Seasonal-to-Decadal Predictability and Prediction of South American Climate

P. NOBRE, J. A. MARENGO, I. F. A. CAVALCANTI, AND G. OBREGON
CPTEC/INPE, Cachoeira Paulista, Brazil

V. BARROS AND I. CAMILLONI
UBA/CIMA, CONICET_UBA, Buenos Aires, Argentina

N. CAMPOS AND A. G. FERREIRA
FUNCEME, Fortaleza, Brazil

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ABSTRACT

The dynamical basis for seasonal to decadal climate predictions and predictability over South America is reviewed. It is shown that, while global tropical SSTs affect both predictability and predictions over South America, the current lack of SST predictability over the tropical Atlantic represents a limiting factor to seasonal climate predictions over some parts of the continent. The model's skill varies with the continental region: the highest skill is found in the "Nordeste" region and the lowest skill over southeastern Brazil. It is also suggested that current two-tier approaches to predict seasonal climate variations might represent a major limitation to forecast coupled ocean–atmosphere phenomena like the South Atlantic convergence zone. Also discussed are the possible effects of global climate change on regional predictability of seasonal climate.

1. Introduction

The variability of the South American climate shows interesting characteristics. The largest fraction of the continent lies within the Tropics, where seasonal climate predictability is higher compared to midlatitudes (Koster et al. 2000; Marengo et al. 2003). Also, South America encompasses important geographical features such as the Amazon rain forest, which covers a considerable fraction of the continental area and contributes to the existence of an important source of upper-level mass and heat at low latitudes, thus impacting both the general circulation of the atmosphere and the local climate (Buchmann et al. 1995). South America is also subject to the effects of two atmospheric convergence zones: the intertropical convergence zone (ITCZ) and the South Atlantic convergence zone (SACZ). The ITCZ is modulated in part by surface features, like the interhemispheric gradient of SST anomalies (SSTAs) over the equatorial Atlantic (Hastenrath and Druyan 1993; Wagner 1996; Chang et al. 2000), and it modulates the interannual variability of seasonal rainfall over north-central Amazonia and the northern portion of northeast Brazil (called also the Nordeste) (Hastenrath and Heller 1977; Moura and Shukla 1981; Marengo 1992; Nobre and Shukla 1996).

Atmospheric general circulation models (AGCMs) simulate the seasonal rainfall interannual variability over the Nordeste strikingly well when observed SST in the global Tropics are prescribed as lower boundary conditions, especially during El Niño years (Goddard and Mason 2002; Marengo et al. 2003). The oceanic extension of SACZ, on the other hand, is also influenced by SSTA over the southwestern tropical Atlantic, has a strong impact on the rainfall regime over the southern Nordeste, southeast, and southern Brazil and contributes to modulate underlying SSTs over the southwest tropical Atlantic (Chaves and Nobre 2004).

Previous studies have identified the role of remote SST forcing in the west Pacific during austral summer on the position of the SACZ (Liebmann et al. 1999),

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Corresponding author address: Dr. Paulo Nobre, Rodovia Presidente Dutra, Km 40, Cachoeira Paulista, SP 12630-000, Brazil.
E-mail: pnobre@cptec.inpe.br

while the Amazon basin as a source of moisture seems to be important for the intensity of the SACZ (Figueroa et al. 1995). In contrast to the ITCZ, however, the SACZ is observed predominantly over areas with negative SSTA (Robertson and Mechoso 2000), suggesting that atmospheric-forcing coupling is operative at zero lag. AGCM simulations show near zero or even negative skill in the SACZ region (Marengo et al. 2003). The high reproducibility by AGCMs of seasonal rainfall interannual variability over the Nordeste contrasts sharply with the low reproducibility over south eastern Brazil, indicating that different processes should be operating to modulate seasonal rainfall over those regions.

On longer time scales, from decades to centennial, South America also plays an important role in the climate system. This is primarily because of the carbon sink in the Amazon forest in today's CO_2-rich atmosphere. Yet, recent global climate change research indicates that the capacity of tropical and temperate forests to grow—and therefore to extract carbon dioxide from the atmosphere through photosynthesis—as temperature increases has a threshold beyond which the biological systems breakdown and start liberating large amounts of CO_2 and other greenhouse gases into the atmosphere (Cox et al. 2001). It is not yet known to what extent seasonal climate predictability will change on regional scales in a scenario of global climate change: whether it will increase (in the case of increased dryness over semiarid regions) or diminish (e.g., in the case of increased frequency of extreme events on a warmer and more humid atmosphere) as a consequence of climate change, both natural and anthropogenic. In any case, the prospects of regional climate change are robust enough to justify a continuous scientific undertaking to improving the models and monitoring the environment, aiming at helping society to learn to adapt to a changing climate.

The goal of this paper is to review the current knowledge concerning predictability and predictions of South American climate on interannual and longer time scales. The structure of the paper is as follows: section 2 describes the principal processes that modulate seasonal climate predictability over South America. In section 3, regional climate variability and change are discussed. The state of the art on predictions and predictability over South America are discussed in section 4. Further research and data needs are described in section 5 and conclusions presented in section 6.

