ENSO Influence on Atlantic hurricanes via tropospheric warming

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[1] A new pathway for the negative impact of ENSO on tropical North Atlantic (NAtl) storm activity is examined empirically. Anomalous tropospheric temperatures communicated from the Pacific by wave dynamics are hypothesized to impact storm development by affecting column stability relative to equilibrium with NAtl sea surface temperature (SST). This combines recent teleconnection theory with the role of tropospheric temperature-SST differences in hurricane intensity theory. An equilibrium principle component (EQ PC) in which NAtl SST and tropospheric temperature covary, explains most of their variance. A disequilibrium PC (DEQ PC), measuring column stability relative to SST, correlates highly with hurricane season indices for storm frequency and intensity. The hurricane season (Jun.–Nov.) DEQ PC is closely related to ENSO SST just prior to and within the season, consistent with NAtl SST not having had time to adjust to the teleconnected tropospheric warming from onsetting ENSO events. The EQPC is related to prior winter ENSO SST. *INDEX TERMS:* 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3314 Meteorology and Atmospheric Dynamics: Convective processes; 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology. **Citation:** Tang, B. H., and J. D. Neelin (2004), ENSO Influence on Atlantic hurricanes via tropospheric warming, *Geophys. Res. Lett.*, *31*, L24204, doi:10.1029/2004GL021072.

1. Introduction

[2] Tropical cyclone activity in the North Atlantic has long been known to be negatively correlated with indices of El Niño/Southern Oscillation (ENSO) sea surface temperatures (SST) [*Gray*, 1984]. One hypothesized mechanism is suppression by wind shear [*Gray*, 1984; *Shapiro*, 1987; *Goldenberg and Shapiro*, 1996]. Recent teleconnection theory suggests that warm free tropospheric temperatures that are spread eastward from the Pacific by equatorial wave dynamics can be unfavorable to convection and can influence Atlantic SST [*Chiang and Sobel*, 2002; *Giannini et al.*, 2001; *Neelin et al.*, 2003]. Measures of the difference between tropospheric temperature and SST, such as potential intensity, hold a central role in hurricane intensity theory [*Emanuel*, 1986; *Rotunno and Emanuel*, 1987; *Bister and Emanuel*, 1998]. There is numerical [*Shen et al.*, 2000; *Knutson and Tuleya*, 2004] evidence that tropospheric temperatures that are warm relative to SST tend to disfavor tropical cyclone intensification and observation-based indications that measures of column stability affect hurricane statistics [*DeMaria et al.*, 2001; *Emanuel et al.*, 2004]. If prolonged tropospheric temperature anomalies associated with ENSO occur over the Atlantic development region during the hurricane season without being compensated by underlying SST anomalies, it is reasonable to hypothesize that hurricane season tropical cyclone frequency and intensity may be impacted by the effect on column stability.

[3] In evaluating this hypothesis, the interplay between Atlantic SST and tropospheric temperature must be taken into account. North Atlantic SST itself has a lag relationship to ENSO [*Enfield and Mayer*, 1997; *Klein et al.*, 1999; *Saravanan and Chang*, 2000; *Lau and Nath*, 2001; *Mo and Häkkinen*, 2001] as well as variance driven by atmospheric internal variability [*Dommenget and Latif*, 2000]. Moist convection is hypothesized to play a role in communicating teleconnected temperature anomalies to the boundary layer, inducing surface fluxes that tend to bring the SST toward equilibrium with the troposphere [*Chiang and Sobel*, 2002] while temporarily reducing convection. SST can also slow the tropospheric warming locally (H. Su and J. D. Neelin, personal communication) relative to the widespread pattern associated with the mature ENSO [*Wallace et al.*, 1998].

[4] The disequilibrium of tropospheric temperature and SST may thus be anticipated to affect storm statistics. For instance, suppose during the hurricane season, the tropical North Atlantic is in a state where El Niño teleconnections are inducing anomalously warm upper tropospheric temperatures, but tropical North Atlantic SSTs have not had a chance to equilibrate. Then the tropospheric column stability relative to SST is conjectured to disfavor storm development.

