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INTERANNUAL AND DECADAL VARIABILITY OF SUMMER RAINFALL OVER SOUTH AMERICA

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1. INTRODUCTION

Interannual and decadal variability of rainfall over South America have had major social and economic impacts in countries of this continent. In a pioneering study, Walker (1928) documented a remarkable coincidence of the anomalous warming of the eastern equatorial Pacific Ocean and drought in Northeast Brazil (Nordeste), where the peak of the annual rainfall occurs during austral fall.

There are two major hypotheses for the Nordeste drought: the shifts in the large scale atmospheric circulation caused by SST anomalies in the tropical Pacific versus the tropical Atlantic. It was suggested that in El Niño years, an anomalous eastward displacement of the Pacific Walker circulation occurs with upward motion over anomalously warm waters of the central and eastern Pacific and sinking motion over eastern Amazon, Northeast Brazil and the equatorial Atlantic, leading to drought conditions in Nordeste. An alternative explanation showed the intensification of the intertropical convergence zone (ITCZ) to the north of the equatorial Atlantic, which occurs in association with local warm SST anomalies, leads to increased descending motion over the region of cold SST anomalies in the adjoining ocean, from which stems the rainfall reduction over Nordeste.

Positive rainfall anomalies related to ENSO have been found at the Ecuador-Peru coast, and over the subtropical southeastern South American (SSESA) region, including southern Brazil, Uruguay, and northeastern Argentina. The SSESA region is just about $15° - 20°$ south of Nordeste and the regional precipitation is mostly concentrated in austral summer (December-January-February), which is different from the timing of the peak rainfall over Northeast Brazil. The mechanistic distinction between these two regional rainfall anomalies in association with ENSO has yet been understood.

In addition to the influence of the tropical SST anomalies discussed above, remote influence from mid-high latitudes was reported by Namias (1972). He found that increased cyclonic activities in the Newfoundland area were associated with the abundant rainfall in Northeast Brazil. This implied a relationship with the North Atlantic Oscillation (NAO), which varies in the decadal time scale and is strongest in boreal winter.

In recent years the advancement of rainfall estimation and data assimilation has greatly improved the data quality especially over the areas with sparse observing stations. Using these data we have conducted a new study on those previously unresolved problems in regard to the interannual and longer time scale variabilities of summer rainfall over South America.

2. DATA PREPROCESSING

The rainfall product used in this study is the monthly mean CPC (Climate Prediction Center) Merged Analysis of Precipitation (CMAP), which is constructed on a 2.5° latitude-longitude grid and covers a 17-year period from January 1979 to December 1995. To explore the mechanisms, the Climate Analysis Center (CAC) SST analyses and the Goddard Earth Observing System (GEOS) reanalysis are also used.

To focus on interannual and longer time scales, we subtract the monthly mean climatology from each monthly value and apply a low-pass Lanczos filter. The cut-off frequency f_c is set to $1/12$ month^{-1} to remove the variations of the time scale less than or equal to twelve months. The filtered DJF monthly data are then used in the EOF analysis. For consistency, this procedure has also been applied to SST and the atmospheric data used for the analysis.

3. CLIMATOLOGICAL FEATURES

The climatology of monthly mean precipitation migration over South American continent and the tropical western Atlantic shows distinct moving characteristics due to different surface properties. Over the land precipitation band advances from the northern equatorial northwest toward the subtropical southeast. In January it reaches its southernmost position. This rainfall movement is closely related to the development of South American summer monsoon (SASM), which has been documented by Zhou and Lau (1998) recently. Over the western North Atlantic Ocean, the ITCZ moves southward much slower than its counterpart over the South American continent. In December and January the ITCZ breaks, being almost twenty degree latitude apart at the east coast of Brazil. When the season migrates from summer to fall, the summer monsoon and the

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Using the CPC (Climate Prediction Center) Merged Analysis of Precipitation product along with the Goddard Earth Observing System reanalysis and the Climate Analysis Center sea surface temperature (SST) data, we conduct a diagnostic study of the interannual and decadal scale variability of summer rainfall over South America. Results show three leading modes of rainfall variation identified with interannual, decadal, and long-term trend variability. Together, these modes explain more than half the total variance.