2. The physical basis for South American seasonal climate predictability

Seasonal to interannual and longer climate variability has two components: (i) the externally forced component, which is the response to slowly varying external boundary forcing (SST, sea ice, albedo, soil moisture, and snow coverage) and radiative forcing (greenhouse gases and aerosol concentration), and (ii) the internally forced component, which is the atmospheric variability induced by internal dynamics and the daily weather variations or by strong land surface feedbacks due to land surface processes (Brankovic et al. 1994; Koster et al. 2000; Zheng and Fredericksen 1999). Also, the climatic variability of a region can be strongly influenced through teleconnection patterns originated by anomalies in distant regions, such as in the El Niño–Southern Oscillation (ENSO), Pacific–North America (PNA), Pacific–South America (PSA), or the North Atlantic Oscillation (NAO) phenomena.

Predictability is seen to be high in tropical regions of South America where the models respond well to the SST forcing. Model simulations discussions in Brankovic and Palmer (1997), Carson (1998), Sperber and Palmer (1996), Sperber et al. (1999), and Marengo et al. (2003) show high skill for northeast Brazil. High values of correlations between model and observed precipitation anomalies are also seen in northeast Brazil and northern region of South America in simulations with the CPTEC/COLA AGCM (Cavalcanti et al. 2002a; Marengo et al. 2003).

Over South America, rainfall anomalies over eastern central Amazonia and the Nordeste appear to be the opposite to regions such as southern Brazil in ENSO years (Ropelewski and Halpert 1987), and all of those regions are sensitive to SST anomalies both over the tropical Atlantic and in the equatorial Pacific. On the other hand, the tropical Atlantic interhemispheric SST gradient has a strong influence on precipitation in the Nordeste and Amazonia (Moura and Shukla 1981; Mechoso et al. 1988, 1990; Marengo 1992; Hastenrath and Greischar 1993; Uvo et al. 1998; Folland et al. 2001; Cavalcanti et al. 2002b). The SST gradient between the tropical North and South Atlantic is the key element associated with rainfall anomalies during austral summer and autumn in the Amazon and Nordeste. The ENSO signal on observed precipitation anomalies over southern Brazil seems to be weaker in summer than in spring and exhibits considerable spatial variability (Grimm et al. 2000). Moreover, there are variations in the precipitation anomalies over South America among different ENSO warm events or among different ENSO cold events that cannot be clearly associated with the variability of the tropical Pacific SST anomalies solely (Marengo et al. 1998).

The interannual variability simulated by the Centro de Previsão de Tempo e Estudos Climáticos/Center for Ocean–Land–Atmosphere Studies (CPTEC/COLA)

AGCM has been examined in several studies (Marengo et al. 2003; Cavalcanti et al. 2002a; and references therein). In these studies, the tropical SST forcing together with the regional land surface processes forcing contribute to the seasonal to interannual climate variability in the northern coast of Peru–Ecuador, southern Chile, and in tropical South America to the east of the Andes, with the notable exception of southeastern Brazil where prescribed SST forcing has been shown to be unable to simulate SACZ variability. The interannual variability of the Southern Oscillation index, which reflects the SST forcing in the tropical Pacific, is very well simulated by the model (Cavalcanti et al. 2002a). The model ability in reproducing ENSO features has a large influence on prediction for northeastern and southern regions of South America, as will be discussed in the next sections.

a. *Northern South America: Amazonia and the Nordeste*

Enfield and Mayer (1997), Enfield and Alfaro (1999), and Martis et al. (2002) have identified the relative influence of the eastern Pacific (ENSO) and equatorial Atlantic SST on rainfall over the Caribbean and northern South America. Tropical Pacific SST forcing correlates well with rainfall and river discharge anomalies in the northern Amazonia–Nordeste region, in Colombia, and southern Brazil–Argentina (Marengo 1992; Poveda and Mesa 1997; Uvo et al. 1998; Grimm et al. 2000; Marengo et al. 2003). Earlier empirical studies using correlations between rainfall in Amazonia and SST indices in the tropical Pacific suggests that SST anomalies in the tropical Pacific Ocean account for less than 40% of the rainfall variability in northern and central Amazonia (Marengo 1992).

SST anomalies in the tropical Atlantic Ocean affect the meridional position of the ITCZ and thus the interannual variability of rainfall in the Nordeste (Hastenrath and Heller 1977; Moura and Shukla 1981; Wagner 1996; Nobre and Shukla 1996; Folland et al. 2001). Based on previous studies using the CPTEC/COLA AGCM simulations (Marengo et al. 2003; Cavalcanti et al. 2002a), as well as from other GCMs used for seasonal predictions issued by other meteorological centers (Barnston et al. 2003), the seasonal rainfall anomaly correlation maps in Fig. 1 show that Amazonia, the Nordeste, and northwest Peru–Ecuador exhibit seasonal predictability that can be characterized as medium to high.