2. Data Sets and Index Choices

[5] The annual hurricane season is defined to be June–November. Yearly hurricane season SST anomalies are derived from the HADISST (1979–1981) [*Rayner et al.*, 2003] and the OISSTv2 (1982–2003) [*Reynolds et al.*, 2002] data sets, and yearly hurricane season column averaged tropospheric temperature anomalies are derived from the NCEP reanalysis [*Kalnay et al.*, 1996]. Due to a spurious jump in the NCEP tropospheric temperature in 1979 [*Bister and Emanuel*, 2002] at the introduction of satellite data, the most current 25 years (1979–2003) is chosen for this study. An ENSO index is defined using the Niño3.4 (5S–5N, 120W–170W) June–November average anomalies. Two indexes, NAtl-SST and NAtl-T, are defined

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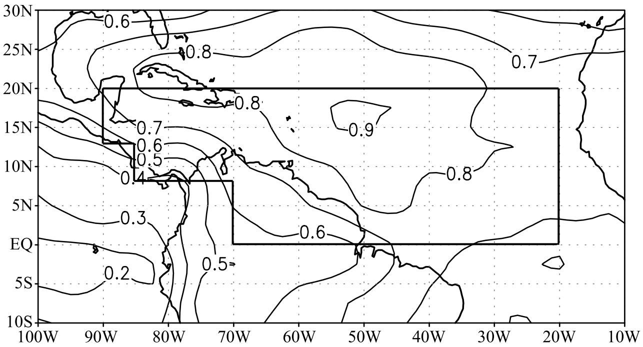

Figure 1. Correlation of hurricane season column averaged tropospheric temperature to NAtl-SST (contour interval 0.1). Dark outline shows the region used to define the NAtl-T column averaged tropospheric temperature index and the NAtl-SST index (omitting land portions). The EQ PC and DEQ PC discussed in the text are derived from these.

in the Atlantic for 0–20N, 20–90W with the Pacific area masked out (Figure 1). NAtl-SST consists of the yearly hurricane season area averaged SST anomalies, and NAtl-T consists of the yearly hurricane season area averaged tropospheric temperature anomalies. The area is chosen to capture the large-scale environment in which tropical cyclones develop while minimizing noise from the midlatitudes. Figure 1 confirms June–November column averaged tropospheric temperature anomalies are strongly related to NAtl-SST with correlation values well above 0.7 in most of the boxed region.

[6] Using the Best Track Reanalysis Data, the departure from the 1979–2003 average number of named storms in each hurricane season is used to compute a storm frequency index. Similarly, the departure from the 1979–2003 average maximum wind speed of all named storms in each hurricane season is used to compute a storm intensity index. This measure of storm intensity is chosen because it does not correlate highly with the measure of storm frequency [*Landsea et al.*, 1999].

3. NAtl-T/NAtl-SST Equilibrium and Disequilibrium PCs

[7] NAtl-SST explains 31% of the variance of storm frequency, which is consistent with prior studies that conclude SSTs are an important factor in storm formation [*Saunders and Harris*, 1997; *Shapiro and Goldenberg*, 1998; *Landsea et al.*, 1999]. NAtl-T explains only 1% of the variance of storm frequency. However, a multiple regression model with both NAtl-SST and NAtl-T as independent variables explains 60% of interannual storm frequency. Similar results are obtained using storm intensity. Along with NAtl-SST, ENSO also has significant correlations to the storm indices (Table 1). Since the troposhere over the North Atlantic serves as a pathway for ENSO teleconnections and is also strongly influenced by North Atlantic sea surface temperatures, there is strong reason to suspect the large increase in storm frequency variability explained in the multiple regression model over the simple regression models is due to the fact that NAtl-T contains information important to the physical pathways, namely from ENSO, that influence tropical cyclone intensity and frequency.

