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Connection between Spring Conditions and Peak Summer Monsoon Rainfall in South America: Role of Soil Moisture, Surface Temperature, and Topography in Eastern Brazil

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ABSTRACT

A link between peak summer monsoon rainfall in central-east Brazil, composing part of the South American monsoon core region, and antecedent conditions in spring is disclosed. Rainfall in this region during part of spring holds a significant inverse correlation with rainfall in peak summer, especially during ENSO years. A surface–atmosphere feedback hypothesis is proposed to explain this relationship: low spring precipitation leads to low spring soil moisture and high late spring surface temperature; this induces a topographically enhanced low-level anomalous convergence and cyclonic circulation over southeast Brazil that enhances the moisture flux from northern and central South America into central-east Brazil, setting up favorable conditions for excess rainfall. Antecedent wet conditions in spring lead to opposite anomalies. The main links in this hypothesis are confirmed through correlation analysis of observed data: spring precipitation is negatively correlated to late spring surface temperature in central-east Brazil, and surface temperature in southeast Brazil is positively correlated with peak summer monsoon precipitation in central-east Brazil. The intermediary links of the surface–atmosphere feedback are tested in sensitivity experiments with the regional climate model version 3 (RegCM3). These experiments confirm that the proposed links are possible: the reduced soil moisture in central-east Brazil is shown to increase the surface temperature and produce a cyclonic anomaly over southeast Brazil, as well as increased precipitation in central-east Brazil. A crucial role of the mountains of southeast Brazil in anchoring the patterns of intraseasonal variability, and sustaining the "dipolelike" precipitation mode observed over South America, is suggested. The low predictability of monsoon rainfall anomalies in central-east Brazil during the austral summer might be partially ascribed to the fact that the models do not well reproduce the topographical features and the land–atmosphere interactions that are important for the variability in that region.

1. Introduction

The annual cycle of precipitation over most of South America is monsoonlike, with great contrasts between winter and summer (Rao et al. 1996; Grimm 2003; Gan et al. 2004; Grimm et al. 2005). Summer is the rainy season in most of the continent, including subtropical regions. In the monsoon core region, central Brazil, precipitation is more than 10 times greater in summer than in winter. The quality of the monsoon season is important for agriculture, hydroelectric power generation, and water management. In addition, very densely populated areas, in southeast Brazil, are severely affected by oscillations in the South Atlantic convergence zone (SACZ), whose enhancement frequently causes urban floods and landslides during summer. It is therefore important to understand the mechanisms responsible for the variability of the South American Monsoon System (SAMS) in order to improve the ability to predict it.

The SAMS undergoes variations at several temporal scales. Previous studies have found that the main source of interannual variability of precipitation during the summer monsoon season is the El Niño–Southern Oscillation (ENSO; Zhou and Lau 2001; Nogués-Paegle and Mo 2002).

The ENSO impact shows strong regional differences

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and strong changes within the monsoon season, suggesting an important role of regional processes during the peak monsoon (Grimm 2003, 2004, hereafter G03 and G04, respectively). In spring of ENSO years precipitation anomalies of the same sign are found over northern South American and central-east Brazil, especially in November, while opposite anomalies occur in southern Brazil. In summer, despite the relative persistence of the remote sea surface temperature (SST) forcing in the Pacific Ocean, there is a significant reversal of anomalies in January over central-east Brazil, while in southern Brazil the anomalies weaken or even change sign. G03 and G04 suggest that spring soil moisture anomalies induce surface temperature anomalies, which support a regional circulation pattern that redirects moisture flux and enhances/suppresses convection over central-east Brazil. This process seems to be enhanced by SST anomalies off the southeast coast of Brazil and by the topography of central-east Brazil. These studies provide the motivation to pursue the following objectives: (i) to verify whether antecedent anomalous conditions in spring influence the summer monsoon not only in ENSO but also in non-ENSO years; and (ii) to investigate the possible role of soil moisture, SST, and topography through sensitivity experiments with a regional model.

Soil moisture is a key parameter for land–atmosphere interaction. The influence of soil moisture on precipitation has been investigated in many numerical modeling studies. Most of them concluded that there is a positive feedback between soil moisture and rainfall (e.g., Rowntree and Bolton 1983; Mintz 1984; Atlas et al. 1993; Beljaars et al. 1996; Pal and Eltahir 2001). Recently, Koster et al. (2004) showed that summer precipitation over Northern Hemisphere monsoon regions is sensitive to soil moisture variations. The influence of snow cover and related soil moisture anomalies in premonsoon seasons (winter and/or spring) on the interannual variability of the Asian summer monsoon has been extensively studied. The spring soil moisture influence on the North American monsoon has also been investigated (e.g., Higgins et al. 1998; Higgins and Shi 2000; Zhu et al. 2005). This is not the case, however for the South America monsoon and therefore, following the indications of G03 and G04, we investigate here the relationship between spring soil moisture and summer rainfall anomalies over a region that comprises most of the core South America monsoon. In particular, we test the hypothesis that reduced (enhanced) soil moisture in spring might produce the observed circulation and precipitation anomalies in the peak summer monsoon season.

The diagnostic study of G03 also demonstrated a relationship between SST off the southeastern coast of Brazil in November and rainfall in central-east Brazil in January. Here we test whether this possible feedback contributes to the circulation and precipitation anomalies observed in the peak summer monsoon season.

Finally, studies on the influence of topography on the South American circulation and precipitation, particularly during the summer monsoon, have mostly focused on the effects of the Andes (e.g., Lenters and Cook 1995; Figueroa et al. 1995; Byerle and Paegle 2002). Thus far, however, there has been no assessment of the importance of the mountains in the eastern part of the continent, especially in southeast Brazil, which encompasses several peaks above 2500 m including the third highest peak in Brazil, the Pico da Bandeira (2890-m height). These peaks affect regional circulation patterns and may be important in shaping the dipolelike intraseasonal oscillations during the South American summer monsoon. In this study we also explore this issue.

Because the effects of soil moisture, southeastern Brazil coastal SST, and southeast Brazil topography are essentially regional in nature (G03; G04), a regional climate modeling framework is especially suitable for testing if some of the hypothesized links are possible. Therefore, besides presenting diagnostic studies, we also address the issues described above with the use of a regional climate model [the Abdus Salam International Centre for Theoretical Physics (ICTP) regional climate model version 3 (RegCM3); Pal et al. 2007] run over a large domain covering South America and the adjacent ocean areas.

The paper is organized as follows. Section 2 reviews the ENSO impact on summer precipitation in Brazil, with focus on the reversal of this impact from spring to summer. In section 3 we verify whether the behavior observed during ENSO years does also manifest itself in other years. Section 4 describes the regional model, data, and experimental approach, while in section 5 results are shown of some sensitivity experiments that test the feasibility of the proposed links. Results are discussed and conclusions are drawn in section 6.

2. Review of the ENSO impact on the summer monsoon and its reversal from spring to summer in central-east Brazil

The anomalous tropical heat sources associated with ENSO events in the tropical central-eastern Pacific perturb the Walker and Hadley circulation over South America and generate Rossby wave trains that produce important effects in the subtropics and extratropics of South America, especially in spring (e.g., Ambrizzi et

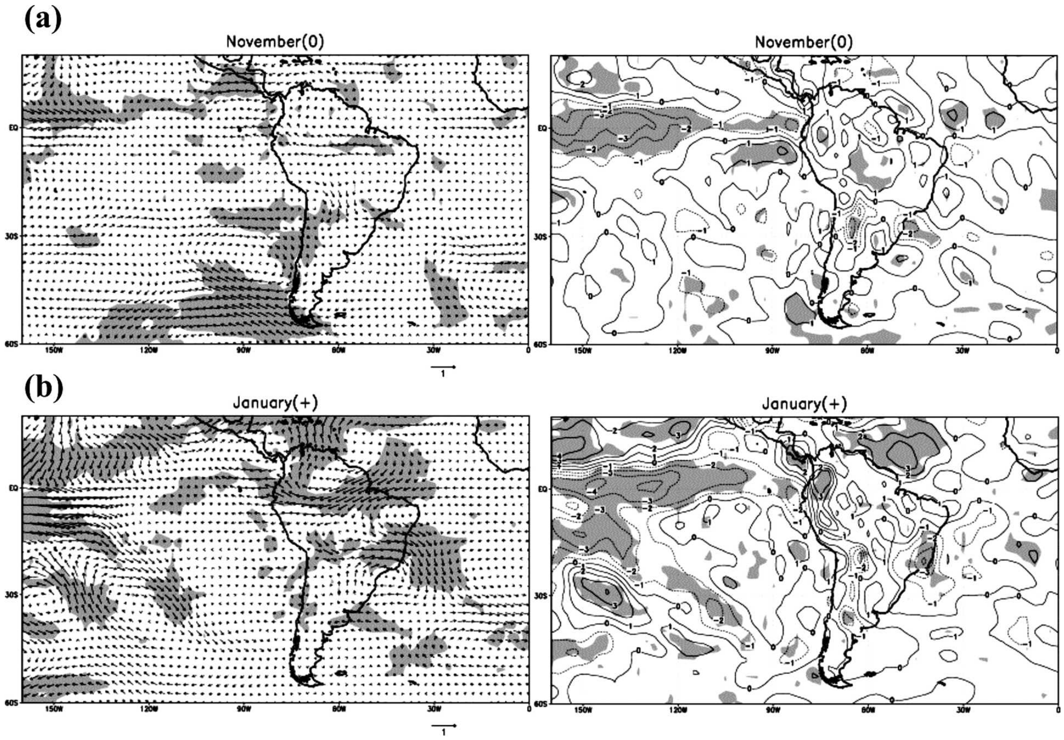

FIG. 1. (left) Composite of vertically integrated moisture flux anomalies and (right) its divergence for (a) November and (b) January of El Niño events. Units are 10^{-2} mg s^{-1} kg^{-1} and 10^{2} g s^{-1} kg^{-1}, respectively. The shaded areas indicate anomalies consistent over the 90% confidence level (from G03).