Land surface characteristics and processes also serve as slowly varying boundary conditions on climate simulations. Realistic representation of land surface–atmosphere interactions is essential to a realistic simulation and prediction of continental-scale climate and hydrology. Experiments on changes in land surface, such as regional and large-scale deforestation in the Amazon basin developed during the last 20 years [see reviews in Marengo and Nobre (2001) and Costa and Foley (2000)] have identified the sensitivity of rainfall to changes in vegetation and soil moisture conditions in the region, even though those models did not exhibit a representation of a dynamic vegetation embedded in the parameterization of land surface processes. Koster et al. (2000) suggest that both in the real world and the modeling system, the "memory" associated with continental moisture and the limited ability to forecast land surface moisture state reduces predictability in some regions of South America, specifically southeastern Brazil and the southern Amazonia–South American monsoon region.

Experiments using the CPTEC/COLA AGCM (Marengo et al. 2003) show that the model systematically underestimates rainfall during the January–May peak of the rainy season in Amazonia. The underestimation of rainfall in northern central Amazonia is found in other global models as well: Goddard Institute for Space Studies (GISS: Marengo and Druyan 1994), Geophysical Fluid Dynamics Laboratory (GFDL; Stern and Miyakoda 1995); European Centre for Medium-Range Weather Forecasts (ECMWF: Brankovic and Palmer 1997); National Center for Atmospheric Research Community Climate Model version 3 (NCAR CCM3: Hurrell et al. 1998), and the Third Hadley Centre Coupled Ocean–Atmosphere General Circulation Model (HadCM3: Cox et al. 2001), and deficiencies were linked to the convection and planetary boundary layer schemes in various models.

In the adjacent Nordeste, the CPTEC/COLA AGCM tends to overestimate rainfall systematically. Yet, the model depicts a realistic annual cycle and interannual variability of rainfall anomalies. The large-scale forcing associated with large SST anomalies in the equatorial Pacific during El Niño determines a quite realistic simulation of rainfall anomalies over the Nordeste. The model reproduced the low rainfall amounts in this region during the 1983 and 1987 El Niño events and excess of precipitation during the 1985 and 1989 La Niña events (Marengo et al. 2003). The Nordeste drought in March–May (MAM) 1998 was well predicted by the model, while in normal years the prediction is not as successful as during the extreme ENSO years.

These simulations from the CPTEC/COLA AGCM are comparable to the interannual variability of rainfall in the Nordeste, discussed in Folland et al. (2001) and the original and revised Atmospheric Model Intercomparison Project (AMIP) simulations by Sperber et al.

