Interdecadal changes in eastern Pacific ITCZ variability and its influence on the Atlantic ITCZ

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Abstract. The eastern Pacific and Atlantic Intertropical Convergence Zones (ITCZ) exhibit the largest year-to-year variations in boreal spring. We show evidence suggesting that Atlantic ITCZ April-May variability is linked to that for the eastern Pacific through the Walker circulation as it respond to changes in equatorial Pacific convection. Analysis of ITCZ proxy indices shows the link appears to be strong in the 1980-90's and 1920-30's but virtually nonexistent in the 1950-60's. We argue that this apparent nonstationarity results from the nonlinear relationship between sea surface temperature (SST) and convection in the eastern equatorial Pacific and its consequent effect on the Walker circulation and the Atlantic ITCZ. This mechanism was modulated over 1856-1998 by interdecadal changes in peak SST attained in the eastern equatorial Pacific during boreal spring.

The Tropical Atlantic (TA) Intertropical convergence zone (ITCZ) strongly influences rainfall of neighboring land regions, particularly northeast Brazil where interannual variability of rainfall results in severe socioeconomic consequences [*Hastenrath and Heller*, 1977]. The TA ITCZ shares similar characteristics with the eastern Pacific (EP) ITCZ: they reside in the northern hemisphere most months of the year, and their latitudinal migration follows an annual cycle despite a significant semiannual component in near-equatorial solar insolation [*Mitchell and Wallace*, 1992]. This is due to strong coupling between the ITCZs and their respective oceanic cold tongues. The largest interannual variability in both ITCZs occurs in boreal spring when the ITCZs are at their southernmost extent. The EP ITCZ variability is thought to be controlled by the El Niño-Southern Oscillation (ENSO) [*Rasmusson and Carpenter*, 1982], with the largest southwards ITCZ extension occurring in the spring immediately following the mature phase of major El Niño events.

Controls of the TA ITCZ are more complex and still debatable. In particular, how the Pacific influences the TA ITCZ is not well understood. Previous studies have demonstrated the importance of the TA cross-equatorial sea surface temperature (SST) gradient and its variability [*Hastenrath and Greischar*, 1993; *Nobre and Shukla*, 1996]. ENSO impacts strongly on the northern TA SST during its mature phase in boreal winter, and in the spring immediately following [*Enfield and Mayer*, 1997; *Giannini et al.*, 2000]. This remote teleconnection, possibly mediated though a northern midlatitude "atmospheric bridge" [*Nobre and Shukla*, 1996], is thought to be the pathway for Pacific influence on the Atlantic ITCZ. However, recent atmospheric General Circulation Model (AGCM) results [*Saravanan and Chang*, 2000] suggest an alternative mechanism of Pacific influence on the Atlantic ITCZ through an anomalous Walker circulation. This paper demonstrates from observational analysis the plausibility of this mechanism for ENSO influence on the Atlantic ITCZ, as an alternative to the one proposed by Nobre and Shukla. We show that this mechanism can readily explain an apparent interdecadal modulation of the ENSO influence on the Atlantic ITCZ, analogous to the recent hypothesized explanation for the changing relationship between ENSO and the Indian monsoon [*Kumar et al.*, 1999].

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Inter-basin ITCZ connection

There is an apparent connection between the Pacific and Atlantic ITCZs: whenever the EP ITCZ positions itself near or south of the equator during April-May, the TA ITCZ tends to stay north of the equator. We show this by regressing observed global April-May rainfall anomalies [*Xie and Arkin*, 1997] onto an index of April-May rainfall anomalies over the equator in the EP (figure 1a) - hereafter the 'EEP index' (see appendix for details). The regression shows a reduction of rainfall south of the equator and intensification to the north in the TA, together with increased rainfall over the EP. This pattern is statistically significant at the 1% level. A similar pattern is obtained with the dominant mode of a principal component (PC) analysis of observed April-May rainfall anomalies over the global tropics (20^oS to 20^oN), explaining 30% of the variance.

SST anomaly (SSTA) and near-surface wind conditions (from the NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) reanalysis dataset [*Kalnay et al.*, 1996]) associated with the EEP index reveal the air-sea coupled nature of this pattern (figure 1b). Strong warming occurs over a narrow strip (5^oS-5^oN) from the date line to the west coast of South America, co-incident with the anomalous rainfall there. In contrast, the SSTA response in the TA is much smaller in magnitude. The associated surface winds show sizable anomalous westerlies in the central equatorial Pacific, a consistent response to anomalous convective heating over the equatorial EP, but also a possible cause of warm SSTAs through its effect on upwelling and surface fluxes. The TA cross-equatorial flow

