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HURRICANE VARIABILITY AND TRENDS: THE VARYING ROLES OF SEA SURFACE TEMPERATURE

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1. INTRODUCTION

Recent literature has been refocusing on the association between tropical sea surface temperature (SST) and hurricane activity (hurricane is used here in a generic sense and the term will be applied globally). 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. He found that the time series of seasonal-mean PDI and SST in the Main Development Regions of the Atlantic and Western North Pacific 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 SST variability on decadal time-scales.

Physical reconciliation of the relationships between SST and hurricane activity is generally posited using potential intensity 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 size) this will result in a uniform increase across the intensity distribution (Emanuel 2000; Wing et al. 2007).

Hurricane "activity" comprises three factors: the number of storms in a season (frequency), their duration, and their intensities. Of the three factors that affect hurricane activity, however, only intensity can be directly related to potential intensity theory. The variability of frequency and duration must be physically reconciled by other means. A problem with reconciling the relationship between PDI and large-scale tropical SST with potential intensity arguments is that the time series of total storm periods, which is simply the product of frequency and seasonal-mean duration, correlates very strongly with PDI. So it is clear that intensity variability, which might be partly explained by potential intensity reasoning, explains only a small part of the variability of seasonal hurricane activity as measured by PDI.

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2. COUPLED OCEAN / ATMOSPHERE MODES

Vimont and Kossin (2007) and Kossin and Vimont (2007) argued that tropical Atlantic SST variability is simply a manifestation of (and has acted as a proxy for) a more general variability of ocean-atmosphere patterns that affect Atlantic hurricane activity through a number of factors – specifically, by affecting hurricane frequency, duration, and intensity, and the regions where tropical cyclogenesis occurs (e.g., Fig. 1). They 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 as the Atlantic Meridional Mode (AMM), but also known historically as the "gradient", "inter-hemispheric", or "Atlantic Dipole" mode.

The AMM is the 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).

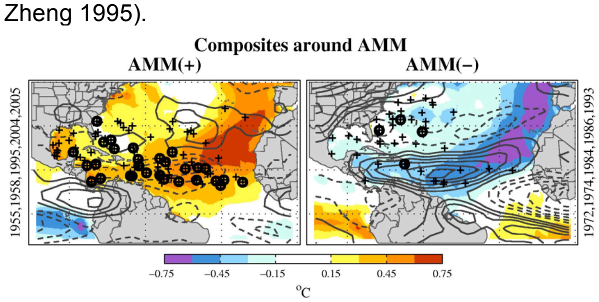

Figure 1: Tropical cyclogenesis points for the five strongest and five weakest AMM years in the period 1950–2005, superimposed on composites of SST (shaded) and shear (contours) anomalies. Crosses show the genesis points for all storms that reached tropical storm strength. Storms that reached "major hurricane" 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. [From Kossin and Vimont (2007)].

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 Niño events achieve (Battisti and Hirst 1986; Zebiak 1993). This allows the emergence of the AMM as the leading coupled mode and the primary modulator of Atlantic hurricane variability [with secondary non-local contributions from Pacific ENSO variability (Gray 1984; Shapiro 1987; Goldenberg and Shapiro 1996; Bove et al. 1998)].

3. HURRICANE ACTIVITY, SEA SURFACE TEMPERATURE, AND COUPLED MODES OF OCEAN-ATMOSPHERE VARIABILITY

The relationship between PDI and SST in the Atlantic and Pacific main development regions (MDR) is shown in Fig. 2. A key point demonstrated by the figure is that while PDI and SST are strongly correlated on decadal time-scales, they are uncorrelated on interannual time-scales. This sort of time-scale-dependent relationship is

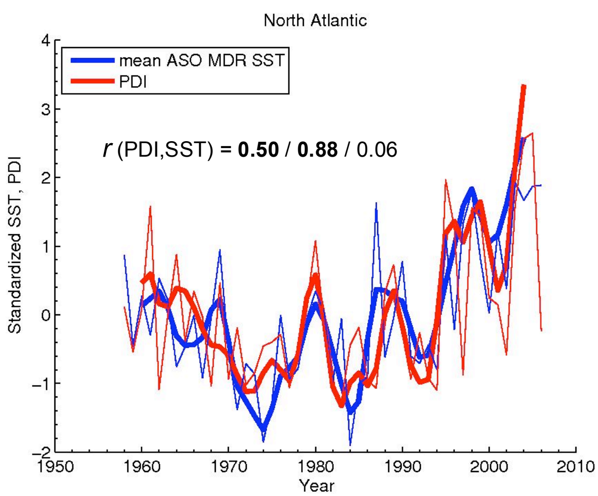

Figure 2: Time series of seasonal-mean Atlantic PDI and ASO-mean SST in the main development region. The raw series are shown by the thin lines, and low-pass filtered series are shown by the thick lines. The correlations of the two series are shown for the raw / low-pass filtered / high-pass filtered series. Boldface indicates statistical significance using effective degrees of freedom.

