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Relationships of inter-American rainfall to tropical Atlantic and Pacific SST variability

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Abstract. Area-averaged anomalies of sea surface temperature (SSTA) and rainfall, developed from large scale data sets, have been used to explore the relative importance of Pacific versus Atlantic SST variability for inter-American (50°S - 50°N) climate variability at interannual time scales. SSTA in the tropical Pacific and tropical North Atlantic are comparably related to rainfall north of 15°S, with clear associations distributed between the southeastern United States (US) in the north and northern South America in the south. Although NINO3 explains 25% of the variance of the North Atlantic SSTA index, the rainfall correlations with North Atlantic SSTA are for the most part opposite in sign to those with NINO3. Hence, a significant part of the Atlantic SSTA probably has a direct association with rainfall, rather than being merely an indirect proxy for Pacific ENSO linkages. In contrast to the North Atlantic, South Atlantic SSTA appear to be only related to rainfall in northeast (NE) Brazil. The entire region between Venezuela and NE Brazil appears to be sensitive to both the ITCZ and to antisymmetric configurations of SSTA across the ITCZ, in a manner consistent with the relationships between SST, surface wind and surface wind divergence fields, and with previous studies.

Introduction

Although ocean general circulation models and coupled ocean-atmosphere models have demonstrable skill at simulating and predicting sea surface temperatures (SSTs), it appears unlikely that the atmospheric components of coupled models will make effective regional rainfall predictions any time soon (*Barnston, et al.*, 1994). In the short term, one strategy for predicting rainfall months to seasons in advance is to use numerical SST predictions as predictor inputs to empirical relationships between SST and rainfall. To prioritize empirical research on these linkages, it is desirable to have some notion of which regions are significantly affected by SST variability both in the Pacific — dominated by El Niño-Southern Oscillation (ENSO) — and in other oceans. *Ropelewski and Halpert* (1987, 1989) have provided important guidance by identifying globally distributed core regions of ENSO-related precipitation, through rainfall composites stratified against the Southern Oscillation Index (SOI). It is appropriate to additionally investigate the rainfall associations with Pacific SST variability as well as with non-ENSO variability in other oceans.

In the western hemisphere, Atlantic Ocean variability also affects rainfall in ways that can improve on the predictability already evident for the Pacific ENSO. Studies by *Moura and Shukla* (1981) and others (whom they cite) bear this out for NE Brazil, for example, while *Folland et al.* (1986) show similar relationships for northwest Africa. The extent to which Atlantic SST affects rainfall in other regions of the Americas is not well understood, but associations have been identified, such as the tendency for droughts in Central America and the Caribbean in conjunction with warm SSTs in the tropical North Atlantic (*Hastenrath*, 1978, 1984). Moreover, there also exists a possibility that some of the western hemisphere correlations of rainfall with ENSO indices are more directly related to the Atlantic SST, a fraction of which may in turn be related to the Pacific ENSO.

Intercorrelations of SSTA between oceans are relevant to SST-rainfall relationships and their interpretation. Past analyses of anomalous tropical Atlantic SST variability (SSTA) have suggested that a dipole behavior exists in SST between the northern and southern tropics, across the Intertropical Convergence Zone (ITCZ) (e.g., *Weare*, 1977). By analyzing a relatively long reconstruction (1950-1992) of the Comprehensive Ocean-Atmosphere Data Set (COADS; *Woodruff et al.*, 1987), *Enfield and Mayer* (1996) show that the SSTA variabilities over large tropical Atlantic regions north and south of the ITCZ are mostly independent of each other at the interannual time scale dominating the data. This supports the conclusions of *Houghton and Tourre* (1992). *Enfield and Mayer* (1996) find that meridional dipole behavior does exist but is highly seasonal, does not affect basin-wide regions, and does not constitute a large fraction of the interannual Atlantic SST variability. However, rainfall in certain regions (e.g., NE Brazil) may be more strongly affected when dipole configurations occur, as shown by *Moura and Shukla* (1981) and others. Dipole behavior may also be a stronger feature of interdecadal time scales (*Mehta and Delworth*, 1995) and it appears stronger in analyses of shorter time periods that straddle interdecadal shifts in SST (e.g., *Carton and Huang*, 1994).