al. 2004). However, abrupt changes of anomalies within the summer indicate the occurrence of regional processes that influence precipitation during part of the season and over part of the continent (G03; G04). An influence function analysis based on Grimm and Silva Dias (1995) shows that remote influences are much weaker in peak summer than in spring, and that the remote influence from the Pacific Ocean does not explain the observed anomalies.

During El Niño events, in the early summer monsoon season (November) remotely produced atmospheric perturbations prevail over Brazil (e.g., Ropelewski and Halpert 1987; Coelho et al. 2002; G03). Anticyclonic low-level anomalies predominate over central-east Brazil due to enhanced subsidence over the Amazon and to Rossby waves in the subtropics. Easterly moisture inflow from the equatorial Atlantic is favored, but diverted toward northern South America and southern Brazil (Fig. 1a). Precipitation anomalies are negative in north and central-east Brazil and positive in southern Brazil (Fig. 2a). These precipitation anomalies are favored by the perturbation in the Walker and Hadley circulation over the east Pacific and South America and by a Rossby wave train over southern South America that originates in the eastern Pacific. Temperatures are higher than normal in southeast Brazil because of the warm advection from the north, surface heating due to anomalous dryness, and the southward shift of the enhanced subtropical jet, which prevents the northward displacement of cold fronts. In the southernmost part of Brazil, where strong positive precipitation anomalies prevail and cold fronts are more frequent, temperatures are below normal (G03).

In January, with the enhancement of the continental subtropical heat low by anomalous surface heating during the spring, there is anomalous low-level convergence and cyclonic circulation over southeast Brazil, while at upper levels divergence and anticyclonic circulation prevail. This anomalous circulation directs the moisture flux toward central-east Brazil, causing moisture convergence in this region (Fig. 1b). A favorable thermodynamic structure enhances precipitation over central-east Brazil, the dry anomalies in north Brazil are displaced northward, and the anomalies in south Brazil almost disappear (Fig. 2b). The surface temperature anomalies in southeast Brazil turn negative due to enhanced precipitation and cold advection from the south. In February, after the above-normal January precipitation, surface temperature anomalies are negative and precipitation decreases in central-east Brazil.

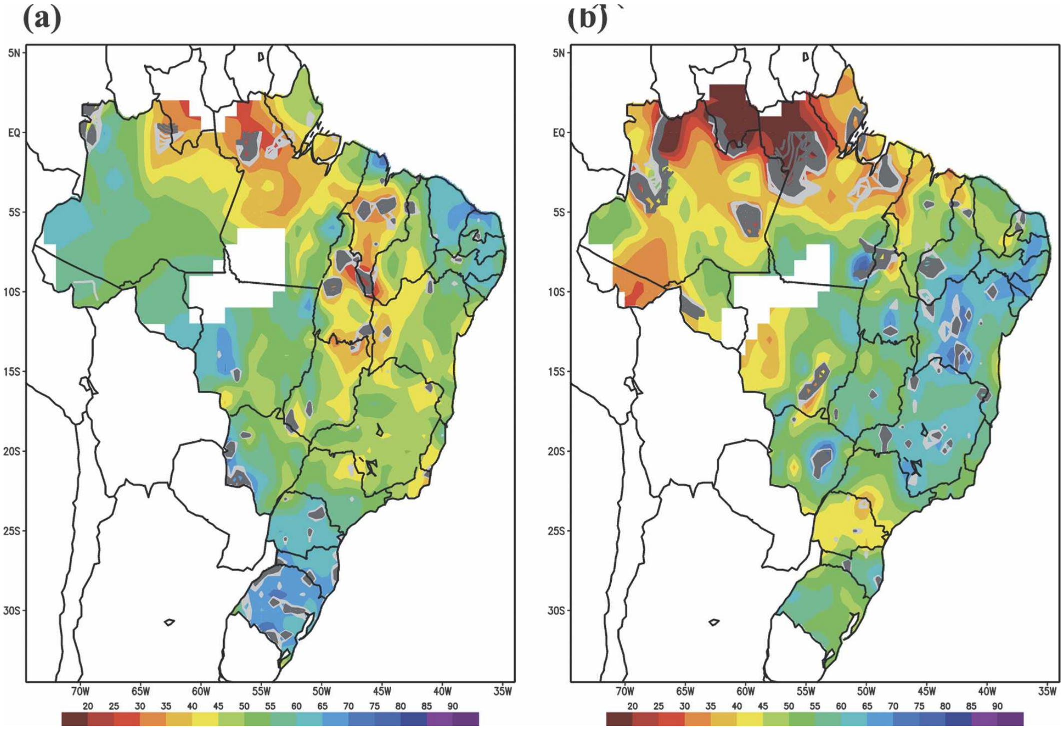

FIG. 2. Monthly mean precipitation percentiles expected for (a) November and (b) January of El Niño events. Dark (clear) shadowed areas have precipitation anomalies consistent over 90% (85%) confidence level (from G03).

The rainfall anomalies are negative in north Brazil and in the SACZ, and positive in south Brazil (G03).

During La Niña events the circulation and precipitation anomalies are mostly of opposite sign compared to those described for El Niño events, sometimes with small shifts in the position of the strongest anomalies and in the magnitude of the anomalies (G04).

Besides the interaction between soil moisture, temperature, and circulation anomalies, SST anomalies and topographic lifting over southeast Brazil may also be responsible for the observed circulation anomalies and precipitation anomalies. January rainfall in central-east Brazil is positively correlated with November SST in the oceanic SACZ, off the southeast coast of Brazil, and is negatively correlated with January SST in the same region (G03). Dry precipitation anomalies in November in the region favor increased shortwave radiation and set up warm SST anomalies. On the other hand, the enhanced convection and rainfall in January leads to negative SST anomalies. One might speculate that the warmer SST in November helps to trigger the regional circulation anomalies that lead to enhanced precipitation in January. Although in the SACZ–SST relationship, the SST anomalies seem to be a result of the convection anomalies in the SACZ, there are possible feedback mechanisms between SST and the atmosphere (Robertson et al. 2003; Chaves and Nobre 2004).

3. Is there a general relationship between spring and summer precipitation anomalies?

As shown in Figs. 2a,b (for El Niño events), precipitation anomalies in November and January of ENSO events show an inverse relationship over parts of central-east Brazil. Furthermore, in ENSO years the surface air temperature in November is higher (lower) than normal in southeast Brazil when precipitation is below (above) normal and the same relationship holds for January (G03; G04). Dry conditions in central-east Brazil during November of El Niño years are associated with heating in the southeast Brazil highlands near the Atlantic Ocean. This heating and the topographic effect associated with the southeast Brazil mountains, along with the warmer SST off the southeast coast of Brazil are hypothesized as leading to lower surface pressure and convergence, causing an anomalous cyclonic regional circulation that directs moisture flux from northern South America into central-east Brazil and enhances precipitation in January over this region (Fig. 1). The anomalies are opposite during La Niña years. Do