The first mode is highly correlated with El Nino/southern oscillation (ENSO), showing severe drought over Northeast Brazil and copious
rainfall over the Ecuador coast and the area of Uruguay-Southern Brazil in El Nino years. This pattern is attributed to the large scale zonal shift of the Walker circulation and local Hadley cell anomaly induced by positive (negative) SST anomaly over the eastern (western) equatorial Pacific. In El Nino years, two convective belts indicated by upper tropospheric velocity potential trough and mid-tropospheric rising motion, which are somewhat symmetric about the equator, extend toward the northeast and the southeast into the tropical North and South Atlantic respectively. Sandwiched between the ascent is a region of descending motion over Northeast Brazil. The southern branch of the anomalous Hadley cell is dynamically linked
to the increase of rainfall over Uruguay-Southern Brazil. The regional response of anomalous circulation shows a stronger South American summer monsoon and an enhanced (weakened) subtropical high over the South Atlantic (South Pacific) Ocean.

The decadal variation displays a meridional shift of the Intertropical
Convergence Zone (ITCZ), which is tied to the anomalous cross-equatorial SST gradient over the Atlantic and the eastern Pacific. In conjunction with this mode is a large scale mass swing between the polar regions and midlatitudes in both hemispheres. Over the South Atlantic and the South Pacific, the changes of the
strength of the subtropical high and the associated surface wind are dynamically consistent with the distribution of local SST anomalies, suggesting the importance of the atmospheric forcing in the decadal time scale. The decadal mode also presents a weak summer monsoon in its positive phase, which reduces the moisture supply from the equatorial Atlantic and the Amazon Basin and results in negative rainfall anomalies over the central Andes and Gran Chaco.

The long-term trend shows decrease of rainfall from the northwest coast to the southeast subtropical region and a southward shift of Atlantic ITCZ that leads to increased rainfall over northern and eastern Brazil. Our result shows a close link of this mode to the observed SST warming trend over the subtropical South Atlantic and a remote connection to the interdecadal SST variation over the extratropical North Atlantic found in previous studies.

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associated heavy precipitation center over subtropical South America retreat equatorward, while the Atlantic ITCZ continues moving toward the south. In March and April, the two heavy convective rainfall bands join together over northern Northeast Brazil, leading to maximum yearly rainfall over the region.

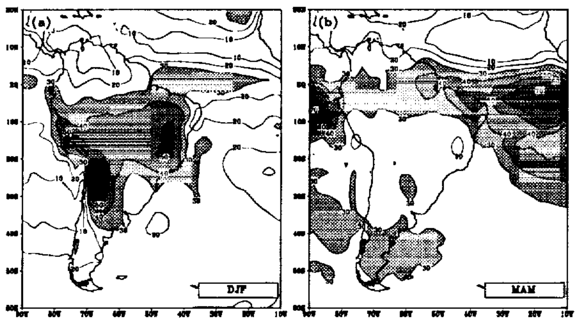

Figure 1: CMAP climatology of seasonal rainfall concentration (percentage of the annual amount) for (a) DJF and (b) MAM respectively.

Figures 1 (a) and (b) show the distributions of rainfall as a percentage of the annual total for DJF and MAM respectively. In austral summer the subtropical land receives about 50% of the local annual rainfall; while in the fall, large percentage of the local annual rainfall concentrates on the northern part of Northeast Brazil and the equatorial Atlantic. Clearly, the two rainfall regimes are quite different. In this paper we focus on the summer regime (DJF), in which the regional precipitation is mostly influenced by the summer monsoon activities over the continent and by the southward advancement of SST ridge over the tropical Atlantic and Nordeste.

4. ANOMALY FEATURES

To assess the summer rainfall variability, we first examine the distribution of standard deviation of the low-pass filtered DJF monthly data. It shows that most variabilities are located over the north-northeast coast of Brazil and the west coast of Ecuador and Colombia. There are moderate variations over the subtropical regions of Bolivia and Southern Brazil. This total variance of rainfall is further decomposed by the EOF analysis. Results clearly show three leading modes, which are separated temporally into interannual, decadal and long-term variations. They together explain more than half of the total variance and individually explain 27.2%, 17.0% and 13.3% of the variance.