Linkages also exist between SSTA variabilities in the Pacific and Atlantic (*Covey and Hastenrath*, 1978; *Hastenrath*, 1978, *Hastenrath et al.*, 1987). *Enfield and Mayer* (1996) confirm that some of the interannual variability of North Atlantic SSTA is correlated with the Pacific ENSO as represented by the ENSO-related mode of Pacific SSTA. They detail the evolution of the Atlantic teleconnections over the period concurrent with and following the Pacific events. The North Atlantic warmings are associated with ENSO-related reductions in surface wind speed within the NE trades, which lower the rates of evaporative and sensible heat loss from the oceanic surface layer as well as cooling due to entrainment across the tropical thermocline. This inter-ocean SST connection occurs outside of the equatorial latitudes and should not be confused with the zonal interactions of the ENSO type that occur at interannual periodicities along the equator in both oceans (*Zebiak*, 1993).

In this paper we have extended the global analysis of *Ropelewski and Halpert* (1987) to include the effects of tropical Atlantic SST variability as well as relationships with a Pacific SST index (NINO3). Any attempts to explore regional details or seasonal breakdowns are beyond the scope of this paper, the

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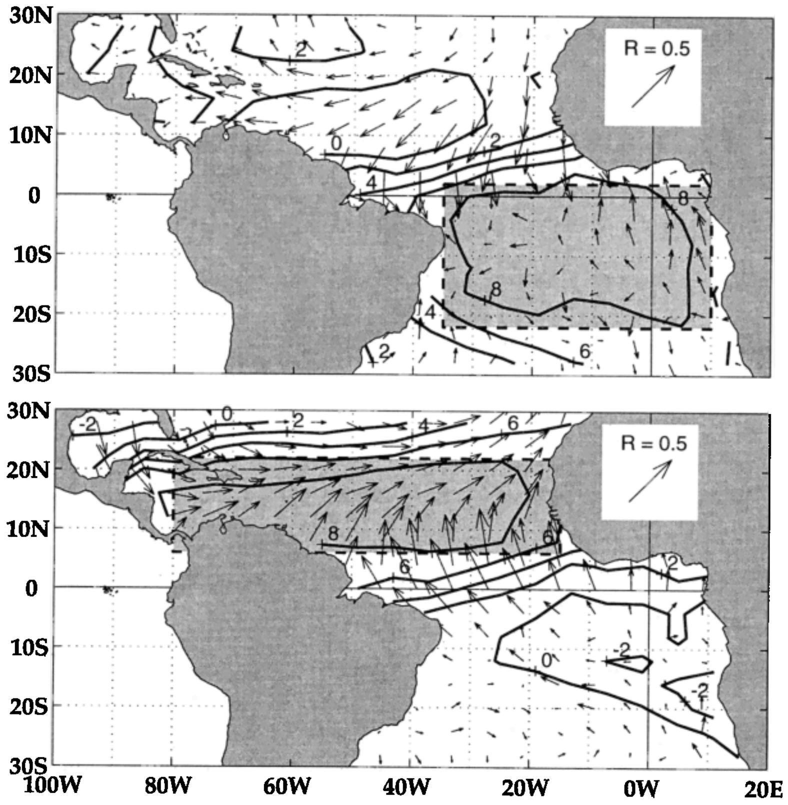

Figure 1. (a) Distribution of correlation (contours, in tenths) between gridded SSTA and a regional index of SSTA (shaded rectangular area) in the tropical South Atlantic Ocean (SATL). Arrows show the direction and proportional magnitude of the vector correlation between the gridded COADS surface wind velocity and the same SATL index (scale is inset). (b) As in (a) but for the tropical North Atlantic Ocean (NATL). A linear trend in the winds has been removed.

main thrust of which is to place the climate impact of Atlantic SST variability (versus the Pacific ENSO) into a hemispheric perspective.