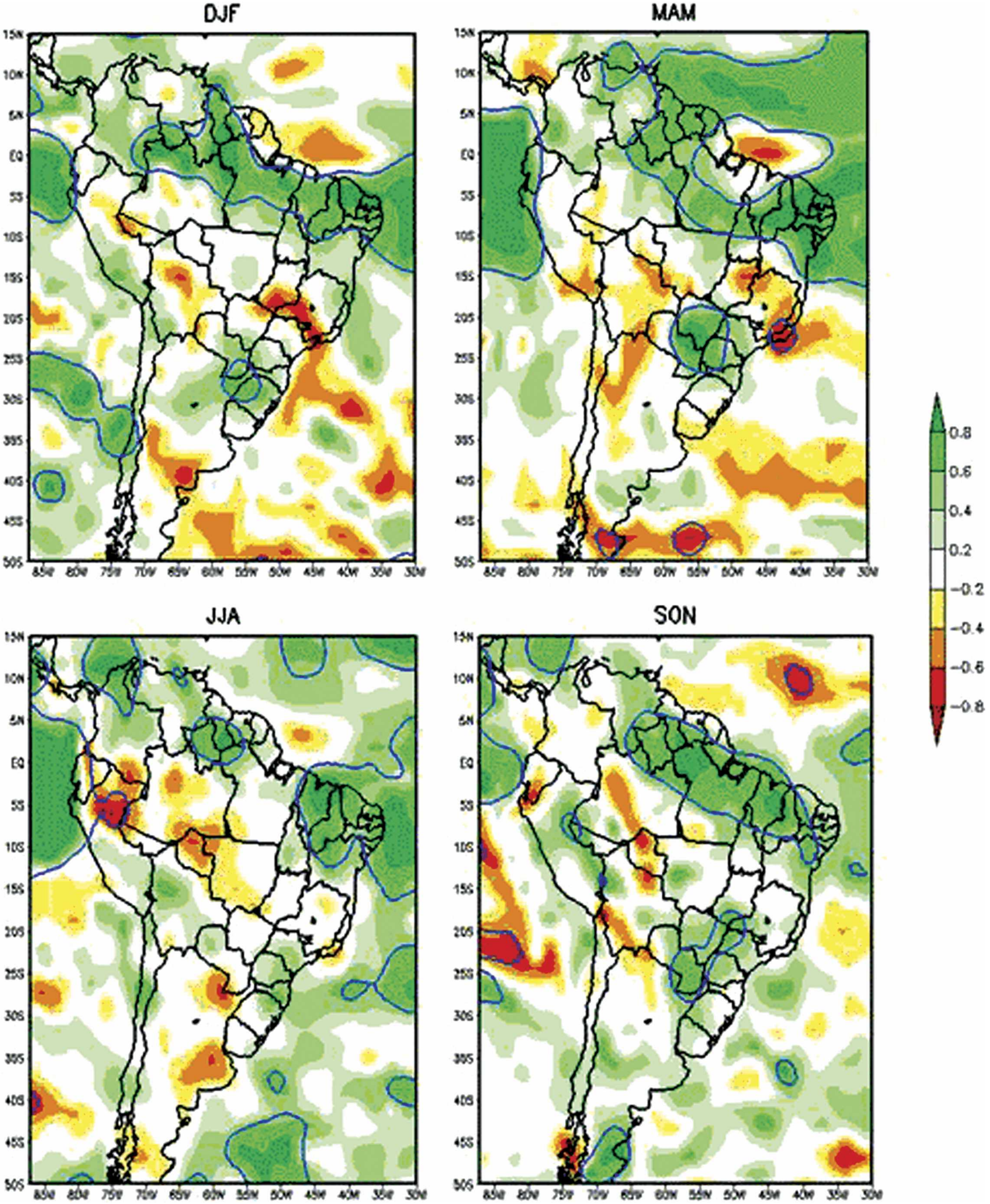

FIG. 1. Ensemble mean seasonal rainfall anomaly correlation maps between the CPTEC/COLA AGCM and observation [Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP)] for (a) December–February (DJF), (b) March–May (MAM), (c) June–August (JJA), and (d) September–November (SON). Color scale shows the values of correlations. The area inside the blue line represents regions where the correlation coefficients reached significance at the 99% level (Marengo et al. 2003).

(1999), with all of them showing negative rainfall departures during 1983, 1987, and 1990 and large positive rainfall departures during 1985 and 1989. The deterministic and probabilistic scores presented for this region as derived by Sperber et al. (1999), Goddard et al. (2001), and Marengo et al. (2003) also demonstrate a good skill in simulating rainfall anomalies at interannual time scales.

b. Southeastern and southern Brazil

The southern and southeastern regions of Brazil are highly populated, with large agricultural areas and high hydroelectrical power capacity. These regions are affected by climate anomalies associated with interannual and intraseasonal atmospheric variability. On the interannual scale, the ENSO phenomenon over the equatorial Pacific is related to floods and droughts in the southern region. The anomalous wet or dry ENSO years in southern Brazil, simulated by the CPTEC/COLA AGCM, occur with opposite sign of the seasonal rainfall anomalies over the Nordeste (Cavalcanti et al. 2001). The CPTEC/COLA AGCM represents well the north–south precipitation dipole of El Niño 1982/83 and La Niña 1988/89 (Rodriguez and Cavalcanti 2006). Southeastern Brazil and the southern Amazonia–South American monsoon, on the other hand, are regions that exhibit relatively low seasonal climate predictability skill, as they are a transition area between the Nordeste and southern Brazil, two regions with medium to high seasonal climate predictability with a clear sign related to ENSO. The southeastern Brazil region is affected by intraseasonal variability or land surface feedbacks that play a role in the summer season convection. Although the model represents several features of intraseasonal variability (Cavalcanti and Castro 2003), this mode of variability is very weak in the three-month forecast of the ensemble mean.

The dependence of rainfall variability over these regions to extreme SST forcing in tropical oceans is better documented and established for southern Brazil as compared to southeastern Brazil (see reviews in Marengo et al. 2003). The circulation anomalies over southeastern Brazil in the spring of El Niño years are mostly due to remote influences from the tropical east Pacific, as shown by Grimm et al. (1998). The influence of the PSA pattern on SACZ convection in austral summer has been discussed in many studies, such as Liebmann et al. (1999), Nogués-Paegle et al. (2000), Mo and Nogués-Paegle (2001), and Castro and Cavalcanti (2003). In this season, which comprises the peak of the annual cycle in the South American monsoon region, the local effects, such as land surface processes and soil moisture, have large contributions (Pisciottano et al. 1994; Marengo et al. 2003; Koster et al. 2000). Chaves and Nobre (2004) used an atmospheric and an oceanic GCM to study the feedback processes linking SST and SACZ variability. Their results suggest that the frequently observed negative SSTA under the SACZ (Robertson and Mechoso 2000) is predominantly an ocean response to the reduction of downward solar radiation due to increased cloudiness during the formation of the SACZ. Their results thus support the speculation that the poor performance of AGCM simulations over the SACZ region is the consequence of the lack of coupled interactions between SST and the model atmosphere in this region. Recent work developed with CPTEC's fully coupled ocean–atmosphere model (P. Nobre 2005, unpublished manuscript) suggests that coupled ocean–atmosphere models can improve austral summer rainfall predictions over the SACZ area. Whether the higher skill presented by the coupled GCM is due to local ocean–atmosphere interactions or due to remote signals in the coupled model is still unknown.