[8] To get past the high degree of collinearity between NAtl-SST and NAtl-T (R = 0.8), their principle components are computed. The first principal component captures 90% of the variance among NAtl-SST and NAtl-T, and is strongly correlated to both NAtl-SST (R = 0.95) and NAtl-T (R = 0.94). The first principal component, which will be referred to as the NAtl-SST/NAtl-T equilibrium PC (EQ PC), describes the typical positive relationship between SST and tropospheric temperature anomalies, taken as a measure of equilibrium between SST and the tropospheric column. A few months after the peak of an El Niño/La Niña event, tropospheric temperature and SST anomalies tend toward an equilibrium relationship due to a combination of convective adjustment and surface heat fluxes [*Sobel et al.*, 2002; *Chiang and Sobel*, 2002]. The EQ PC has a negligible simultaneous correlation with ENSO (R = −0.03). The second principal component captures 10% of the variance among NAtl-SST and NAtl-T and is negatively correlated with NAtl-SST (R = −0.30) and positively correlated with NAtl-T (R = 0.33). The second principal component, which will be referred to as the NAtl-SST/NAtl-T disequilibrium PC (DEQ PC), represents departures of SST and tropospheric temperature anomalies from their typical relationship, such as a disequilibrium state during an onsetting El Niño when the upper tropospheric warming has not been communicated down to SST. The DEQ PC has a rather large simultaneous correlation with ENSO (R = 0.54).

[9] A physical interpretation for the impact of the DEQ PC on tropical cyclones can be deduced by regressing it on layered tropospheric temperature anomalies. The regression coefficients increase in magnitude with increasing height and roughly resemble a deep structure consistent with moist adiabatic processes. Thus, the DEQ PC can be regarded as an empirical measure of atmospheric convective instability relative to SST.

[10] The DEQ PC has much higher correlations with storm frequency and intensity compared to the EQ PC (Table 1). Additionally, the DEQ PC explains much more of the variance of both storm indices compared to either NAtl-SST or NAtl-T in a simple linear regression model.

4. Relationship to ENSO

[11] Figure 2a shows the DEQ PC, storm frequency, and storm intensity regressed on lead/lag Niño3.4 three-month averaged anomalies with 0-lag corresponding to the middle of the contemporaneous hurricane season. The regression coefficients for the DEQ PC are 99% significant using a two-tailed t-test from April of the contemporaneous year through March of the following year. The correlation between the DEQ PC and Niño3.4 lead/lag is above

Table 1. Correlations of Hurricane Season Storm Frequency and Intensity Indices to the NAtl-SST/NAtl-T Equilibrium and Disequilibrium Principle Components (EQ PC and DEQ PC), to Hurricane Season ENSO SST (Nino3.4 index), and to Northern Tropical Atlantic SST and Tropospheric Temperature Indices NAtl-SST and NAtl-T Described in Figure 1

	EQ PC	DEQ PC	ENSO	NAtl-SST	NAtl-T
Frequency	0.36	**−0.68**	−0.50	0.50	0.12
Intensity	0.04	**−0.49**	−0.61	0.20	−0.13

