduction in the numbers of intense TCs that form in the Atlantic basin as a whole during years with negative MDR relative SSTs compared to years positive MDR relative SSTs is quite striking, spans the entire basin, and is not simply a product reduced events originating in the MDR.

[19] Further examination of the MDR relative SST and PI time series suggests that the signal governing storm scaling lies with the MDR relative SST. Specifically, the last two columns of Table 1 show the number of events for decades with respectively the largest/smallest anomalies, first for the PI time series when the MDR relative SST component is removed via a Gramm-Schmidt orthogonalization, and then the MDR relative SST time series when the PI component is removed in a similar manner.

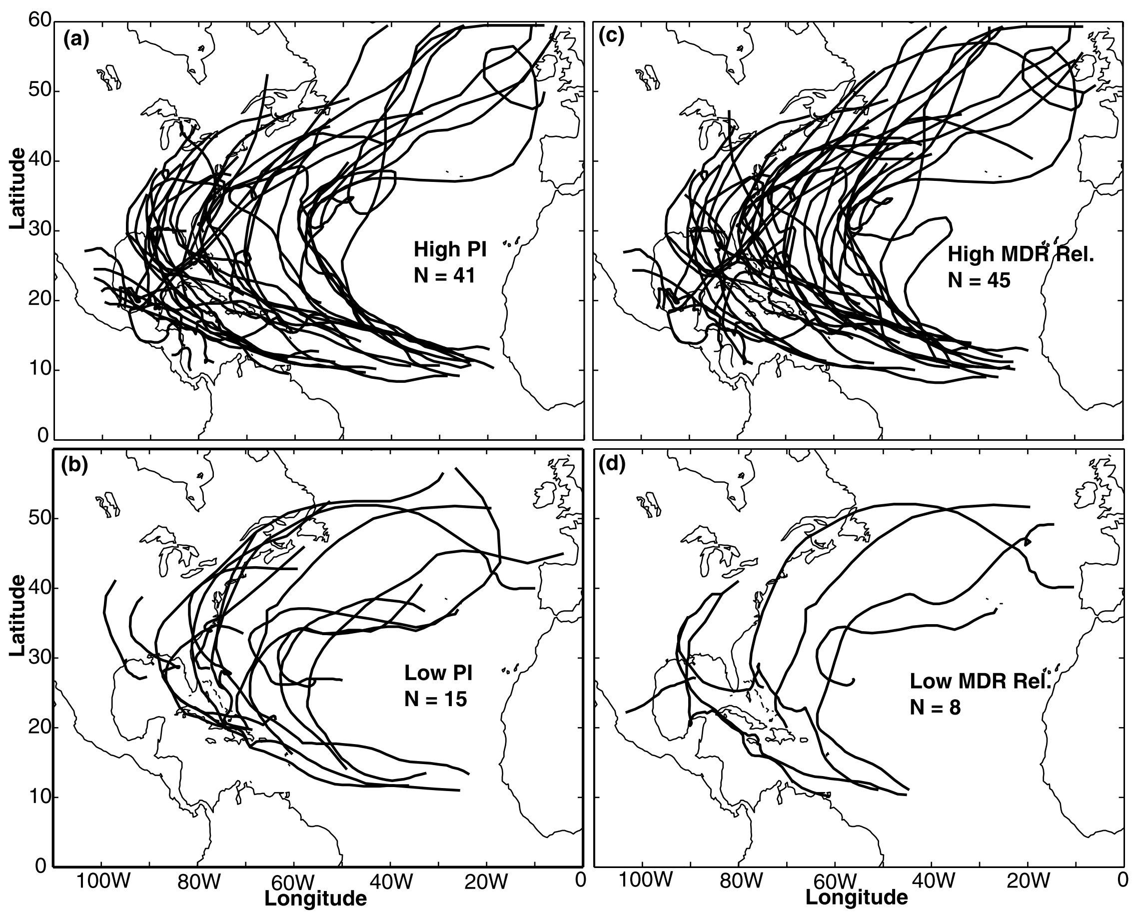

Figure 4. Cyclone tracks for (a) PI+, (b) PI− years, (c) MDR relative+, and (d) MDR relative− years.