Koster et al. (2000) focuses their analyses on precipitation variance and they analyze the contributions of ocean, atmosphere, and land processes using a simple linear model. The resulting clean separation of the contributions leads to the conclusion that land and ocean processes have essentially different domains of influence; that is, the amplification of precipitation variance by land–atmosphere feedback is most important for regions such as southeast Brazil and the South American monsoon, while for the Tropics (Amazonia and the Nordeste) rainfall variance is more affected by SSTA. This is also true for southern Brazil. Yet, SSTA predictions over the southern tropical Atlantic one season in advance can barely beat the skill of persistence. Figure 2 shows the anomaly correlation maps of SSTA forecasts for MAM as the persistence of SSTA from December, January, and February. As the result of a canonical correlation analysis (CCA) prediction scheme developed by Repelli and Nobre (2004); the authors show that the higher skill of the CCA predictions over the northern tropical Atlantic is due in part to teleconnections from the equatorial Pacific ENSO.

The relative influence of the Pacific and Atlantic Oceans on South American precipitation was analyzed in Pezzi and Cavalcanti (2001). Composites of SST from strong ENSO episodes and strong "Atlantic dipole conditions" were combined to integrate the CPTEC/COLA AGCM in order to factor the Pacific and Atlantic Ocean influences on the South America precipitation regimes. Although the method does not completely separate the contributions from each ocean basin, due to the known correlations between the equa-

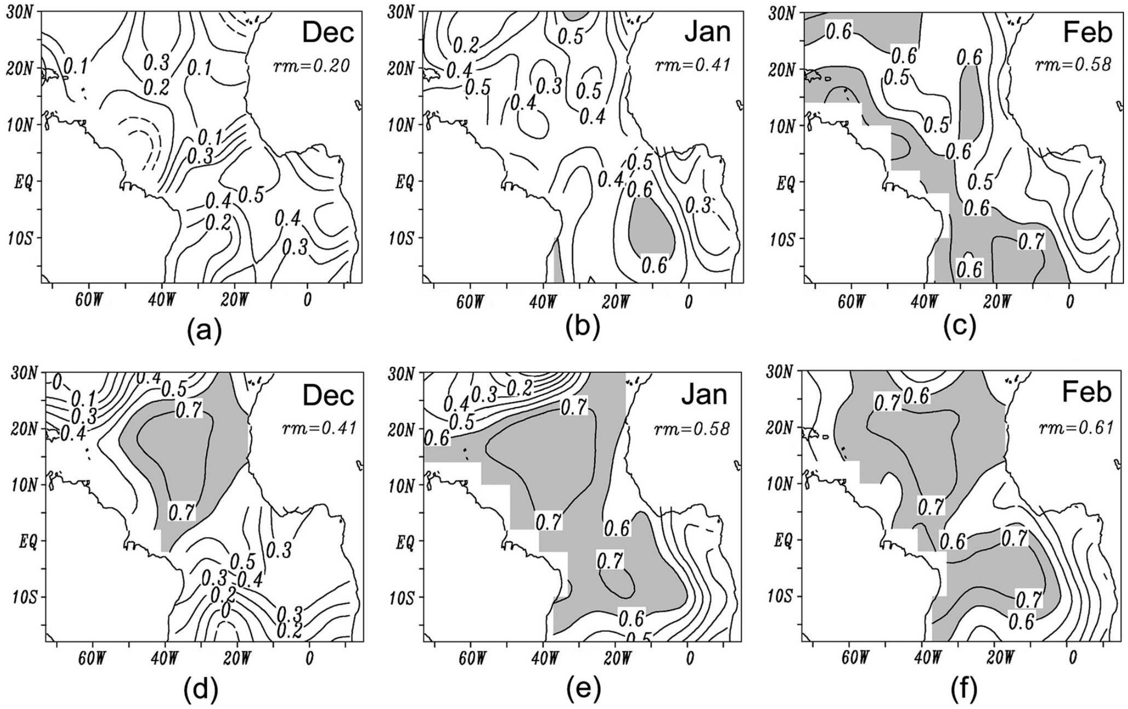

FIG. 2. Anomaly correlation maps between predicted and observed SSTA over the tropical Atlantic for (a)–(c) persistence of SSTA from the month of initial condition and (d)–(f) for the CCA scheme. Month of initial condition and area mean correlations are stated in the upper-right corner of each panel. Adapted from Repelli and Nobre (2004).

torial Pacific and northern tropical Atlantic SST variability (Enfield and Mayer 1997; Chiang and Vimont 2004), it indicated that the Pacific was dominant in inhibiting convection over southern and southeastern Brazil. Yet, the northern portion of the Nordeste was affected by the Atlantic Ocean when there was anomalous warm water in the tropical South Atlantic, even in a strong El Niño episode. In La Niña episodes, the Atlantic SST was the dominant forcing to establish excess (warm South Atlantic Ocean) or deficit (cold South Atlantic Ocean) precipitation over the Nordeste.