4.1 Interannual Variability

As shown in Figs.2(a) and (c), the first mode of the rainfall EOF analysis is highly correlated with the SST first EOF mode which reflects the ENSO variation. Noticeably, the spatial pattern of this mode (Fig.2(b)) shows that the rainfall tends to be above normal over Uruguay-Southern Brazil and the west coast of Ecuador and lower over northeast Brazil during El Niño years.

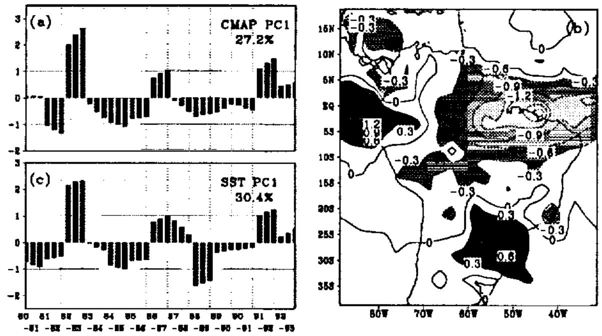

Figure 2: DJF rainfall of (a) PC1 and (b) EOF1 (mm/day). (c) DJF SST PC1.

The pattern of regression with SST shows striking resemblance with that of the first mode of the independent SST EOF analysis, not only in pattern but also in magnitude. High correlations can be found in the areas where SST is sensitive in a typical ENSO event. These clearly indicate that the interannual variability of the South American summer rainfall anomaly is an integral part of the global climate response to ENSO. Over the tropical Atlantic, the moderate cold SST anomaly south of the equator is significantly correlated with the South American summer rainfall anomaly.

To understand the mechanism of the anomalous rainfall pattern over South America, a linear regression is performed with velocity potential. The result pattern shows that a wavenumber-one perturbation with two centers in opposite phase between 850 and 200 hPa over the equatorial eastern and western Pacific respectively. This pattern can be attributed to the eastward shift of the convective heating induced by the ENSO anomaly. Over the eastern Pacific, two upper tropospheric velocity potential troughs with ridges underneath can be clearly identified, one extending northeastward and the other southeastward from the anomalous divergence center over the eastern equatorial Pacific into the subtropical North and South Atlantic respectively. An anomalous ridge is found just above Northeast Brazil. The 500 hPa vertical velocity field shows rising motion along the troughs and sinking motion over the ridge. Our results suggest that ENSO induced anomalous diabatic forcing over the tropical Atlantic sector is symmetric about the equator. The northern and southern branches of the anomalous secondary circulation reinforce the subsidences induced by the anomalous Walker circulation over northeastern Brazil further weakening the local rainfall.

The regressions of PC1 with sea level pressure and 850 hPa wind are also performed. As a result of mass redistribution during El Niño years, the northwest African high and the subtropical South Atlantic high are enhanced, and the South Pacific high and the subtropical high over western North Atlantic are weakened. Consequently, the flows along the summer monsoon path and around the outskirt of the tropical South Atlantic high are substantially enhanced. These two branches of anomalous wind diverge over northeastern Brazil and converge over southern Brazil. We also see the circulation turning cyclonically around Uruguay and its eastern side of the South Atlantic ocean. Over the west coast of Ecuador, anomalous convergence is encountered through above normal westerlies from the displaced Walker circulation over the eastern equatorial Pacific and the increased easterlies of enhanced summer monsoon circulation along equatorial Amazon Basin. The aforementioned circulation changes imply strong low level moisture convergence, which is consistent with the anomalous rainfall distribution over South America noted in Fig.2(b).

4.2 Decadal Variation

The second mode (Fig.3(a) and (b)) varies in decadal time scale. The spatial distribution of this mode displays a meridional shift of ITCZ over both sides of the South American continent with more significant signal over the equatorial Atlantic side. During most of the 1980's, PC2 remains negative, indicating above normal rainfall over northeastern Brazil and from central Andes to Gran Chaco, and below normal rainfall over north of the equator and southern Amazon Basin. The situation seems to reverse after the late 1980's and early 1990's.