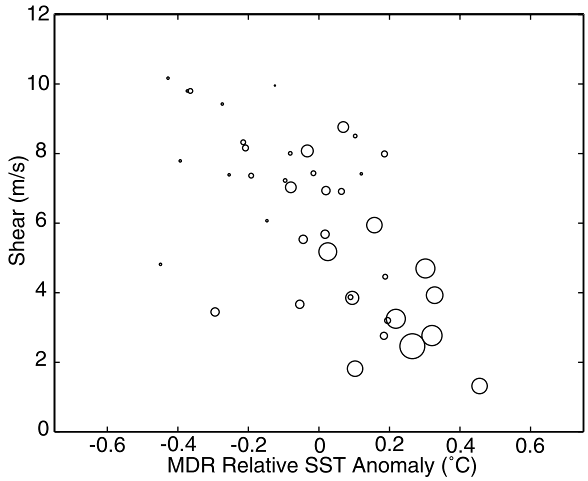

Figure 5. Bubble plot showing dependence of shear over Barbados versus MDR relative SST anomalies. The size of the bubbles indicates relative PDI; the largest bubble is a factor of 20 larger than the smallest bubble.

The PI time series "cleaned" of the MDR relative SST signal shows very little difference in the scaling of TC intensity regardless of whether the cleaned PI is anomalously high or low. In contrast, the cleaned MDR relative SST shows basically the same scaling as the MDR relative SST itself (column 2). This suggests that some factor other than PI controls the enhanced sensitivity of TC intensity to MDR relative SST.

4. Shear

[20] Wind shear provides one possible explanation why intense TC events are more sensitive to changes in MDR relative SST than to changes in PI, as it is broadly recognized to be detrimental to tropical cyclone formation and intensification [*Gray*, 1968; *Goldenberg and Shapiro*, 1996; *Vecchi and Soden*, 2007a]. Shear in the tropics is a natural quantity to be associated with nonlocal control, as it depends upon the distribution of deep convection in the tropics, which itself is a function of SST anomalies relative to the tropical mean [*Sobel et al.*, 2002]. To avoid inconsistencies in the various reanalyses associated with the inclusion of satellite data in the late 1970s, we consider the wind shear associated with a single sounding on the western edge of the MDR, and treat that sounding as being representative of the conditions within the MDR. The specific site we consider is Barbados (WMO ID#78954), at longitude 59°29′W, 13°4′N. Data from 1966 to 2006 are considered and are obtained from NOAA's National Climatic Data Center. The measure of shear we consider is the magnitude of the ASO 250–850 hPa wind vector.

[21] Wind shear appears to provide a plausible explanation why the PDI is much more nonlocal than the PI, as the Barbados shear is correlated with PI at $r = -0.45$, while it is correlated with the MDR relative SST at $r = -0.7$. The difference in correlations in this case is significant, with $p < 0.002$. GCMs also appear to capture this relationship between MDR relative SST and shear, and indeed suggest if may be stronger than the single sounding analysis here indicates. For ASO, the 20th century simulations using the HADCM3 model shows that the 250–850 hPa shear in the vicinity of Barbados (10–20°N, 50–70°W) is correlated with MDR relative SST anomalies at $r = -0.8$. Within the GCM, this is due primarily to the weakening of the Walker circulation over the Pacific when MDR relative SST anomalies are negative. As shown by *Vecchi and Soden* [2007a] this weakening is accompanied by increased shear in the vicinity of the Atlantic MDR. This relationship between MDR relative SST anomalies and wind shear appears to be unique to the Atlantic, although the precise underlying physical mechanism linking the two quantities is obscure.

[22] Wind shear appears to limit storm numbers in a manner similar to MDR relative SST anomalies. Specifically, during the 10 years with the highest shear (1966–2006) over Barbados an average of 2.2 storms/year develop in the MDR, compared to 7.9 storms/year for the 10 years with the lowest shear. High shear also impacts storm scaling in a manner similar to the negative MDR relative SST years shown in Figure 3c. The variability of Atlantic PDI with shear and MDR relative SST anomalies is summarized in the bubble plot of Figure 5; the covariability of these two quantities is apparent, as is the coincidence of large PDI years with positive MDR relative SST anomalies and low shear. It appears as if shear acts in a multiplicative sense with fluctuations in storm numbers largely associated with changes in PI to inhibit the transition of TCs from tropical storm strength to major hurricane strength. Specifically, a 1°C decrease in the MDR relative SST anomaly from its 2005 level leads to a collapse in PDI, where collapse here is used in the biological sense, meaning a decrease of 90%. As suggested by Figures 3 and 4, and Table 1, this collapse is a product of a marked reduction in

storm numbers as well as significantly altered scaling of TC intensities.