c. *Northern and eastern Argentina, Paraguay, and Uruguay*

Northern Argentina and Paraguay are regions with frequent mesoscale convective systems (MCSs) (Velasco and Fritsch 1987). Unlike other subtropical regions, their occurrence extends until autumn and the percentage of precipitation caused by them is determinant for the total seasonal amounts. MCS systems are associated with the low level jet (LLJ) east of the Andes (Marengo et al. 2004), which brings humidity from the Atlantic and Amazonian region southward. Analysis from the CPTEC/COLA 10-yr simulation shows the model ability in simulating features of this LLJ (Cavalcanti et al. 2002c). On the other hand, eastern Argentina and Uruguay are affected by frequent synoptic systems such as cold fronts and extratropical cyclonic vortices. These regions are also affected by intraseasonal variability associated with the PSA pattern, which is weakly represented in model simulations. This could be one of the reasons why the operational prediction systems used both in Argentina and Uruguay have been hardly successful for seasonal prediction, especially in years when the forcing provided by SST anomalies in the tropical oceans is weak. This is in contrast to the potentially high seasonal climate predictability over subtropical Argentina and Uruguay during ENSO years.

In the La Plata–Paraná Basin, results from a 10-yr climatology, nine-member ensemble of the CPTEC AGCM (Marengo et al. 2003) show that, despite the large scatter among members of the ensemble, the model captures quite well the extremes of the observed interannual rainfall variability, especially the above-normal values observed in 1983 and 1998 and the drought conditions in 1989. This also has been noticed in other AGCMs. The annual cycle of rainfall is well reproduced with some underestimation of rainfall during summer and autumn, mainly due to "artificial" overestimation of rainfall along the SACZ in the upper basin (Marengo 2005). The simulated rainfall by four Intergovernmental Panel on Climate Change

(IPCC) coupled ocean–atmosphere GCMs [HadCM3, ECHAM4/Ocean Isopycnal model (OPYC3), GFDL-R30, Commonwealth Scientific and Industrial Research Organisation Mark version 3.0 (CSIRO-Mk2)] shows the systematic underestimation over southeastern South America on interannual time scales and the overestimation over the continental SACZ region also (Camilloni and Bidegain 2005). This has allowed for "statistical" corrections of simulated rainfall with the purpose of applications in water resources, as in the Uruguay River basin (Tucci et al. 2003).

The connection between South Atlantic SSTA and precipitation in the region has received less attention than the ENSO link. However, literature abounds with respect to the SACZ. Nogués-Paegle and Mo (1997) found evidence of a seesaw pattern in the convection over the SACZ, with each phase lasting no more than 10 days, and that the intensification (weakening) of the SACZ is associated with a rainfall deficit (abundance) over the subtropical plains of South America, including eastern Argentina and Uruguay. Doyle and Barros (2002) showed that this dipole behavior appears also as a distinctive feature of the interannual variability of rainfall and that, in western Argentina, precipitation tends to vary in phase with SACZ rainfall. Gandu and Silva Dias (1998) explored the physics of this dipole with numerical experiments, showing that a strong SACZ activity is associated with enhanced subsidence to the south of it.

Barros et al. (2000) found that, during summer, both the intensity and position of the SACZ are related to the SST to the south of it, being displaced northward (southward) and more intense (weaker) with cold (warm) SST anomalies. However, this relation does not mean that SST governs the SACZ variability. There is evidence that phases of the SACZ respond to Rossby wave activity (Liebmann et al. 1999; Robertson and Mechoso 2000) and to the MJO (Carvalho et al. 2004). However, a numerical experiment shows that there is a positive feedback between cold SST in the subtropical South Atlantic and intense SACZ activity (Robertson et al. 2003), and therefore the SST influence on the SACZ, and consequently on the subtropical rainfall, cannot be discarded.

The SACZ connection between SST and rainfall in subtropical Argentina and Uruguay could be one of the mechanisms that relate the interannual variability of SST in the South Atlantic with precipitation in those countries. This relation was studied by Diaz et al. (1998), finding the existence of an association between wet (dry) rainfall anomalies in the northern sector of Uruguay and southern Brazil and warm (cold) SST anomalies in the SACZ region and the equatorial Atlantic in the November–February period.

Doyle and Barros (2002) found that the midsummer interannual variability of the low-level tropospheric circulation and of the precipitation field in subtropical South America is associated with the SST anomalies in the western subtropical South Atlantic Ocean. Composites corresponding to extreme SSTs in the area 20°–30°S, 30°–50°W suggest the existence of two different low-level circulation and precipitation patterns. Recent studies have identified that, when the moisture transport from the Amazon region to the La Plata Basin by the summertime LLJ east of the Andes is weak/strong, the SACZ is strong/weak (Herdies et al. 2002; Marengo 2004).

The aforementioned studies reveal the potential importance of the South Atlantic in the region's climate variability on seasonal to interannual time scales. However, since the SACZ also responds to remote atmospheric forcings, the predictability of the regional climate based on South Atlantic SSTs is still an issue that requires further research.