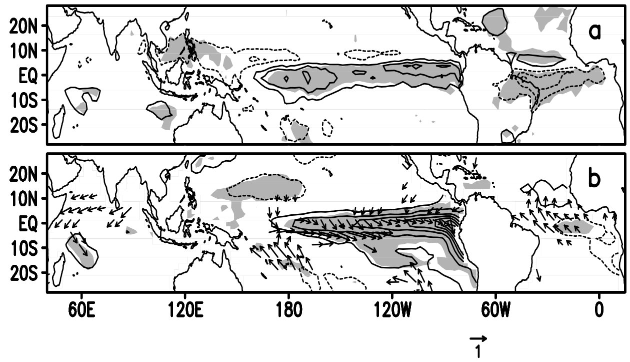

Figure 1. Regression onto the EEP index of a) April-May rainfall anomalies (contour interval (CI) 1mm/day), and b) SSTA (CI 0.25K) and 10m winds (reference vector 1m/s). Negative contours are dashed; the zero contour is not shown. Shaded regions indicate where correlation magnitude with a) rainfall, and b) SSTA, exceed 0.6. Wind vectors in b) are plotted only if correlation magnitude with either u or v exceeds 0.6. Rainfall data is *Xie and Arkin (1997)*; SST and wind data is NCEP/NCAR reanalysis [*Kalnay et al. 1996*].

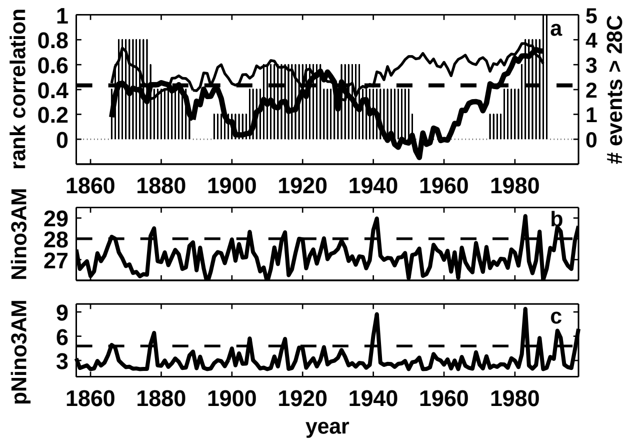

Figure 3. a) 21-year sliding window correlation between Nino3AM and CPI AM (thick solid line), and between Jan-Feb TA cross-equatorial SSTA gradient and CPI AM (thin solid line). The sign of the first correlation is reversed. The dashed line is the 5% (2 sided) significance level based on the Student's t distribution (N-2 degrees of freedom) for the null hypothesis of no association. Bars are the number of Nino3AM events above 28^{o}C in a 21 year sliding window (y axis values to the right). b) Nino3AM (^{o}C) timeseries. c) pNino3AM (mm/day) timeseries. Dashed line in b) shows the 28^{o}C level, and c) the equivalent for pNino3AM.

is consistent with previous studies associating it to TA ITCZ variability [*Hastenrath and Greischar*, 1993]).

Two features of the regressions above suggest that the TA ITCZ is responding to changes in the EP: i) The prominent EP rainfall center over the equator, concurrently with a strong TA ITCZ shift; and ii) the presence of significant and sizable SSTA over the EP, contrasting the relative absence of SSTA over the TA. Gill [*Gill*, 1980] showed that eastward propagating Kelvin waves (and consequent change in the Walker circulation) are produced by convective forcing symmetric about the equator. This is the situation implied in the EP, consistent with requirements of equatorial large-scale dynamics associated with west-to-east communication. To support this interpretation, we regress the EEP index on anomalous 200mb winds (figure 2, vectors). The wind field closely resembles the Gill-type response to heating centered at the eastern equatorial Pacific, with anomalous westerlies over the equatorial Atlantic and off-equatorial anticyclones polewards and westwards of the heating. The regression on velocity potential (figure 2, contours) shows a center of divergence in the far eastern equatorial Pacific accompanied by anomalous convergence centered over the South China Sea, and to a lesser extent over the TA.

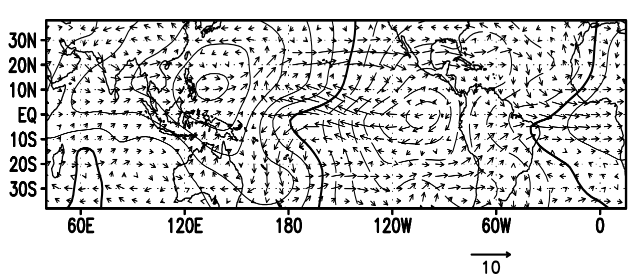

Figure 2. EEP index regressed onto NCEP/NCAR 200mb winds (vectors) and velocity potential (CI 0.5x10$^6 m^2 s^{-1}$). Negative contours are dashed; thick contour is zero. The reference vector is 10m/s.