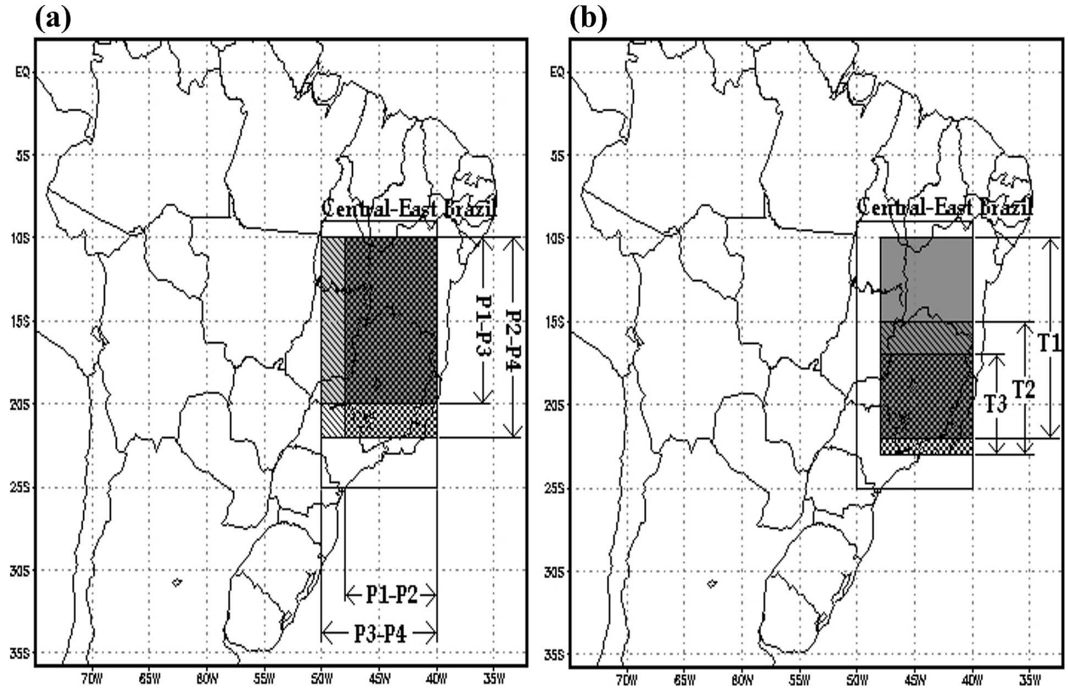

FIG. 3. Regions referred to in the text and tables. (a) The P refers to domains in which precipitation is averaged, and (b) the T refers to domains in which surface air temperature is averaged. The outermost rectangle in both maps limits the region here called central-east Brazil. Southeast Brazil is approximately the southern half of this region.

these relationships and mechanisms also hold in non-ENSO years? To cast some light into this issue, we verify the links in our hypothesis from observations for the period 1960–2000. To this end, we test the relationship between spring and summer precipitation in central-east Brazil along with the two main links in our hypothesis: the inverse relationship between spring precipitation and late spring surface temperature, and the positive correlation between spring surface temperature in southeast Brazil and peak summer monsoon precipitation in central-east Brazil. A positive correlation between SST off the southeast coast of Brazil in November and January precipitation in central-east Brazil in January has already been demonstrated for the entire period in G03.

The correlation analysis is carried out with station precipitation data from the Brazilian Agência Nacional de Águas (ANA) and national meteorological services from some neighboring countries, amounting to more than 10 000 stations, distributed with higher density in the eastern half of the continent. Therefore, the region in which precipitation will be analyzed in more detail is well covered with data. Surface air temperature data are provided by the Brazilian National Institute of Meteorology (INMET; in the stations displayed in Figs. 4 and 5).

Prior to conducting the analysis, South American data are aggregated onto a 2° grid in order to achieve a more homogeneous distribution. November rainfall in each 2° × 2° box is correlated with January rainfall at all the other boxes. In this way, a region with negative correlation between November and January precipitation is identified in central-east Brazil. Then, average series of spring precipitation are correlated with average series of summer precipitation in order to find the strongest relationship. Tests with slightly different regions are carried out in order to refine the location of the regions exhibiting the strongest relationship (Fig. 3a). In each of the boxes of central-east Brazil the correlation between spring temperature and spring precipitation is calculated, along with the correlation between spring temperature in each box and summer precipitation in the part of central-east Brazil with the best correlation with spring precipitation. The correlation between spring temperature and summer precipitation is also repeated for selected areas (Fig. 3b).

The correlation coefficients between precipitation in subperiods within spring and summer are shown in Table 1 for slightly different regions in central-east Brazil (Fig. 3a). Although there is a significant inverse relationship between precipitation in parts of spring and parts of summer for almost all the regions tested, there are some differences in this relationship between ENSO and non-ENSO years. While during ENSO

TABLE 1. Correlation coefficients between precipitations averaged over chosen P regions in periods within spring and the following summer. Correlation coefficients significant at levels better than 0.05 (0.10) are in bold (bold italic). The region in bold (P2) is selected for our analysis.

1960–2000	Periods	All years (40 yr)	Non-ENSO years (21 yr)	ENSO years (19 yr)
P1 × P1	N × J	**−0.30**	***−0.34***	−0.26
10°–20°S	ON × DJ	**−0.34**	−0.09	**−0.51**
40°–48°W	ND × JF	**−0.33**	**−0.45**	−0.17
P2 × P2	N × J	**−0.29**	−0.25	***−0.33***
10°–22°S	ON × DJ	**−0.35**	−0.11	**−0.52**
40°–48°W	ND × JF	**−0.35**	**−0.47**	−0.22
P3 × P3	N × J	**−0.29**	***−0.28***	−0.29
10°–20°S	ON × DJ	**−0.32**	−0.05	**−0.50**
40°–50°W	ND × JF	**−0.34**	**−0.43**	−0.20
P4 × P4	N × J	**−0.28**	−0.20	***−0.36***
10°–22°S	ON × DJ	**−0.33**	−0.08	**−0.50**
40°–50°W	ND × JF	**−0.36**	**−0.45**	−0.24

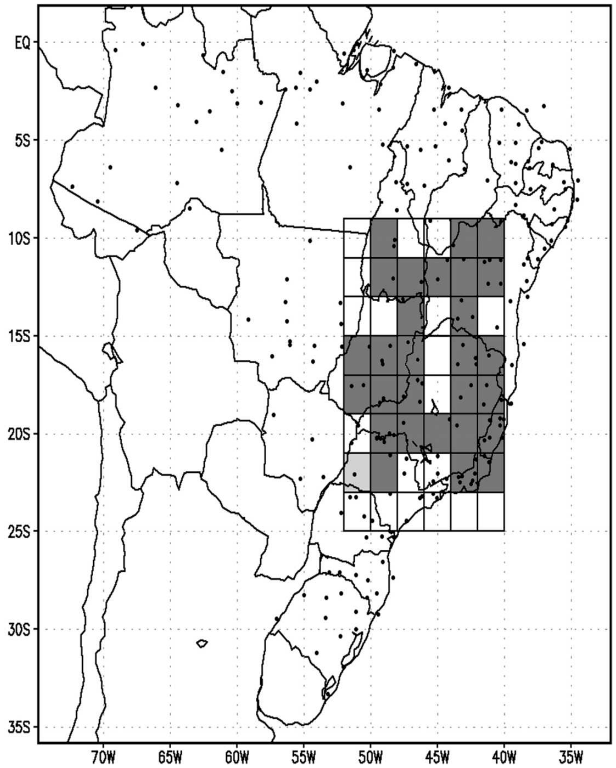

FIG. 4. Correlation of October–November precipitation vs November surface air temperature averaged in 2° × 2° areas in central-east Brazil for the period 1960–2000. Areas shaded in light (dark) gray represent negative correlation significant to a level better than 0.10 (0.05). The dots represent the stations with observed temperature series. Thus, white boxes with (without) stations in them do (do not) mean that the correlation is not significant.

years this inverse relationship is strongest between precipitation in October–November and December–January or November and January, in non-ENSO years it is strongest between precipitation in November–December and January–February or November and January. If the precipitation in November is averaged over a region to the north, the relationship with the precipitation in January strengthens during non-ENSO years but weakens during ENSO years (cf. P1 with P2, and P3 with P4). An extension of the region to the west (to 50°W) does not significantly affect the relationship (cf. P1 with P3, and P2 with P4).

It is not clear why the inverse relationship between spring and summer precipitation is stronger earlier in spring–summer during ENSO years than in normal years. The strong remote influence of ENSO-related SST anomalies during spring might set up the conditions for reversal of precipitation anomalies earlier than during non-ENSO years.

The first link tested in our hypothesis to explain the inverse relationship demonstrated in Table 1 is the one between spring precipitation and late spring surface temperature. The correlation between precipitation and temperature in boxes of 2° latitude × 2° longitude in central-east Brazil is computed for different periods within spring: P (October–November) versus T (October–November), P (November–December) versus T (November–December), P (October–November) versus T (November), and P (November) versus T (November). Although the correlation is generally negative in central-east Brazil for all these periods, the highest negative correlation is achieved between P (October–November) and T (November; Fig. 4). A longer dry (wet) period in spring with less (more) than usual cloudiness and precipitation leads to reduced (increased) soil moisture. As a result, more (less) energy is used for heating and surface air temperature increases (decreases) by late spring. This relationship is not significant in the southern part of the domain, which enters southern Brazil, where the inverse relationship weakens because precipitation is frequently associated with northerly inflow of warm and moist air, and because of the transient systems activity (Barros et al. 2002). These results are consistent with the relationships between summer precipitation and surface temperature found over South America by Trenberth and Shea (2005).