generally viewed as an indication that different physical mechanisms may be at work. Hoyos et al. (2006) applied techniques of Information Theory and found that on longer time-scales, hurricane activity is modulated more by SST and much less by other environmental factors such as vertical wind shear, for example. In a more general study of ocean-atmosphere variability, Kushnir (1994) found that SST was related to coherent patterns of atmospheric variability on interannual time-scales, but on longer time-scales, no such relationship was evident. Kushnir referred to this as the work of "different modes of interaction", and suggested that decadal SST variability is likely to be governed by ocean circulation variability. So given the existing evidence and literature, when considering the variability of hurricane activity there may be a temptation to say that the ocean doesn't matter much on interannual time-scales, and the atmosphere doesn't matter much on decadal time-scales.

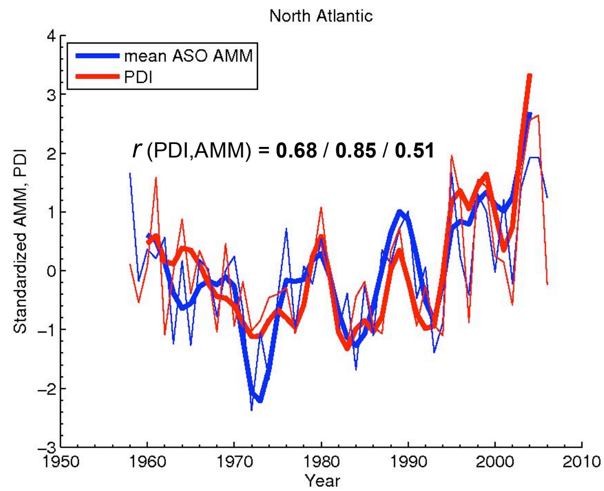

Figure 3: Similar to Fig. 2, but for Atlantic PDI and the ASO-mean AMM index.

Instead of separating the effects of the ocean and atmosphere, however, here I'll suggest that a more relevant way to view this issue is in the framework of coupled ocean-atmosphere modes. Figure 3 shows the relationship between Atlantic PDI and the AMM. In this case, the separations of the time-scales of interaction are not as pronounced as they were when only SST was considered, and the coupled oceanic and atmospheric patterns of the AMM are significantly modulating hurricane activity on both interannual and decadal time-scales. The correlation on decadal time-scales is roughly the same as the decadal relationship between PDI and SST, but here we also have a meaningful interannual relationship. In fact, the relationship between the AMM and Atlantic PDI is significant at monthly timescales (not shown).

A similar situation is also found in the Western North Pacific. Figures 4 and 5 demonstrate marked differences between how hurricane activity relates to SST variability in the hurricane main development region and how it relates to ENSO variability. Here, the relationships between PDI and SST are in opposition between interannual and decadal time-scales (cf. Chan and Liu 2004) resulting in no correlation between the raw series. This, and the different behavior seen between Atlantic SST and PDI, can be understood by considering Fig. 6. In the Atlantic, much of the AMM's center of SST action lies in the heart of the main development region. Thus, when the AMM is positive and the overall structure of the atmosphere is conducive to enhanced hurricane activity, the SST in the main development region is also warm. Contrarily, when ENSO organizes the regional atmosphere in a way that is conducive to enhanced Pacific hurricane activity, the SST in the main development region is anomalously cool, which acts to oppose the enhanced hurricane activity. In the Atlantic, the correlations between the AMM index and SST in the main development region are *r*(AMM,SST) = **0.76** / **0.92** / **0.51** for the raw, low-pass, and high-pass filtered series, respectively (boldface indicates significance). In the Pacific, a very different relationship is found between the Niño 3.4 index and SST in the main development region: *r*(N34,SST) = –0.20 / –0.26 / **–0.56**.

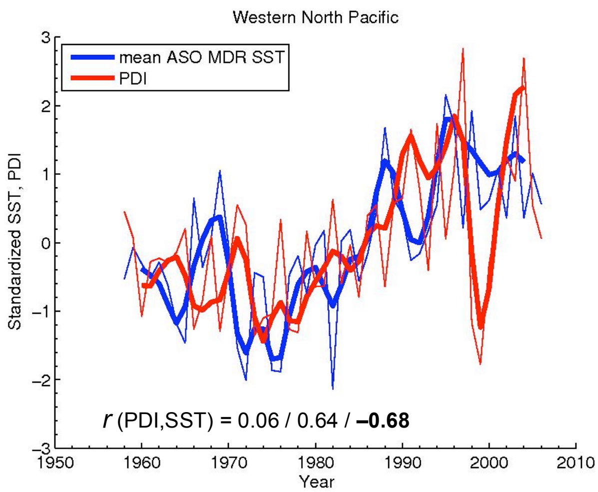

Figure 4: Similar to Fig. 2, but for the Western North Pacific.