3. Regional climate variability and change scenarios

Analysis of climate variations during the instrumental period (since 1850) and evidence inferred by paleoclimatic and other proxy climate information suggests that climate variations and change have been found in several regions in Latin America. Most climate records covering the past century have indicated multidecadal and interannual variability, some linked to extremes of the Southern Oscillation or to decadal-scale variability in the Pacific and tropical Atlantic sectors (Zhang et al. 1997; Wagner 1996). The lack of continuous and long-term records from the past does not allow one to identify climate patterns with a high degree of confidence to determine whether these climates were similar to or much different from that of present times—particularly with respect to the frequency and intensity of extreme events such as drought, floods, freezes, heat waves, and especially hurricanes and tropical storms. However, multidecadal variations have been identified in rainfall and streamflow records in the region, although no clear unidirectional trend indicators of climate change have been identified (Barros and Doyle 1997; Houghton 2001, and references therein; Marengo 2004).

For South America, the present 1961–90 climate simulated by five IPCC coupled ocean–atmosphere GCMs [Canadian Centre for Climate Modelling and Analysis (CCCma), CSIRO-Mk2, GFDL-R30, HadCM3, and Center for Climate System Research/National Institute for Environmental Studies in Japan (CCSR/NIES)] is shown, in Fig. 3, in the form of deviations for annual rainfall with respect to the Climatic Research Unit (CRU) observations. All models show different biases, some of them systematic along the year, especially in regions such as Amazonia and the Paraná–La Plata Basin. All five models show negative rainfall biases in southern Brazil, northeastern Argentina, and Uruguay, while negative biases are shown in the eastern Amazonia region by the GFDL-R30, HadCM3, and CCSR/NIES and in northern and central Amazonia by the CCCma, CSIRO-Mk2, HadCM3, and CCSR/NIES models. Interestingly, all models show rainfall simulations in very close agreement with observations in northeast Brazil. In the present climate, the observed annual cycle of rainfall is well reproduced by the five IPCC models for most of South America east of the Andes (Marengo 2005).

Is climate variability likely to change regionally?

Presently, there are many more atmosphere–ocean coupled GCM projections of future climate available than in the past. We concentrate on the Special Report on Emissions Scenarios (SRES) contrasting A2 (high emissions) and B2 (low emissions) scenarios of the IPCC Third Assessment Report (Houghton et al. 2001) for South America. Results of experiments using those climate change scenarios show that most tropical areas have increased mean air temperature, while the signal in precipitation is not clear with some models showing rainfall reductions or increases. In addition, some of these models, such as the HadCM3 suggest a general drying trend of the midcontinental tropical areas over South America, east of the Andes during summer and spring (decreases in soil moisture). In southern Brazil, the models simulate small increases in rainfall, which would not be enough to produce soil moisture storage because of an increase of potential evaporation due to large increases in air temperature in the region. Seasonal rainfall distribution is unlikely to change in terms of the maximum of the rainy season, but it is possible that the length of the "dry season" in regions such as the La Plata Basin or Amazonia (months with precipitation of 100 mm) may be larger in future warm climates. Climate change scenarios for Argentina and Uruguay derived from the HadCM3 model for the A2 and B2 emission scenarios suggest a regional warming between 1.5° and 5°C for the 2080s with the largest values in northern Argentina and the lower ones in Patagonia. Rainfall scenarios for the same time slice show relatively small changes with increases between 0.2 and 0.8 mm day^{-1} in northeastern Argentina and negative changes in central–western Argentina (Camilloni and Bidegain 2005).

The capability of models to simulate the large-scale variability of climate, such as the ENSO (a major source of global interannual variability) has improved substantially in recent years, with an increase in the number and quality of coupled ocean–atmosphere models and with the running of multicentury experiments and multimember ensembles of integrations for a given climate forcing. The IPCC Third Assessment Report (Houghton et al. 2001) indicates that the results from these models must still be treated with caution as they cannot capture the full complexity of these structures, due in part to the coarse resolution in both the atmosphere and oceans of the majority of the models used, which in part are responsible for some severe systematic errors of surface variables, still present particularly over the eastern equatorial Atlantic of the coupled simulations.

The future climate as projected by the HadCM3 shows a mean Pacific climate base state that resembles an El Niño–like state (i.e., a slackened west to east SST gradient with associated eastward shifts of precipitation and dry conditions in tropical South America east of the Andes). While this is shown in several studies based on the HadCM3 (Cox et al. 2000, 2004; Betts et al. 2004), it is not true for all other IPCC models. Decadal and longer time-scale variability complicates assessment of future changes in individual ENSO event amplitude and frequency. Assessment of such possible changes remains quite difficult. The changes in both the mean and variability of ENSO are still model dependent. Finally, there are areas where there is no clear indication of possible changes or no consensus on model predictions.

Although many models show an El Niño–like change in the mean state of tropical Pacific SSTs, not all models show this ENSO-like variability, and the cause is uncertain. In some models it has been related to changes in cloud forcing and/or changes in the evaporative damping of the east–west SST gradient, but the result remains model dependent. For such an El Niño–like climate change, future seasonal precipitation extremes associated with a given ENSO would be more intense due to the warmer mean base state. There is still a lack of consistency in the analysis techniques used for studying circulation statistics (such as the North Atlantic Oscillation), and it is likely that this is part of the reason for the lack of consensus from the models in predictions of changes in such events.