Is the anomalous summer precipitation over central-east Brazil associated with spring surface air temperature anomalies in southeast Brazil? This is verified by correlating surface air temperature in boxes of 2° latitude × 2° longitude in central-east Brazil during subperiods of spring with precipitation averaged over region P2 during subperiods of summer. Figure 5, which

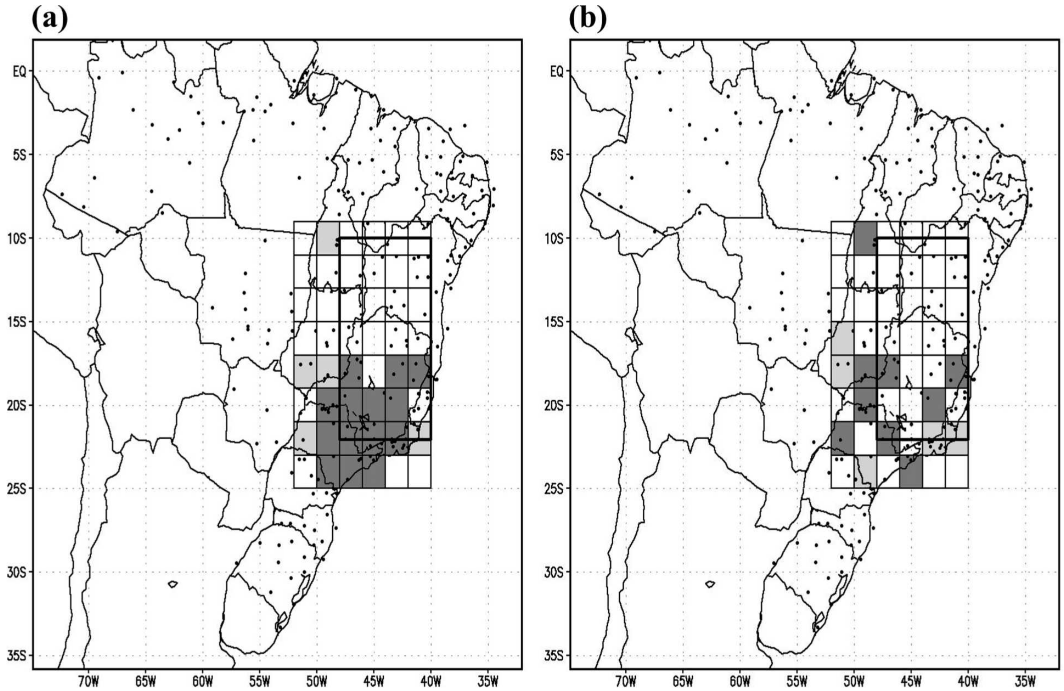

FIG. 5. (a) Correlation of surface air temperature in November in each 2° × 2° box in central-east Brazil vs precipitation averaged over region P2 (bold rectangle) in January. (b) Correlation of surface air temperature in October–November in each 2° × 2° box in central-east Brazil vs precipitation averaged over region P2 in December–January. Areas shaded in light (dark) gray represent positive correlation significant to a level better than 0.10 (0.05). The dots represent the stations with observed temperature series. Thus, white boxes with (without) stations in them do (do not) mean that the correlation is not significant.

shows the boxes in which this correlation is significant, confirms that the correlation is significant in southeastern Brazil and that it is stronger when using only the November temperature (cf. Figs. 5a,b). The concentration of significant correlation coefficients in the highlands of southeast Brazil indicates the importance of both the temperature anomalies and the topographic effect in triggering the regional circulation anomalies that lead to the precipitation anomalies in peak summer. The significant correlation is mainly due to ENSO years, when higher (lower) spring temperature over southeast Brazil is more persistent and more related with higher peak summer precipitation in central-east Brazil. Table 2 confirms that the positive correlation increases toward the south of the region analyzed, concentrating over southeast Brazil, that November and January are the periods within spring and summer in which the temperature–precipitation relationship is stronger, and that the highest correlation is really concentrated in ENSO years. The relationship is also significant for the entire period, but it is not highly significant in non-ENSO years. During ENSO years the relationship is stronger for November and January, but it also holds for other periods of spring and summer (Table 2). This might be due to stronger and more persistent anomalies during spring of ENSO years compared to non-ENSO years.

In summary, although an inverse relationship between central-east Brazil precipitation in spring and summer and the associated temperature anomalies are much stronger during ENSO years (because strong

TABLE 2. Correlation coefficients between surface air temperature averaged over chosen T regions in periods within spring and precipitation averaged over region P2 (10°–22°S, 40°–48°W) in the following summer. Correlation coefficients significant at levels better than 0.05 (0.10) are in bold (bold italic). Region T1 (10°–22°S, 40°–48°W), region T2 (15°–23°S, 40°–48°W), and region T3 (17°–23°S, 40°–48°W).

1960–2000	Periods	All years (40 yr)	Non-ENSO years (21 yr)	ENSO years (19 yr)
T1 × P2	N × J	**0.26**	0.19	***0.33***
	ON × DJ	0.15	−0.12	0.26
	ND × JF	0.14	0.07	0.19
T2 × P2	N × J	**0.35**	0.20	**0.48**
	ON × DJ	***0.25***	−0.08	**0.39**
	ND × JF	0.17	−0.04	***0.31***
T3 × P2	N × J	**0.37**	0.22	**0.49**
	ON × DJ	***0.27***	−0.06	**0.41**
	ND × JF	0.16	−0.06	***0.31***

ENSO-related anomalies are set up in spring), this relationship can also manifest itself during other years, with small shifts in time and geographic location, provided that strong precipitation anomalies are set up in spring.

As the exact mechanisms of the relationship between the spring and summer precipitation in the focused region are still unclear it is interesting to test with a regional model if the proposed links are possible.

4. Design of numerical experiments

a. Model description

The experiments to test the hypothesis proposed on the basis of the diagnostic analysis are carried out with the ICTP RegCM3 (Pal et al. 2007). It is a modified version of the RegCM developed at the National Center for Atmospheric Research (NCAR; Giorgi et al. 1993a,b). The dynamics are based on the fifth-generation Pennsylvania State University–NCAR (PSU–NCAR) Mesoscale Model (MM5; Grell et al. 1994). The radiation scheme is based on that of the NCAR Community Climate Model, version 3 (CCM3; Kiehl et al. 1996). The surface–atmosphere exchange of heat (radiative, sensible, and latent), moisture, and momentum is performed using the Biosphere–Atmosphere Transfer Scheme (BATS; Dickinson et al. 1993). The resolvable (large scale) cloud and precipitation processes are handled with the Subgrid Explicit Moisture Scheme (SUBEX; Pal et al. 2000). We utilize two options to account for the unresolvable precipitation processes (cumulus convection): the Grell scheme (1993), with the Fritsch–Chappell closure assumption (Fritsch and Chappell 1980), and the Massachusetts Institute of Technology (MIT) scheme (Emanuel 1991; Emanuel and Živković-Rothman 1999). The Grell scheme assumes a single cloud with two steady circulations: an updraft and a downdraft, with no mixing between the cloud and environmental air except at the cloud top and base. The MIT scheme assumes that the mixing in clouds is highly episodic and inhomogeneous (as opposed to a continuous entraining plume) and considers convective fluxes based on an idealized model of subcloud-scale updrafts and downdrafts. The use of these two schemes in the sensitivity experiments gave similar responses, therefore we only show results based on the Grell scheme.

b. Data

The initial and lateral boundary conditions for the experiments shown here are provided by the National Centers for Environmental Prediction (NCEP)–NCAR reanalysis project (NNRP; Kalnay et al. 1996), with the exception of the initial conditions for soil moisture and SST. The large-scale fields are driving the model only in a lateral buffer zone of eight grid points. Soil moisture is initialized as a function of the land-cover type, as described in Giorgi and Bates (1989). The SST is prescribed from the Optimum Interpolation Sea Surface Temperature (OISST) 1° weekly analysis available from the National Ocean and Atmosphere Administration (NOAA; Reynolds et al. 2002).

The control precipitation field is compared with the Climate Research Unit (CRU; University of East Anglia, United Kingdom) precipitation 0.5° resolution data (New et al. 1999).

c. Experimental approach

The experiments are designed to test the sensitivity to changes in surface forcing (soil moisture and SST) and to topography in central-east Brazil. They are intended as preliminary tests of possible mechanisms for the observed intraseasonal changes. The grid spacing is 60 km, which allows us to capture the main topographic features (Fig. 6), and the domain encompasses South America and parts of the adjacent oceans (domain size: 8820 km × 7800 km; Fig. 6). The RegCM3 vertical resolution used in these experiments is 18 σ-pressure levels, with the top level at 70 hPa, and finer resolution in the boundary layer.