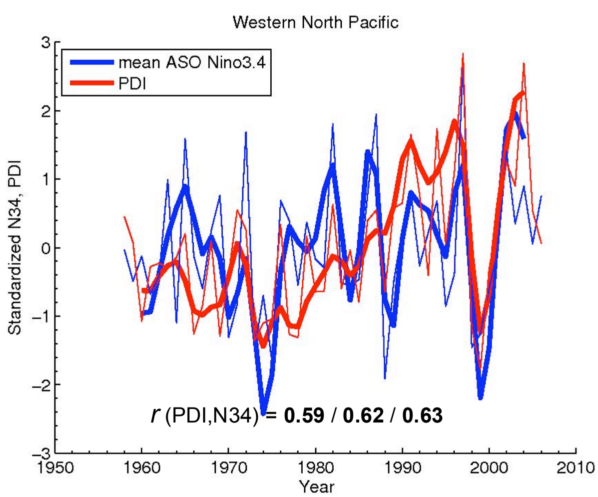

Figure 5: Similar to Fig. 4, but for Pacific PDI and ASO-mean Niño 3.4 index.

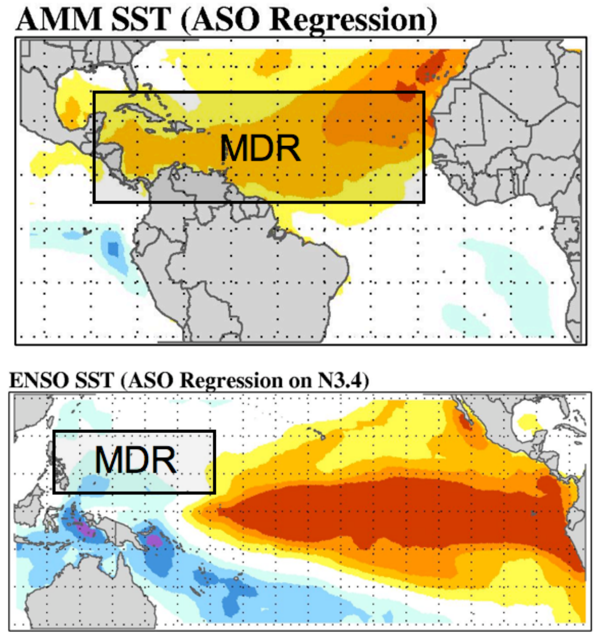

Figure 6: Regressions of ASO-mean SST onto the ASO-mean AMM index (top) and ASO-mean Niño 3.4 index (bottom).

To summarize a few of the previous points, considering SST alone may not be the best way to understand observed hurricane variability, even on decadal time-scales. *By considering the dominant coupled modes of ocean-atmosphere variability intrinsic to each basin, the physical mechanisms that govern hurricane variability might be unified, instead of being segregated according to different time-scales of variability.*

This reasoning may be extended to understanding trends. For example, the trends in hurricane activity that are found in the present best track data suggest that PDI has been increasing in both the Atlantic and Western North Pacific during the last 50–60 years. The variability and trend in Atlantic PDI correlates well with the AMM, and since the region of associated SST variability lies in the main development region, similar relationships are found between PDI and SST. In the Atlantic, PDI trends appear to be robust to reanalysis (e.g. Kossin et al. 2007) and we also find that the AMM has been following a very similar trend (Figs. 2–3). In the Western North Pacific, however, these relationships are less obvious. For example, it is not clear from Fig. 5 that ENSO indices contain any decadal trends (cf. Wolter and Timlin 1998), and the trends in Western North Pacific PDI do not stand up as well to a reanalysis of the past 25 years (e.g. Kossin et al. 2007).

4. DISCUSSION

One problem that we face then with trying to reconcile trends in Pacific hurricane activity is that we must base our conclusions, in part, on a correlation with essentially one degree of freedom (correlation of trends of SST and PDI) and an attendant physical mechanism that is best realized on longer time-scales (potential intensity theory). For some, this may constitute fairly solid ground on which to form a conclusion that hurricane activity is increasing in concert with warming SST, and for others it may not. These differences are sometimes discussed along with questions regarding what the appropriate null hypothesis should be. To argue that the null hypothesis is that hurricane activity is expected to increase with increasing SST (due to increases in intensity) requires the assumption that SST is the primary modulator on the longest time-scales, and that any offsetting atmospheric changes that come with global warming will play a second-order role. As stated earlier, there is evidence for this. But if the regional coupled ocean-atmosphere modes of variability are the primary modulators of hurricane activity on the longer time-scales, as suggested here, then SST is not the only relevant indicator of multidecadal variability, and the question of how hurricanes will vary in the projected warming climate becomes significantly harder to answer.

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