Atlantic SST variability

For both the Pacific and Atlantic we use time series of three-month running mean averages of SSTA computed from the 2x2 degree, 43-year reconstruction of *Smith et al.* (1996), 1950-1992. For the Pacific, the NINO3 SSTA index is recalculated from the 2x2 data for the region ±6°, 90°W-150°W, which correlates at 0.97 with the standard NINO3 index (±5°, 90°W-150°W). To characterize the Atlantic SSTA variability and index its effects on rainfall, we compute simple area averages for the tropical South Atlantic (SATL: 22°S-02°N, 35°W-10°E) and North Atlantic (NATL: 6°N-22°N, 80°W-15°W). These area definitions are based on the distributions of variance explained by the first two empirical orthogonal function (EOF) modes of *Enfield and Mayer* (1996), which together explain 53% of the total SSTA variance for the same period between 30°S and 30°N. Those modes are well separated and explain large fractions (50-80%) of the SSTA variance over large regions of high loadings. Hence, the SATL and NATL indices are an efficient representation of the overall tropical Atlantic SSTA variability and they have correlations higher than 0.95 with their EOF counterparts.

Figure 1 shows the correlation fields for the SATL and NATL indices with the gridded Smith et al. (1996) SSTA and with the COADS surface wind anomalies. They show that the indices represent spatially coherent SSTA variability over large regions south and north of the Atlantic Intertropical Convergence Zone (ITCZ), respectively. Up to 77% (85%) of the local SSTA variance is explained in the SATL (NATL) index area. The anomalous wind crosses the ITCZ in the direction of warming in each of the respective regions, and the NE trades weaken (intensify) in association with warming in the North (South) Atlantic. Crosscorrelations between the NATL and SATL indices are nearly zero at lags of a few months or less. The NATL and SATL also reveal no significant relationship at larger lags, within ±15 months, showing that the modes are truly independent and not, for example, quadrature-related components of a propagating interannual mode (as occurs in the Pacific). (All correlation significance levels are computed by adjusting the degrees of freedom in a way that accounts for serial correlation in the data. See *Davis*, 1976).

There are, of course, times at which the indices are oppositely signed in a dipole fashion (warm-cold or cold-warm); such occurrences may or may not be the result of an ocean-atmosphere process linking the north and south regions. Such antisymmetric configurations across the ITCZ can be indexed by the NATL minus SATL difference series.

Consistent with *Enfield and Mayer* (1996), when the Atlantic SSTA area indices are compared with the Pacific NINO3 index, there is a highly significant, lagged correlation (+0.5) with NATL, with the Pacific warmings preceding those of the North Atlantic by 4-5 months. The correlation for the SATL index is only +0.3 at a lag of 4 months and is just significant at the 95% level. Hence, the Pacific ENSO variability explains 25% of the NATL variance, but only 9% of the SATL variance.

Correlation fields for rainfall

As a measure of the space-time variability of rainfall in the western hemisphere, we use the US Department of Energy (DOE) three-month, 5° by 5° area averages of rain gauge data, 1953-1990, as objectively analyzed by *Eischeid et al.* (1995).