First, a control run (EN-Jan98) is performed for January 1998, during an El Niño event (actually for the period 25 December 1997–1 February 1998, but only the January fields are shown). Next, sensitivity experiments to soil moisture, SST anomalies, and topography were carried out (Table 3).

To test the spring soil moisture effect, in one of these tests the soil moisture is reduced to half the standard initial values in an area of central-east Brazil, where precipitation in spring is below normal during El Niño episodes (0.5*SM). In another test, the soil moisture is increased to 1.5 the standard initial values over the same area (1.5*SM). To test the sensitivity to SST values off the southeast coast of Brazil, in the 0.5*SM experiment the SST is increased by 1°C in this region (0.5*SM+SST), similar to the largest observed anomalies. Finally, in experiment 0.5*SM−TOPO the topographical elevation in eastern South America (east of 60°W) is limited to 100 m to test the influence of the southeast Brazil mountains on the response to soil moisture forcing. In these sensitivity experiments we are interested in just the qualitative aspects of the resulting anomalies, and not in their magnitude.

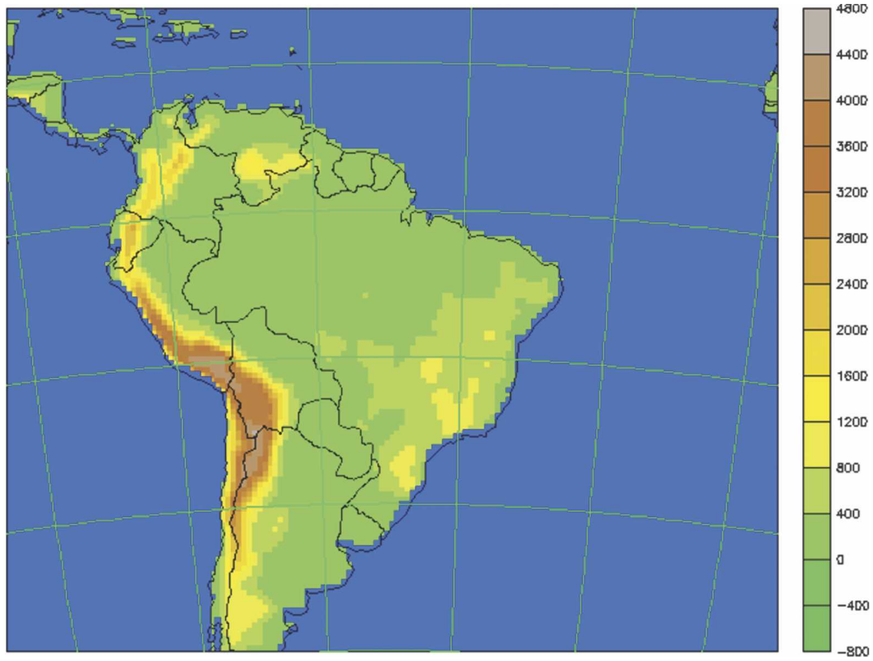

FIG. 6. Domain with topography in South America. Horizontal resolution is 60 km and altitudes are in m.

5. Sensitivity to local forcing

The control run for January 1998, while well reproducing the precipitation in most of South America, underestimates it in parts of central and northern Brazil (Fig. 7). The precipitation in these regions, especially in the Amazon, is frequently underestimated by regional models (Seth and Rojas 2003). In this control run the soil moisture is initialized in 25 December 1997 from standard values attributed to each class of land cover/vegetation and does not reflect the very dry condition in central-east Brazil during the spring of 1997.

Are the dry conditions in central-east Brazil during spring, such as those observed in El Niño events, able to contribute to the higher temperatures observed in November and December and could they lead to the cyclonic anomalies observed in January in southeast Brazil? The results of experiment 0.5*SM, wherein the soil moisture is set to half its usual initial value in the region defined by the box in Fig. 8a, show higher temperatures in central-east Brazil and an anomalous cyclonic circulation around it (Fig. 8b). The precipitation is increased in central Brazil, and reduced to the south, consistent with the proposed hypothesis (Figs. 8c). The result gives a better representation of the observed precipitation in January 1998 in central-east Brazil if compared with Fig. 7a (for which standard initial soil moisture is prescribed), as higher precipitation is extended northward (cf. Figs. 7a and 8a with Fig. 7b). The cyclonic anomaly, and increased rainfall over a great part of the region with reduced soil moisture is an unusual result, different from previous results attained for other regions, such as those in Seth and Rojas (2003) for the western Amazon, and Pal and Eltahir (2002, 2003) for different regions of the United States. Notwithstanding, it supports the hypothesis of G03 and G04. Small changes of the region with a dry soil moisture anomaly with respect to the inserted box in Fig. 8 do not qualitatively change the results of experiment 0.5*SM, producing small shifts and changes of magnitude.

The impact of increasing the soil moisture in the same region as in the previous experiment (experiment 1.5*SM) is of the opposite sign, as expected from the hypothesis. The surface temperature turns lower, a weak anticyclonic anomaly appears (Fig. 9b), and the

TABLE 3. RegCM experiments shown in this study.

Expt	Description
EN-Jan98	Control run
0.5*SM	0.5*usual initial soil moisture in central-east Brazil
1.5*SM	1.5*usual initial soil moisture in central-east Brazil
0.5*SM+SST	0.5*usual initial soil moisture in central-east Brazil + 1° in SST off the coast of southeast Brazil
0.5*SM−TOPO	0.5*usual initial soil moisture in central-east Brazil—no topography above 100 m east of 60°W

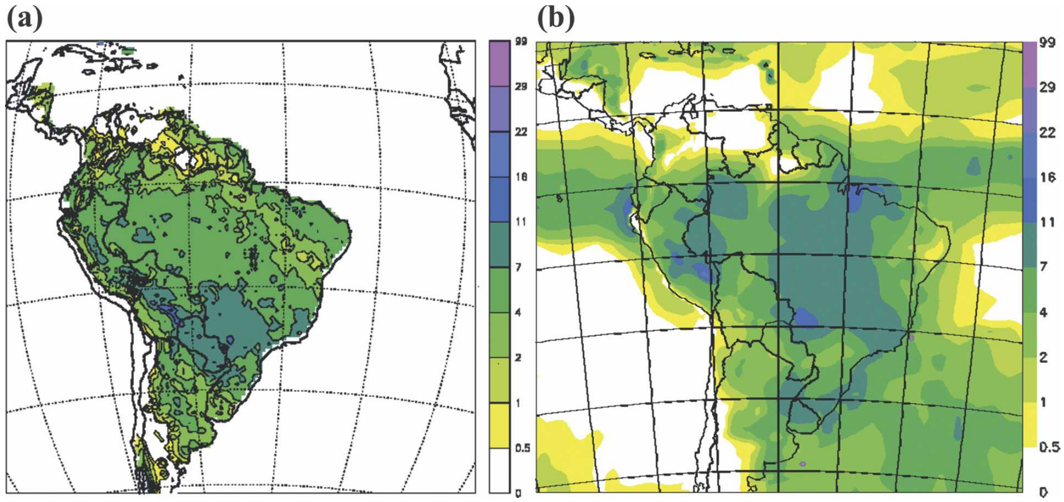

FIG. 7. Jan 1998 precipitation (mm day^{-1}) from (a) the RegCM control run and (b) CRU-CMAP.

precipitation is reduced over central Brazil and increased to the south (Fig. 9c), although the precipitation signal in this sensitivity experiment is small and probably within the model noise. The effect is stronger if the soil moisture is further increased. These anomalies are opposite to what is observed in January of El Niño years (Fig. 2b; G03), when the spring precipitation anomalies in central-east Brazil are negative, but consistent with the observed anomalies in January of La Niña years (G04), when the spring precipitation anomalies are positive in that region. It is worth pointing out that increasing the soil moisture in central-east Brazil leads to a worst representation of the precipitation in January 1998 with respect to Fig. 7a, for which standard initial values are used, as higher precipitation is shifted southward, where in observations it is weaker (cf. Figs. 7a and 9a with Fig. 7b, and also Figs. 8a and 9a to see how the contrasting soil moisture anomalies generate different precipitation fields, specifically in central Brazil).

Warmer SST off the southeast coast of Brazil in late spring is statistically related with above-normal rainfall in central-east Brazil in January (Fig. 13 of G03). The possible contribution of warmer SST in this region to establish the right circulation anomaly over southeast Brazil and the right precipitation anomaly over central-east Brazil in January is tested by adding 1° to the SST in the inserted box in southwestern Atlantic (experiment 0.5*SM+SST, Fig. 10). The warmer SST effectively enhances (in the right sense) the precipitation and circulation anomalies obtained by reducing soil moisture, extending them into southeast Brazil (cf. Figs. 8 and 10). Therefore, there may be a role of previous SST anomalies in enhancing the precipitation in central-east Brazil in January, by enhancing the SACZ. Notwithstanding, once enhanced cloudiness and precipitation prevail over central-east Brazil in January, there is an inverse simultaneous relationship between precipitation and SST, with enhanced precipitation corresponding to colder SST (G03).