Since the movement of ITCZ over oceans mainly follows the progressing of the equatorial SST ridge, the relation between the principal component of this mode and SST is investigated. Figure 4 shows the regression pattern of PC2 with SST and 1000 hPa wind. A series of anomalous meridional SST highs and lows are noted. These SST anomalies are roughly zonally symmetric about the South American continent and meridionally span the Southern Hemisphere mid-latitudes to northern tropical oceans. The pattern is highly significant at the southward of 20°N over the Atlantic, where the cross-equatorial dipole structure is clear. Over the eastern Pacific, distinct temperature anomalies are con-

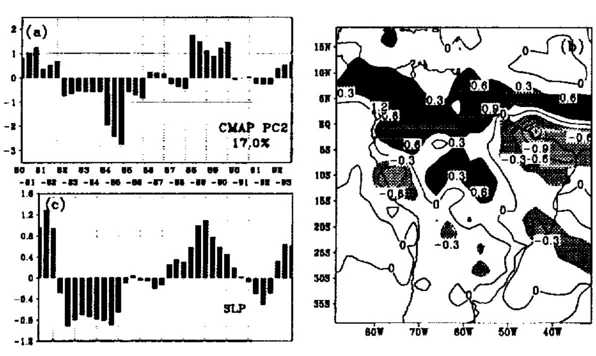

Figure 3: DJF rainfall (a) PC2 and (b) EOF2 (mm/day). (c) DJF SLP (hPa) area averaged over 90°E-90°W and 55°-35°S.

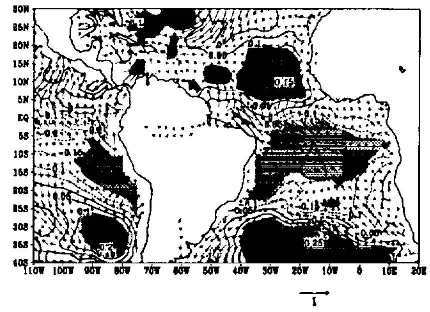

Figure 4: Regression of DJF rainfall PC2 with SST (K) and 1000 hPa wind (m/s). The shaded areas indicate the correlation is statistically significant at above 95% level.

fined to the area close to the South American continent between 40°-5°S. Though the SST anomaly over north of the eastern Pacific is not significant due to large ENSO variability, a weak dipole pattern still can be identified across the equator.

To seek for the mechanism of the decadal variability over the tropical oceans, some inspirations can be drawn from the above analysis. Since the two oceans are separated by the South American continent, the rather zonally symmetric SST anomaly across the continent implies the atmospheric forcing. Additionally, the stronger anomalous signals are found in mid-latitudes and not in the tropics, suggesting the source of perturbation could be located at higher latitudes. The regression pattern of SLP with the rainfall PC2 shows that significant amount of mass is moved from polar regions to the extratropics during the positive phase, creating an anomalous extratropical high belt around the polar low. In the Northern Hemisphere, the Aleutian low is weakened and the anomalous high from western Europe to the east of US in association with the anomalous low pressure over the polar region resembles the pattern of the the North Atlantic Oscillation (NAO). In the Southern Hemisphere, the subtropical highs over the South Atlantic and the eastern South Pacific are enhanced and expand poleward. The SST warming over the belt of 40° – 30°S is consistent with the overlaid anomalous surface wind (see Fig.4), which follows the contours of anomalous SLP anticyclonically and produces wind drift of warm warter from lower latitudes. In the tropics of the South Atlantic between 20°S and the equator, stronger than normal southeasterly trade wind at the northern fringe of the anomalous high system increases the sensible and latent heat loss from the ocean surface, hence lowers the local SST. In the tropical eastern South Pacific, the southerlies along the west coast of South America induce anomalous upwelling, creating cold SST anomaly nearby the continent. Consequently, the meridional SST gradient increases and the cross-equatorial wind intensifies on both sides of the continent. Over north of the equator the winds veer round to the northeast, compelled by the Coriolis force. It weakens the northeasterly trades hence reduces the heat loss from the ocean surface, resulting in warm poles. The temporal variation of SLP averaged over the Southern Hemisphere extratropical anomalous high belt is plotted underneath the rainfall PC2 in Fig.3(c). The high correlation between the two time series is self-evident.