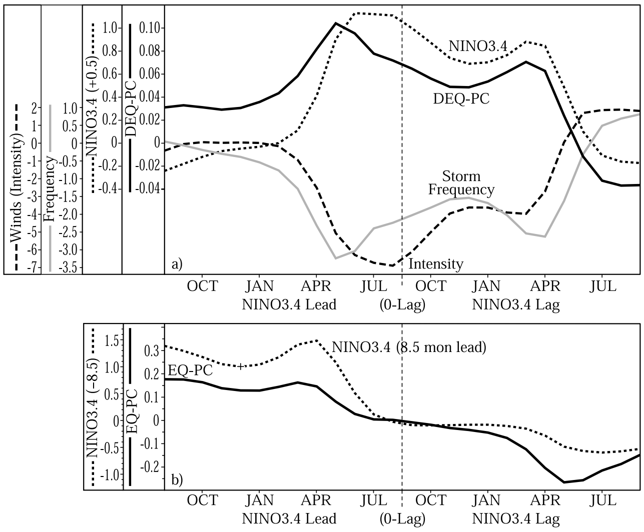

Figure 2. (a) Regression coefficients for hurricane season DEQ PC [K/K], Storm Frequency [storms/K], Intensity [knots/K], and Aug.–Oct. Niño3.4 (0.5 month lag) [K/K] on 3-month averaged Niño3.4 anomalies at various leads/lags. Zero lag corresponds to the middle of the Jun.–Nov. hurricane season. (b) As in (a) but for EQ PC [K/K] and Nov.–Jan. Niño3.4 at 8.5 month lead [K/K] regressed on lead/lag 3-month averaged Niño3.4 anomalies. See color version of this figure in the HTML.

0.5 through this period. For comparison, the Niño3.4 autoregression shows a very similar pattern to the DEQ PC regression with both having substantial regression coefficients from one month prior to the start of the hurricane season through the following winter. This indicates that the DEQ PC is most influenced by onsetting El Niño/La Niña events. A year by year comparison of the sign of the DEQ PC and the trend of monthly Niño3.4 anomalies during the hurricane season (not shown) generally supports this interpretation. Also note the regression coefficients for the DEQ PC are much lower for the previous winter months. If an El Niño/La Niña occurs during the previous winter, the hurricane season DEQ PC is not substantially influenced because the troposphere and sea surface have already equilibrated by the time the hurricane season starts.

[12] Storm frequency and intensity regressed on lead/lag Niño3.4 both show a striking similarity to the regression coefficients of the DEQ PC except inverted. For storm frequency, the window of high correlations ($R > 0.48$) and significant regressions at the 98% level begins May of the contemporaneous year and continues to April of the following year. Storm intensity has a similar window, though slightly narrower with stronger correlations and regressions around the peak of the hurricane season. This strongly supports a pathway between ENSO and storm intensity and especially storm frequency via those processes which govern the DEQ PC.

[13] Figure 2b is similar to Figure 2a except for the EQ PC regressed on lead/lag Niño3.4 with the Niño3.4 autoregression to its previous Nov–Jan Niño3.4 anomalies displayed for comparison. The EQ PC regressions and NDJ Niño3.4 regressions show a similar pattern to one another, particularly for large Niño3.4 lead encompassing the previous fall and winter months. Correlations with lead Niño3.4 during this time frame are above 0.4 for the EQ PC and above 0.9 for NDJ Niño3.4. This pattern indicates the EQ PC of the contemporaneous hurricane season is strongly influenced by El Niño/La Niña from the preceding fall and winter. From June to February of the following year, the regression coefficients for the EQ PC are near zero which suggests the EQ PC is not influenced by ENSO during the hurricane season.

[14] To further support the DEQ PC's connections with ENSO, yearly hurricane season column averaged tropospheric temperature anomalies (Figure 3a) and yearly hurricane season SST anomalies (Figure 3b) are regressed on the DEQ PC. In Figure 3a, a long belt of significant regression coefficients at the 95% level covers most of the tropics with the greatest values in the East Pacific between 20S–20N. The same pattern appears if yearly hurricane season column averaged tropospheric temperature anomalies are regressed on 2–3 month lead Niño3.4 anomalies (not shown). This is consistent with the tropospheric response to an onsetting El Niño/La Niña [*Wallace et al.*, 1998]. Significance values and regression coefficients are notably lower in the tropical North Atlantic. In Figure 3b, the ENSO pattern in the Pacific is clearly evident and is consistent with the correlation of the DEQ PC to ENSO. There is also a small area of significant negative regression values in the Atlantic between 0–10N as might be expected for the DEQ PC due to the negative correlation between the DEQ PC and NAtl-SST.