Finally, the unusual response to changes in soil moisture in central-east Brazil, when compared with studies testing sensitivity to soil moisture in regions with rather flat topography (e.g., Seth and Rojas 2003; Pal and Eltahir 2002, 2003), poses the question about the role of the mountains in southeast Brazil in shaping the circulation and precipitation anomalies. This question is addressed by the last experiment, in which the topography in east South America is limited to 100 m (experiment 0.5*SM−TOPO, Fig. 11). In the absence of the mountains in eastern South America, the response to reduced soil moisture is very different from that obtained in experiment 0.5*SM, and similar to that obtained for regions of flat topography in the above mentioned previous studies. Instead of a cyclonic anomaly over southeast Brazil, an anticyclonic anomaly develops with a center poleward of the region with reduced soil moisture (Fig. 11b). Rainfall is reduced in eastern Brazil, and increased in the subtropical plains to the south/southwest (Fig. 11c). The circulation anomalies indicate that the SACZ is shifted southward (Figs. 11b). Therefore, besides playing a role in the variability of the SACZ, the elevated terrain in southeast Brazil may play a role in the climatological location of the SACZ, by enhancing ascending motion and convergence.

There are aspects that can significantly influence regional model results, such as convective scheme, resolution, and domain (Seth and Rojas 2003). We per-

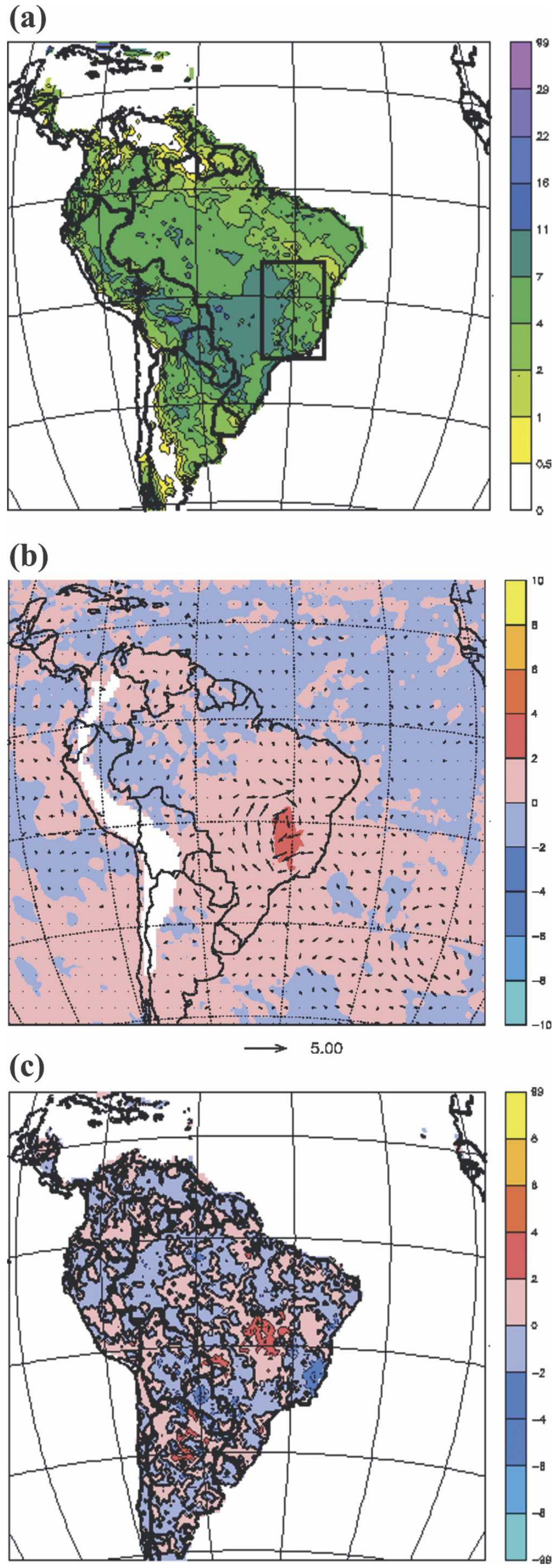

FIG. 8. (a) Precipitation (mm day^{-1}) for Jan 1998 from experiment 0.5*SM, (b) the difference from control for air temperature at 2 m (K) and winds at 850 hPa (m s^{-1}), and (c) the difference from the control for precipitation (mm day^{-1}).

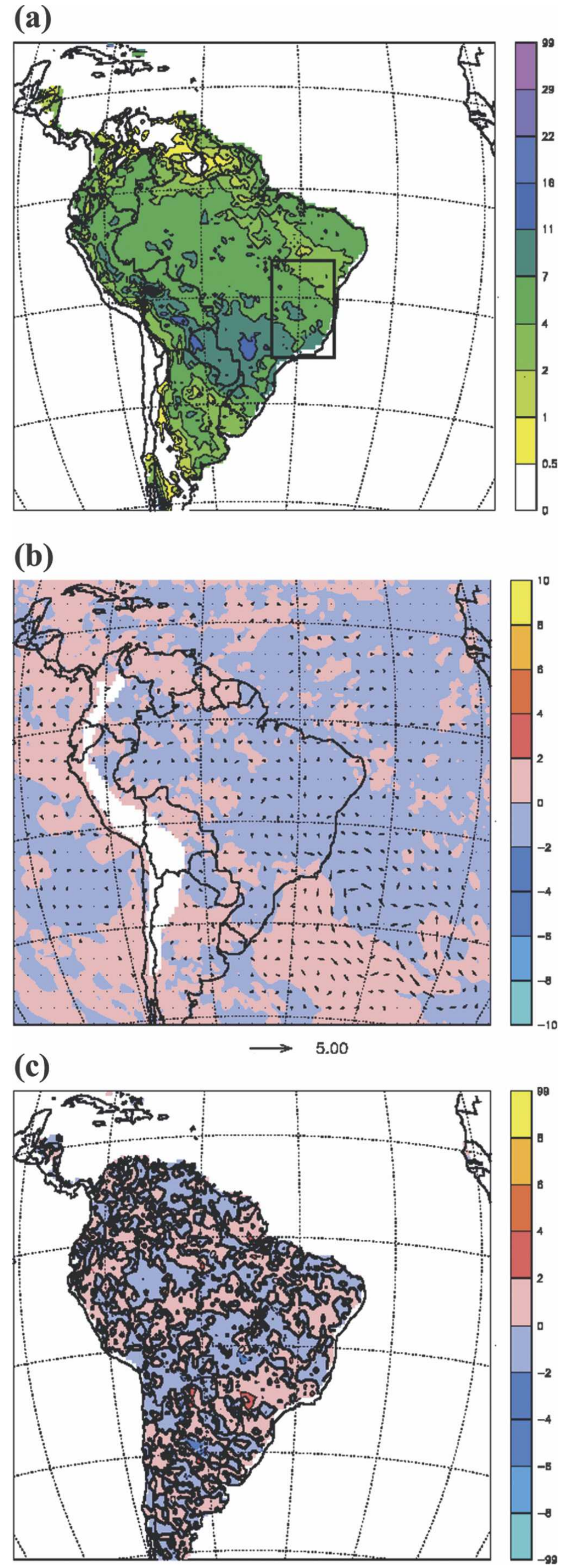

FIG. 9. Same as in Fig. 8, but from experiment 1.5*SM.