Our observational results support a similar conclusion of a recent AGCM study [*Saravanan and Chang*, 2000] of ENSO's influence on the TA. In particular, their regression of Nino3 March-May (nino3MAM) index on 'TOGA-TAGA' rainfall (their figure 7a), representing the direct influence of ENSO on the TA, shows a pattern similar to our figure 1a in the EP and TA, except that the positive anomaly in the northern TA is not present in their figure. This suggests the additional influence of local SST in our results (P. Chang, personal communication). Similarly, our regression of 200mb winds on the EEP index resembles their 'TOGA-TAGA' 200mb winds regressed on Nino3MAM (their figure 9a).

Our results may seem in conflict with previous results [*Enfield and Mayer*, 1997; *Giannini et al.*, 2000] showing the warming of the northern TA SST with El Niño. Our results (figure 1b) do show northern TA warming, although weak (around 0.25^{o}C), and significant only at the 5% level. We think the relationship in our analysis is weaker because it extracts covariance with eastern equatorial Pacific rainfall anomalies rather than SSTA, and hence extracting that part of Atlantic ITCZ variability directly associated with the Walker circulation.

It is not obvious that the TA ITCZ response to the anomalous Walker circulation should be a modification of its observed southward extent. Tropospheric stabilization in the TA through anomalous subsidence by the forced Kelvin wave should be symmetric about the equator, suggesting the same for the rainfall response. However, since the TA ITCZ-cold tongue complex is highly nonlinear, and has a meridionally asymmetric basic state, the ITCZ response to the subsidence is unlikely to be symmetric. The paradigm we suggest is that the TA ITCZ has a preferred mode of variability - the meridional displacement in convection - and that increased subsidence over the TA forces this mode to favor a northwards ITCZ displacement in April-May. Local

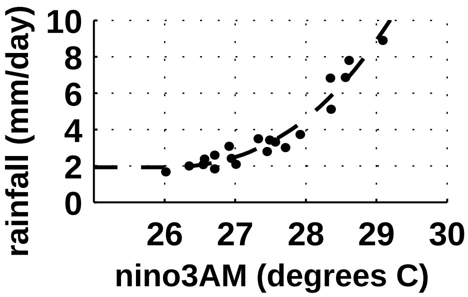

Figure 4. Scatterplot of observed (1979-98) April-May rainfall averaged over the Nino3 region, versus Nino3AM. The dashed line from 26^{o}C onward is the cubic polynomial fit. Below 26^{o}C, we extrapolate the relationship by simply assuming the fitted value at 26^{o}C.

feedbacks are likely to play an important role in setting up this response [*Saravanan and Chang*, 2000].

Interdecadal variability

In the years covered by the Xie-Arkin rainfall analysis (1979-98), there is significant correlation ($r = 0.835$) between the EEP and the Nino3 index (see appendix for details of the index) averaged over April-May (Nino3AM), and likewise ($r = -0.815$) with a northeast Brazil rainfall index (see appendix for details) averaged over the rainy season April-May (hereafter CPI AM). We take advantage of Nino3AM and CPI AM as century-long proxies for the EP ITCZ displacement and TA ITCZ displacement, respectively. A 21 year sliding window rank correlation between the two April-May indices (figure 3a, thick solid line) shows that the EP-TA association appear to have changed quite dramatically over the last 143 years. The correlation is strong over the last 20 years, and also to a lesser extent in the mid 1920's and from the 1870's to the 1890's. There is little association in a period around the 1950's and around the 1900's. By comparison, local SST influence on northeast Brazil rainfall - assessed by computing the same sliding window correlation between CPI AM and the January-February average of a cross-equatorial gradient index of TA SSTA (figure 3a - thin solid line) - remained relatively constant. We chose a January-February index to show unambiguously that the SST gradient causes the April-May rainfall anomaly, and is not itself a consequence of the ITCZ displacement.

We interpret the sliding window correlations as measures of the relative influence of local SST versus direct EP influence on TA ITCZ variability. In general, local SST has stronger influence, but instantaneous EP SST has comparable influence over the three time intervals in the instrumental record. This interpretation requires that Nino3AM and the cross-equatorial SSTA gradient are not themselves significantly correlated. A similar sliding window correlation between those two indices shows that correlation is low ($|r| < 0.25$), except during the 1880's, and, to a lesser extent, the last 20 years.

The April-May SST in the eastern equatorial Pacific (figure 3b) shows a striking interdecadal variation in its peak seasonal value: the warmest SSTs occur in the 1980-90's, a less pronounced period over the 1870's and 1920's, and a conspicuous quiet period during 1950-80. This is summarized in a 21 year sliding window of the number of Nino3AM cases larger than 28^{o}C (figure 3a - bars). This function suggestively follows the sliding window correlation of Nino3AM with CPI AM.