5. Discussion

[15] ENSO and NAtl-SST are known important factors in Atlantic hurricane frequency and intensity variability. The physical pathways responsible for this relation may occur via tropospheric temperature teleconnections, even though NAtl-T itself does not have a strong correlation to storm frequency and intensity. NAtl-SST and NAtl-T have a strong positive correlation, and the EQ PC associated with this relationship is interpreted as an estimate of the SST and

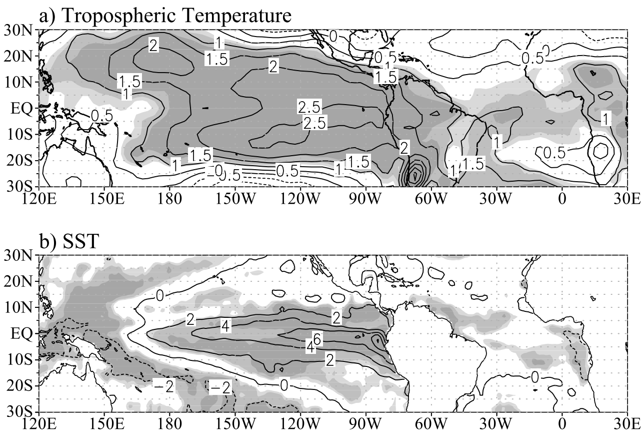

Figure 3. (a) Hurricane season column averaged tropospheric temperature anomalies regressed on the DEQ PC (contours, K/K) with 90, 95, and 99% significance levels (shaded) using two-tailed t-test. (b) As in (a) but for hurricane season SST anomalies regressed on the DEQ PC. See color version of this figure in the HTML.

troposphere varying in equilibrium. The DEQ PC associated with departures from this can be interpreted in terms of changes in column convective instability relative to SST, akin to an empirical measure of potential intensity. Separating this smaller disequilibrium signal from the large (90%) variance due to the EQ PC yields results supportive of the hypothesized role of column stability. The DEQ PC has substantially higher correlation to storm indices than do NAtl-SST, NAtl-T, or the EQ PC, implying that it extracts information important to the storm indices. The DEQ PC is also related (R = 0.54) to hurricane season ENSO Niño3.4 SST. The spatial pattern of tropospheric temperature and SST associated with the DEQ PC (Figure 3) appears consistent with tropospheric warming (cooling) beginning to occur over the tropical Atlantic during an onsetting El Niño (La Niña). The resulting disequilibrium state in which NAtl-T is warmer (cooler) relative to its normal relationship to NAtl-SST would lead to anomalously small (large) mean potential intensity [*Emanuel*, 1986; *Bister and Emanuel*, 1998] over the Tropical Atlantic. The large-scale environment would be less (more) conducive to tropical cyclogenesis [*DeMaria et al.*, 2001] via the same pathways that affect convection and precipitation [*Giannini et al.*, 2001; *Chiang and Sobel*, 2002; *Neelin et al.*, 2003].

[16] The mechanism suggested here is not exclusive of a role for El Niño induced wind shear [*Gray*, 1984; *Shapiro*, 1987; *Goldenberg and Shapiro*, 1996], as there can be contributions from different environmental factors [*Emanuel et al.*, 2004]. Wind shear is approximately related to gradients of the temperature field. However, any impact of wind shear in the large scale indices used here would have to enter via NAtl-T which alone has low correlations to storm indices. This suggests that the evidence for a strong stability-related DEQ PC impact is independent of possible shear effects.

[17] The lag relationships of the EQ and DEQ PCs to ENSO SST fit well with an interpretation of adjustment toward equilibrium between SST and teleconnected tropospheric temperature. The hurricane season DEQ PC has large correlation and regression values to Niño3.4 anomalies from April through the hurricane season, consistent with the tropical Atlantic not having had time to adjust to the remote forcing. The lag regression values remain large through the following winter, suggesting that these impacts are typically associated with an onsetting El Niño/La Niña event.

[18] The hurricane season EQ PC has little contemporaneous relation to Niño3.4 but has a clear relation to the prior winter ENSO SST, consistent with equilibrium being established with past ENSO forcing on a time scale of several months. The low correlations between the hurricane season EQ PC and the storm indices suggest that once NAtl-T and NAtl-SST equilibrate there is less impact on storm frequency and intensity.

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