5. Discussion and Conclusions

[23] There are two primary points arising from this work that deserve further comment. First, in the Atlantic the MDR relative SST appears to provide a reasonable "poor man's" approximation to the PI, one which does not require knowledge of thermodynamic profiles to calculate. This is important, as it allows for interpretation of historical fluctuations in TC intensity prior to the advent of consistent atmospheric sounding in the tropics during the 1950s. In addition, it allows for easier interpretation of PI variability in climate model simulations, as outlined by *Vecchi and Soden* [2007b]. Secondly, this work highlights the fact that changes in TC behavior are not simply a response to changing SSTs in the Atlantic MDR. TC intensities in the Atlantic appear to depend as much on the tropical mean SSTs (in a negative sense) as they do upon SSTs local to the MDR. This dependence is a function of changes both in the thermodynamic profile of the atmosphere as well as in the shear. The strength of the statistical relationship between Atlantic TC intensities and Atlantic MDR SSTs relative to the tropical mean SST (i.e., MDRN SST anomalies) shown in Figure 1c is remarkable, and it is curious that it has escaped notice. This is particularly true in light of the fact that the tight relationship between these two quantities should have implications for seasonal forecasting of TC intensities [*Gray et al.*, 1993].

[24] That much said, the tropical Atlantic certainly could evolve toward a state where TC intensities are locally determined under climate change scenarios. In particular, this would occur if Atlantic SSTs became much warmer than the tropical mean SST, a situation in which one would expect the entire thermodynamic profile over the Atlantic to be controlled by local SSTs driving the overlying atmosphere toward a consistent moist adiabat. However, this does not appear to explain what has happened in the Atlantic MDR since the 1970s. While Atlantic MDR SSTs have warmed relative to the tropical mean SST over that period, at no time have they significantly exceeded the tropical mean. Whether this enhanced warming of Atlantic MDR SSTs relative to the tropical mean SST is a signature of global warming and will continue into the future is not apparent. However, climate change simulations suggest that Atlantic MDR relative SST anomalies will increasingly turn negative through the 21st century [*Vecchi and Soden*, 2007a, 2007b]. Given the roughly equal importance of MDR SST anomalies and tropical mean SST anomalies in the negative sense in determining Atlantic TC intensities, it is far from apparent whether efforts to apportion "blame" for the hyperactive 2005 season to global warming [*Trenberth and Shea*, 2006] or to the Atlantic Multidecadal Oscillation (AMO) along the lines of *Goldenberg et al.* [2001] are well founded.

[25] Insofar as the relationship between MDR relative SST anomalies and TC intensities extends to other hurricane basins, it is worth noting that the result here is consistent with the lack of trends in TC intensity in other basins [*Kossin et al.*, 2007]. Not all hurricane basins can be anomalously warm relative to the tropical mean at the same time, hence TC intensities may not be able to be simultaneously above average. In this light, *Vecchi and Soden* [2007b] show that a proxy for PI in the Atlantic, which in their case is simply the difference between local SST and the tropical mean, fails to show any trend in the 21st century in spite of a significant increase in SST in the Atlantic MDR over that period. Instead, it is the western Pacific basin that warms consistently relative to the tropical mean SST over the 21st century, and as such captures the bulk of the increase in TC intensity.

[26] Finally, the relationship between relative MDR SST anomalies and PDI shown in Figure 1c suggests an additional role for TCs in the climate system. It is well understood that TCs actively cool local SSTs via the breaking of inertial waves that entrain water from the ocean mixed layer base [*Emanuel*, 2001; *Sriver and Huber*, 2007]. The response to relative SST anomalies suggests that TCs may act to homogenize SSTs within the tropics, preventing the SST in any one area of the tropics from greatly exceeding the tropical mean SST. Thus, it may be that TC intensity fluctuations in a given basin are self-correcting. Whether such self correction actually occurs, and if so whether it will continue to do so under climate change scenarios is an important question that deserves further examination.

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