The functional link between the April-May SST in the Pacific, and the Atlantic ITCZ, appears to be nonlinear. What is the physical basis for this nonlinearity? The strength of the anomalous Walker circulation is best measured not by Nino3, but by the magnitude of rainfall anomalies in the eastern equatorial Pacific, which directly relates to atmospheric diabatic heating. The SST-rainfall relationship in the Nino3 region is very strong (figure 4); and functionally highly nonlinear. We convert Nino3AM to rainfall by least-square cubic polynomial fit over the data points in figure 4. This new index (figure 3c), labeled pNino3AM, shows the contrast between the 'quiet' and 'active' intervals.

A simple scatterplot of CPI AM vs. pNino3AM (figure 5) shows the impact of EP rainfall on the TA ITCZ. As pNino3AM increases, both CPI AM mean and range tend to decrease. They stop decreasing above a pNino3AM of 5mm/day (corresponding to Nino3AM just above 28^{o}C), beyond which CPI AM values are uniformly low. We interpret this to mean when the EP SSTs are cold and little convection occurs over the eastern equatorial Pacific, the TA ITCZ is influenced by other factors, primarily the Atlantic cross-equatorial SST gradient. As convection increases over the eastern equatorial Pacific, anomalous subsidence over the tropical Atlantic reduces the range that northeast Brazil rainfall can take, reducing the upper bound (wettest years are less wet) but maintaining the lower bound. The lower bound does not change simply because rainfall cannot fall below zero. When EP rainfall exceeds 5mm/day, the anomalous Walker circulation dominates the TA ITCZ behavior, and Northeast Brazil rainfall is restricted to values at, or just above, the minimum.

Closing remarks

The presence of secular changes in the influence of the equatorial Pacific on global climate anomalies has been

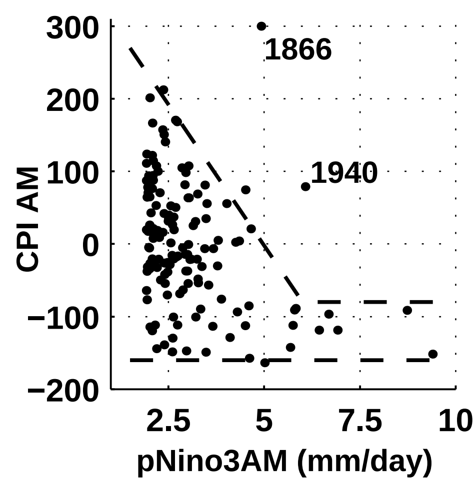

Figure 5. Scatterplot of CPI AM versus pNino3AM (1856-1998). Dashed lines represent the approximate range of CPI AM for a given value of pNino3AM. Dates of two outliers are also shown. Nino3 values prior to 1900 may be suspect because of poor data coverage; and 1940 because of World War II.

noted before [*Ramage*, 1983; *Kumar et al.*, 1999]. We reveal and confirm the presence of similar apparent changes in the link between the Pacific and Atlantic ITCZ variability, with major consequences to the semi-arid region of northeast Brazil. The fact that the changes can readily be explained by tropical air-sea interaction concepts and equatorial dynamics lends support to our statistical analysis. We wonder about the existence of other teleconnections of ENSO to global climate that are highly nonlinear with EP SST and are seasonal. Such connections are not easily discerned using the standard practice of linear correlation with tropical Pacific SSTA, and disregarding the season.

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Appendix A: Appendix: definitions of indices

EEP index: We project monthly mean rainfall at each longitude onto a meridionally-varying Gaussian centered on the equator with an e-folding of 1967km. We sum the projection from 180^oW to 80^oW, compute its normalized anomalies, and averaged over April-May to obtain the index. The Gaussian profile was chosen as it is the meridional structure of the equatorial Kelvin wave; the e-folding was obtained by assuming an equivalent depth of 200m.

Nino3 index: SSTA averaged over 150^oW-90^oW, and 5^oS-5^oN. Our version is from the Lamont Reduced Space Optimal Interpolation SSTA [*Kaplan et al.*, 1998] extending from 1856 to 1991, and continues to the present using the NCEP SST product [*Reynolds and Smith*, 1994]. See Kaplan et al. for discussion on the reliability of this index.

CPI index: The rainfall index for the Ceara region of Northeast Brazil is compiled by T. Mitchell. CPI is derived from rain gauge data at Fortaleza and Quixeramobim from 1849-1987, and extended using the Xie-Arkin dataset to 1998. The extension was done by averaging over the nine land gridpoints with correlations above 0.5 with the station CPI for the period of overlap (1979-1987), and applying the appropriate normalizations for consistency.

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