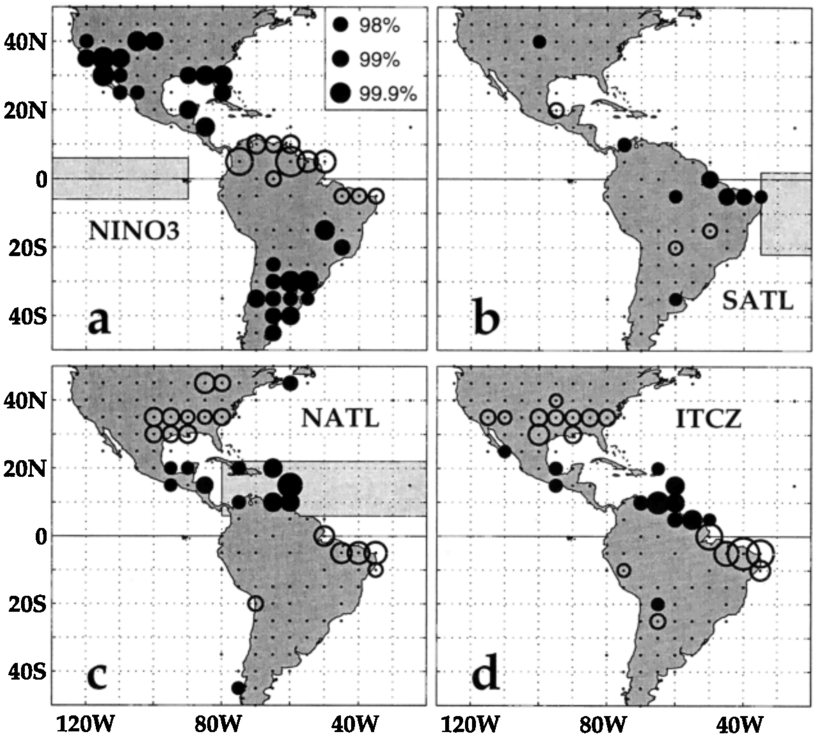

Figure 2. Relative magnitudes (circle diameters) and sign (solid positive, unfilled negative) of lagged correlations between DOE rainfall departures and various indices of SSTA and ITCZ variability. The inset legend shows the circle diameters corresponding to several significance levels.

The area-averaged data are appropriate for this analysis because they effectively capture the relationships at the largest, hemispheric scale. They are not, however, well-suited for more detailed regional analyses because in some regions the averages cut across rainfall provinces distinguished by orography or other process-related effects.

Figure 2 shows the distributions of maximum lagged correlation of the DOE rainfall anomalies (all seasons) with the various indices. Correlations are shown only if they exceed the 95% significance level and rainfall lags an index by zero to three seasons. The smallest and largest correlation magnitudes shown are in the range of 0.12 to 0.17 and 0.40 to 0.50, respectively. We infer an association with SSTA where organized regional clusters of significant correlation and uniform sign occur, and we ignore geographically isolated cases that could arise by chance. If the significance threshold is increased to 98% (minimum magnitudes of 0.17 to 0.23), the regional clusters become somewhat less populated and geographically isolated correlations disappear, but neither the regions discussed nor the conclusions are altered.

As a known metric by which to put the Atlantic correlation fields in perspective, we correlate the rainfall departures with the NINO3 SSTA index (Figure 2a). Because the NINO3 index has a large negative correlation with the SOI index, we expect to see a robust pattern of correlations that is similar in distribution but opposite in sign to the findings of *Ropelewski and Halpert* (1987). Accordingly, we see that positive SST departures in the equatorial Pacific (negative SOI) are associated with increased rainfall in South America south of 20°S, the western United States (US) and NW Mexico, and over the southeastern US. Rainfall decreases along the northern part of South America as far east as NE Brazil. We note that the correlations do not resolve the well-known excess rainfall known to occur in the coastal regions of Ecuador and northern Peru because the DOE averages merge coastal rainfall with the variabilities in the Andes and the Amazon basin. Similarly, there is a hint of excess rainfall along the Caribbean coast of Central America, but resolution problems caused by orography appear to mask the known dryness (in association with ENSO warmings) of the Pacific coast.

Correlations with the South Atlantic (SATL) show a generally weak pattern (Figure 2b). Isolated correlations of either sign are scattered through North, Central and South America. Only NE Brazil shows a regional cluster of correlations, with South Atlantic warmings being associated with rainfall increases. In contrast, North Atlantic (NATL) warmings are associated with dry conditions in NE Brazil (Figure 2c), just as NINO3 is (Figure 2a). Thus, we cannot unambiguously infer which ocean is linked directly to NE Brazil rainfall because the oceans are intercorrelated and are related to rainfall in the same manner.

Most significant for the North Atlantic warmings, however, is a robust pattern of rainfall increases throughout the Caribbean and Central America, and decreases over the southern US. The correlation signs in these regions are mostly opposite to those for NINO3 (Figure 2a), unlike those for NE Brazil. In this case, no ambiguity exists because the intercorrelations of the SSTA indices do not explain the oppositely signed rainfall correlations. We therefore infer that both oceans probably have direct linkages with rainfall surrounding the Caribbean and Gulf of Mexico.