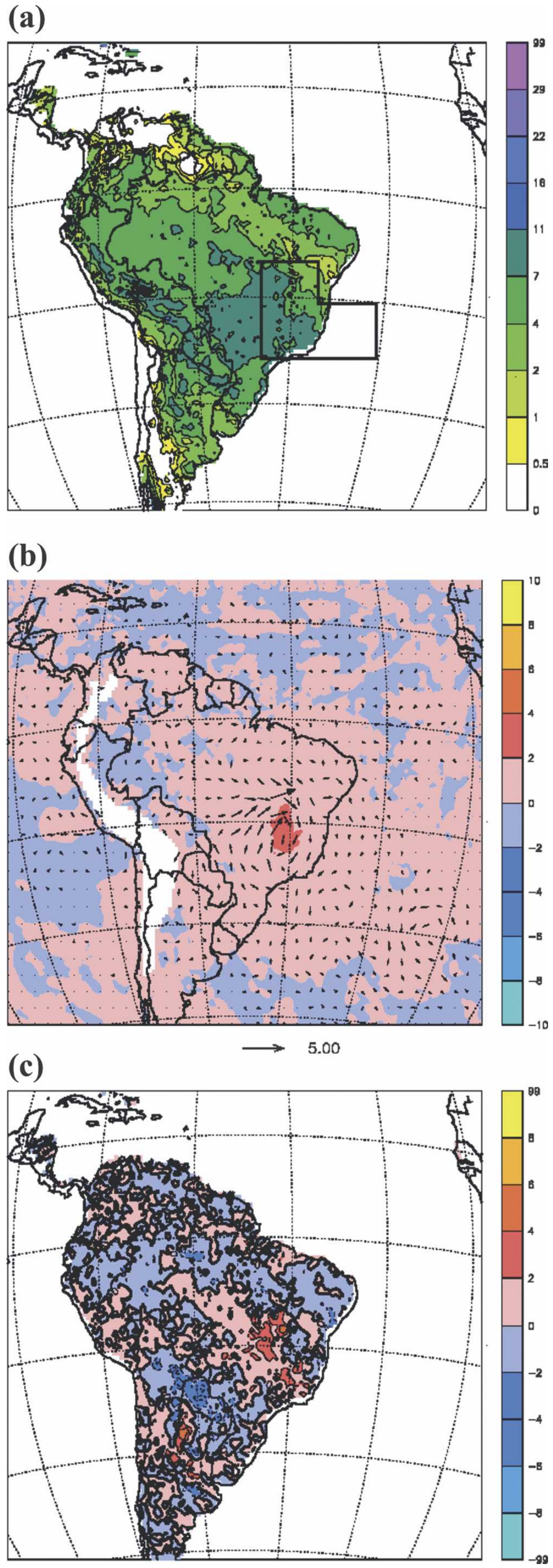

FIG. 10. Same as in Fig. 8, but from experiment 0.5*SM+SST.

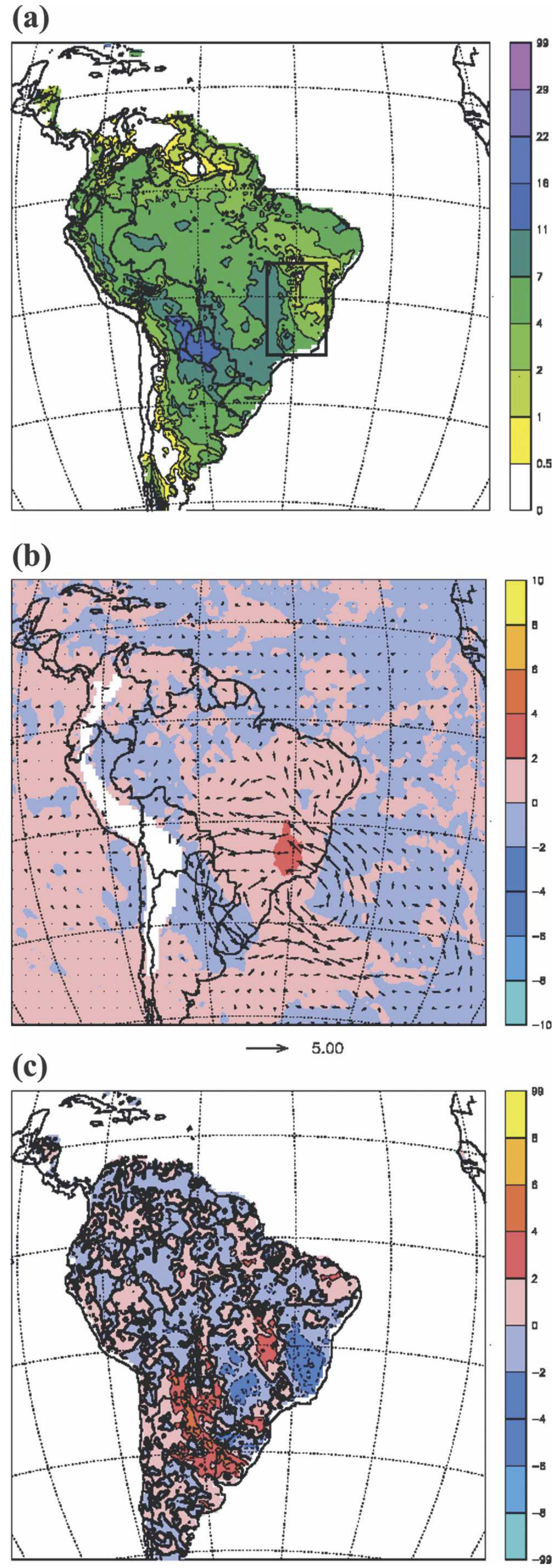

FIG. 11. Same as in Fig. 8, but from experiment 0.5*SM−TOPO.

formed a number of additional experiments using the Emanuel convection schemes with varying domain and resolution. The results of the experiments carried out for this study using the Grell and MIT convective schemes with slightly different domains and resolutions are consistent. However, when the domain is changed significantly by including less of the Pacific Ocean and North Atlantic and almost all the South Atlantic Ocean, the cyclonic pattern of experiments 0.5*SM and 0.5*SM+SST, and the anticyclonic pattern of experiment 0.5*SM−TOPO are shifted a few degrees northward, as are the precipitation anomalies. Although the reasons for this behavior are not clear, they might be associated with the fact that during ENSO events, especially over subtropical South America, circulation and precipitation anomalies are predominantly forced by the Pacific SST anomalies. The Atlantic SST anomalies are mainly a response to atmospheric anomalies forced by the Pacific Ocean, and their influence on the South America circulation seems to be limited to the coastal regions. Extending the domain over the Atlantic might favor the development of nonrealistic model circulations forced by SST, which may interfere with the South Atlantic high and the circulation over South America. Interference with boundaries may also be responsible for the observed differences.

As a result of these tests, the preliminary experiments presented here are not intended to be conclusive and their robustness should be further verified with a broader selection of cases, resolutions, and domains.

6. Discussion and conclusions

The reversal of precipitation anomalies from spring to summer in central-east Brazil is statistically significant over the entire period analyzed (Table 1), although it is more significant during ENSO years, probably because the precipitation anomalies set up in spring are much stronger and persistent than those in non-ENSO years. These anomalies might be able to produce, via soil moisture anomalies, impact on the subsequent circulation and precipitation anomalies in peak summer. Although we have not focused on the further reversal of anomalies observed during ENSO years from January to February–March (G03; G04), it is possible that a similar mechanism leads to dry (wet) conditions in late summer starting from the wet (dry) conditions in January, or simply that the anomalous conditions in January weaken and disappear due to the negative feedback.

During spring of El Niño events there are negative precipitation anomalies in north and central-east Brazil and positive ones in south Brazil and the surface temperature is warmer than normal over southeast Brazil. In January, there is a well-established anomalous low-level convergence and cyclonic anomaly over southeast Brazil, which directs moisture flux from northern Brazil toward central-east Brazil. Precipitation is enhanced in this region, while in southern Brazil it is reduced. In February, after the above-normal precipitation of January, the surface temperature anomalies in the southeast turn negative, the low-level cyclonic anomalies disappear and the precipitation anomalies diminish and reverse their sign. During the La Niña events, opposite anomalies are observed.

A surface–atmosphere feedback hypothesis, summarized in Figs. 12 and 13, is proposed to explain at least part of the inverse relationship between spring and peak summer precipitation anomalies. According to this hypothesis, dry conditions in central-east Brazil (including SACZ) during November are associated with less soil moisture and higher surface temperature in late spring. Besides, less cloudiness produces more net surface solar radiation and higher SST off the southeast Brazil coast. An anomalous surface thermal low sets up and, associated with the topographic effect in southeast Brazil, produces convergence and cyclonic circulation that directs moisture flux into central-east Brazil, where it converges, enhancing precipitation in this region in January. Initial wet conditions in spring lead to opposite anomalies.

Warm surface air and SST temperatures are correlated with simultaneous dry conditions in central-east Brazil during the monsoon season, but they may be important in leading to wet conditions. However, as soon as the cyclonic anomaly is set up and wet conditions start to prevail, the temperature drops, due to enhanced soil moisture, cloudiness and even southerly cold advection associated with the cyclonic anomaly. The convergence and cyclonic anomaly are still maintained for a while due to the tropospheric heating supplied by the cumulus [conditional instability of the second kind (CISK) mechanism], and this cyclonic anomaly will supply the necessary moisture into central-east Brazil. However, after a while, the cold surface temperature may lead to a weakening of the anomalies and to a reverse situation.