Over the subtropical land, precipitation is mainly brought by the summer monsoon circulation. The result of regression between the rainfall PC2 and 850 hPa wind reveals that anomalous westerlies prevail over the equatorial North Atlantic and abnormal southerlies appear between 10°S and the equator. This indicates a weakened summer monsoon circulation that reduces moisture transport from the equatorial Atlantic and the Amazon Basin and results in negative rainfall anomalies over central Andes and Gran Chaco.

4.3 Long-term Trend

The third principle component shows a clear long-term trend from 1980s to early 1990s. The spatial pattern shows increase of precipitation over Northeast Brazil and the northwest coast of Ecuador-Colombia, and decrease of rainfall over the surrounding areas from the north equatorial Atlantic to subtropical South America. Over the equatorial western Atlantic, the pattern shows a southward shift of ITCZ. The magnitude of the anomaly over the north is more distinct than that over the south.

This mode exhibits that the areas of significant correlation with SST are mostly confined at the poleward of 20° in both the South and the North Atlantic. Over the South Atlantic a distinct warming band across the basin at about 25°S coincides with the subtropical western South Atlantic warm tongue. Over the North Atlantic there is a significant dipole pattern with warming over the east of United States and cooling over the northeast of Newfoundland. The 1000 hPa wind anomalies show anticyclonic (cyclonic) circulation over the warm (cold) area, which is dynamically consistent with the SST anomalies. The above findings are supported by many observational SST studies, most of which investigate the South or the North Atlantic only. Our result reveals a broader connection of this mode. Due to the short time coverage of our data, we are not in a position to make further explanation. We leave this important issue for future study.

Taking account of all the three leading modes, now we can appreciate the complex variabilities of the South American summer monsoon rainfall. Figure 5 shows the time series of the area mean observed rainfall and the reconstruction by the three leading modes over northern Nordeste and the equatorial North Atlantic, where the rainfall variability is prominent. Overall, the reconstructions mimic the variations of the observed rainfall time series. The individual time series shows that the interannual mode varies inphase and the other two modes

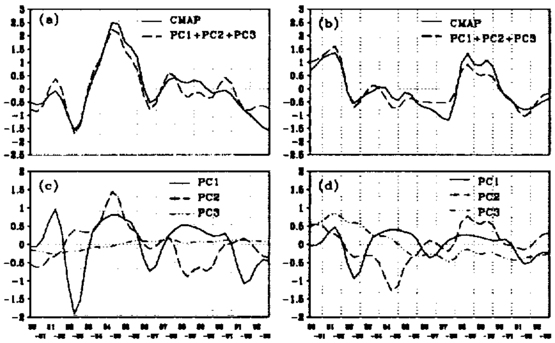

Figure 5: Area averaged rainfall (solid) and the reconstruction by leading three PCs (dash) over (a) northern Nordeste (50°-35°W, 10°-2°S) and (b) equatorial North Atlantic (60°-30°W, 2°-8°N). (c) and (d) are the leading three PCs for the reconstruction of (a) and (b) respectively. Unit: mm/day.

out of phase over the north and the south of the equator. The interannual mode dominates the anomalous dry condition in El Niño years. However, the decadal mode has larger impact in La Niño years. We can see rainfall is significantly enhanced over northern Nordeste in the 1984-85 case due to the interannual and decadal modes and over the equatorial North Atlantic in the 1988-89 case due to the decadal mode. The modification by the long-term trend is small over northern Nordeste but has comparable amplitude with other leading modes over the tropical North Atlantic.

5 CONCLUSIONS

South American summer (DJF) rainfall variability is dominated by three distinct modes of interannual, decadal and long-term trend variations. Each mode is closely related with SST variation of the corresponding time scale, implying the significance of the atmospheric-ocean coupling to the variability of the hydrological cycle.

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