When rainfall is correlated with the NATL-SATL difference, a stronger association occurs in NE Brazil than with any of the three SSTA indices alone (not shown), consistent with the results of *Moura and Shukla* (1982) and others. The associations over the Caribbean and North America are similar to those for NATL alone, but weakened, suggesting that dipole configurations have little or no effect there while the inclusion of SATL variability introduces more noise than signal into the correlations.

To see the effect of the Atlantic ITCZ, we compute the divergence of the COADS surface winds along 29°W, which gives minimum (negative) values close to the equator in the boreal winter and near 9-10°N in the summer, as expected. We define an index of ITCZ behavior to be the anomalous latitude of minimum (negative) divergence. The wind patterns associated with the SATL and NATL indices (Figure 1) suggest that the ITCZ latitude should undergo anomalous shifts toward warmer SSTA and (by inference) lower sea level atmospheric pressure. This is confirmed by large zero-lag correlations of the ITCZ index with SATL (-0.33), NATL (+0.47) and the NATL-SATL difference (+0.54).

The ITCZ index (Figure 2d) is associated with a strong regional pattern of increased and decreased South American rainfall north (Venezuela) and south (NE Brazil) of the equator, respectively. This is consistent with the expected effect of North and South Atlantic SSTA variabilities on the ITCZ (wind patterns in Figure 1), the associations of NE Brazil rainfall with SSTA (Figure 2b,c), and the correlations noted above. The higher correlation of ITCZ latitude with NATL (than with SATL) is consistent with the fact that the ITCZ correlation pattern (Figure 2d) closely resembles the NATL pattern (Figure 2c). The very large and geographically dense correlations over northeastern South America (Figure 2c) suggest the ITCZ behavior and its relationship with NATL variability have a direct effect on rainfall, as might be expected for that region. The negative rainfall correlations in the southeastern US in association with both NATL (Figure 2c) and the ITCZ (Figure 2d) are likely related to some process other than the ITCZ.

One region that is conspicuous by the absence of organized correlation clusters in Figures 2b-d is the southernmost portion of South America (south of 20°S). This region is only associated with the Pacific ENSO variability (Figure 2a).

Conclusions

While confirming much of the previous work, this study is complementary in its approach because it considers the Pacific SST rather than the SOI and examines the correlation distributions of rainfall with respect to SSTA indices rather than of SSTA with respect to rainfall indices. The present hemispheric analysis confirms the previous results of *Ropelewski and Halpert* (1987, 1989) regarding the ENSO impacts on rainfall in the Americas. It also confirms the results of *Moura and Shukla* (1981) and others regarding the strong linkages of NE Brazil rainfall to SSTA variability in the tropical North and South Atlantic, including the stronger effects of meridional dipole configurations in SSTA and their relationship to anomalous ITCZ activity. Tropical North Atlantic SSTA appears to explain rainfall variability in several regions: the Caribbean, Central America, northern South America and the southeastern United States. The effects over the Caribbean region are consistent with the findings of *Hastenrath* (1978, 1984). Over this large contiguous area the North Atlantic associations are comparable to those with Pacific SST variability. The Atlantic warmings are associated with rainfall increases over the northern part of South America and decreases over the southeastern US, both opposite to the sense of Pacific warmings. The Atlantic warmings are also associated with increased rainfall in the eastern Caribbean, for which a Pacific influence is not evident. Because the equatorial Pacific and North Atlantic SSTA variabilities are correlated and affect rainfall in some regions in similar ways (e.g., NE Brazil), there exists the possibility that one ocean or the other is not directly associated with rainfall. In other regions the effects of both oceans are probably direct, because the rainfall associations are of opposite sign while most of the Atlantic SSTA variability is unrelated to the Pacific ENSO.

The results of this study strongly suggest that more highly resolved and seasonally stratified empirical analyses of rainfall relationships with tropical North Atlantic SST can contribute significantly to better short term climate forecasts for the entire region surrounding the Caribbean and Gulf of Mexico, including NE Brazil.

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