A diagnostic analysis confirmed the two main links in the hypothesis: the inverse relationship between spring precipitation and late spring surface temperature in central-east Brazil (Fig. 4), and the positive correlation between spring surface temperature in southeast Brazil and peak summer monsoon precipitation in central-east Brazil (Fig. 5). Although the relationship between spring precipitation and temperature in late spring holds practically over the entire central-east region, Fig. 5 shows that only the temperature in the southeast part

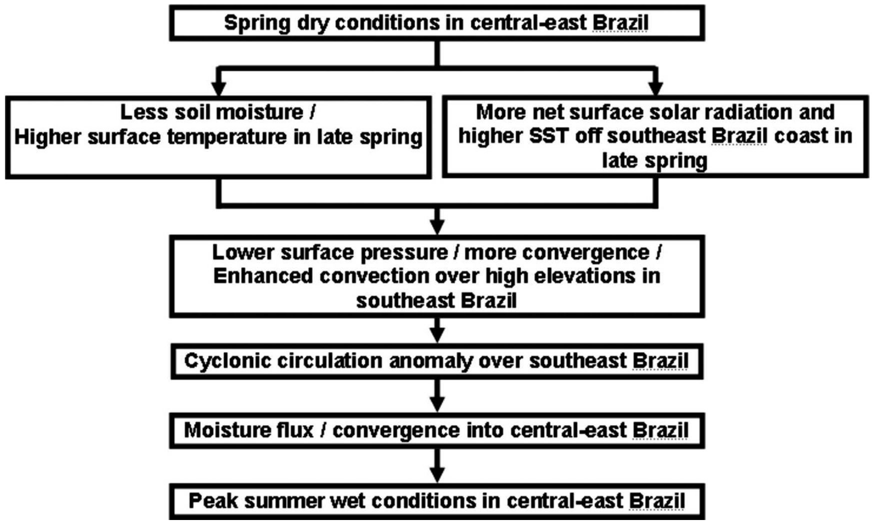

FIG. 12. Diagram of the pathway through which spring anomalous dry conditions may lead to subsequent peak summer wet conditions in central-east Brazil. The above diagram is also valid for opposite anomalies, starting from spring wet conditions in central-east Brazil.

is significantly related with excess rainfall in the region in January, which emphasizes the topographic effect in producing the circulation anomalies that lead to the rainfall anomalies.

The preliminary regional modeling sensitivity experiments performed in this study show that the intermediary links in the hypothesis (Fig. 12) are plausible, and lend support to the local forcing role in the intraseasonal modulation of precipitation. Reduced soil moisture in central-east Brazil is shown to increase surface temperature and produce a cyclonic anomaly over southeast Brazil, tending to increase precipitation in central-east Brazil. This output is enhanced if warmer SST is considered off the southeast coast of Brazil. Warm SST anomalies in this region are observed before enhanced precipitation in central-east Brazil (G03).

The anomalous low-level cyclonic circulation that develops in southeast Brazil under reduced soil moisture seems to be shaped by the topography. Most of the region is above 600 m and a large part of it is a chain of mountains above 1000 m, with several peaks above 2500 m. When the mountains are withdrawn, the circulation anomaly turns anticyclonic over the southern part of the region with reduced soil moisture, which happened in previous experiments for other regions with flat topography. The crucial role of the topography is clear when comparing Figs. 8 and 11, whose only difference is the topography. In both experiments anomalous easterly flow from the Atlantic Ocean enters the eastern coast of Brazil, in the subtropics. In the experiment with topography this flow is concentrated in southeast Brazil, and turns cyclonically around the highlands (Fig. 8). In the experiment without mountains the easterly flow crosses central Brazil and turns anticyclonically toward Paraguay, northern Argentina, southern Brazil, and Uruguay (Fig. 11). The impact on precipitation is also different.

Therefore, the mountains in southeast Brazil seem to have a key role in anchoring the patterns of intraseasonal variability, and may explain the geographically fixed precipitation "dipolelike" mode observed over South America (e.g., Nogués-Paegle and Mo 1997; Robertson and Mechoso 2000). They also seem to have an important role in anchoring the SACZ in its climatological position, for the experiment with reduced topography shows a very strong enhancement of the rainfall in the subtropical plains, much stronger than any other change in the previous experiments with changed soil moisture, indicating that the SACZ would be displaced southward in the absence of the mountains in southeast Brazil (cf. Fig. 11 with Figs. 8, 9, and 10).

The influence of soil moisture on the variation of monsoon precipitation is an example of the impact of local forcing, although in this case soil moisture does not have a local impact on precipitation as in Pal and Eltahir (2002). In that case, increased soil moisture enhances local convective precipitation via local processes involving the energy and water budgets. Here, the soil moisture anomaly induces circulation anomalies that are modified by the topographic effect and provide the moisture transport that produces the precipitation anomalies.

Recently, Zhu et al. (2005) tested a hypothesis that links the possible influence of antecedent land surface

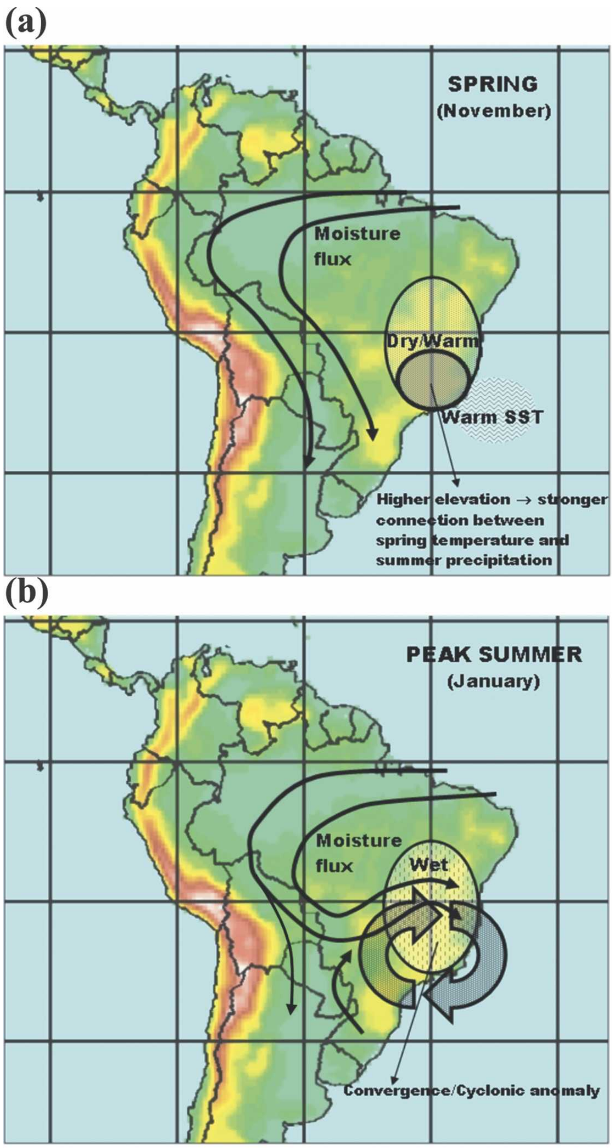

FIG. 13. Schematic evolution from (a) spring dry conditions to (b) peak summer wet conditions in central-east Brazil, through decreasing low-level pressure, convergence, and a cyclonic anomaly over southeast Brazil.

conditions on the intensity of the North American Monsoon. According to this hypothesis, winter precipitation leads to more winter and early spring snow water equivalent in an area in the southwestern United States, hence more spring and early summer soil moisture is expected, as well as lower spring and early summer surface air temperature. These conditions would feed back to the atmosphere and induce a weaker onset (and less rainfall) of the monsoon and vice versa. However, Zhu et al. (2005) did not find a significant soil moisture–surface temperature–precipitation relationship in most of the study area, and concluded that the local premonsoon land surface conditions such as soil moisture do not play an obvious role on the magnitude of the monsoon, at least not according to their hypothesis. In case of the SAMS, no similar relationship involving the snowpack has been proposed or observed. With the exception of the Andes region and some regions in southern South America, far from the core monsoon region over central South America, there are no regions covered with snow during winter. We demonstrated, however, an inverse relationship between precipitation in spring and summer in a region that composes part of the core monsoon region. There is also a significant positive relationship between surface temperature in spring over southeast Brazil and rainfall in central-east Brazil in peak summer. This relationship, however, does not involve just precipitation associated with local surface convergence triggered by a surface thermal low that sets up a pressure gradient that draws moisture from the adjacent ocean into the heated land, according to the hypothesis in Zhu et al. (2005). As a matter of fact, when precipitation is above normal in central-east Brazil most of the anomalous moisture flux does not come from the adjacent Atlantic Ocean, but from northern and central South America. The influence of the antecedent conditions manifests itself through a regional cyclonic (or anticyclonic) circulation anomaly around southeast Brazil that drives the moisture flow that comes from northern South America toward central-east Brazil (or toward Paraguay, northern Argentina, and southern Brazil). It is, therefore, a more indirect effect than that hypothesized in Zhu et al. (2005).

Several studies indicate low predictability of seasonal anomalies in central-east Brazil during austral summer (e.g., Marengo et al. 2003). Perhaps this low predictability might be partially ascribed to the fact that the models do not reproduce well the land–atmosphere interactions that are important for the variability in that region, as well as important characteristics of the topography.

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