The possibility that climate change may be expressed as a change in the frequency or structure of naturally occurring modes of low-frequency variability has been

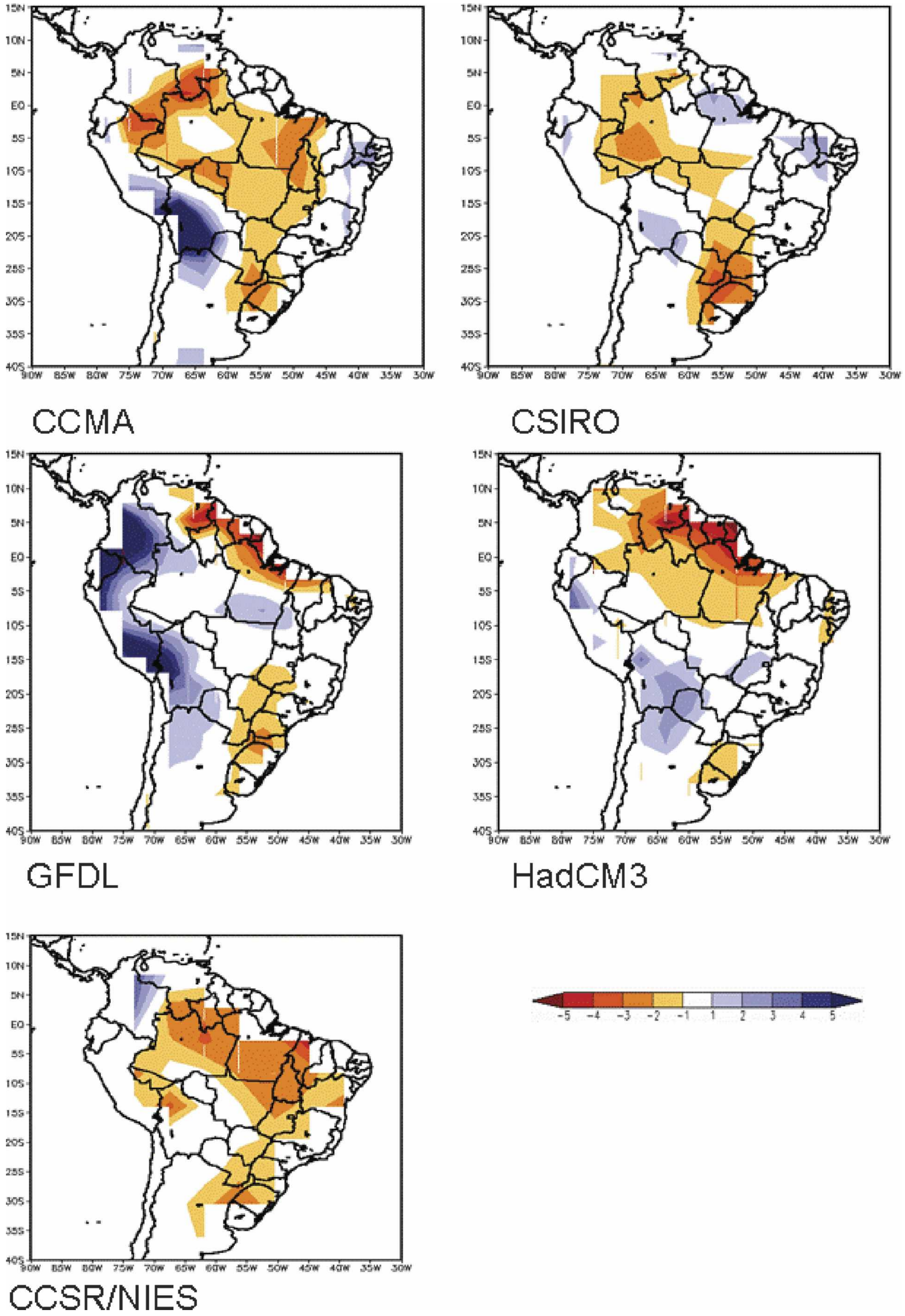

FIG. 3. Differences between 1961–90 rainfall simulated by five IPCC models (CCCma, CSIRO-Mk2, GFDL-R30, HadCM3, and CCSR/NIES) and observed from the CRU. Units are in mm day^{-1}. Color bar scale is shown at the bottom (Marengo 2005).

raised. If true, this implies that GCMs must be able to simulate such regime transitions to accurately predict the response of the system to climate forcing. This capability has not yet been widely tested in climate models. A few studies (Osborn et al. 1999; Paeth et al. 1999; Ulbrich and Christoph 1999) have shown increasingly positive trends in the indices of the NAO and the SST interhemispheric gradient in the tropical Atlantic in simulations with increased greenhouse gases, although this is not true in all models, and the magnitude and character of the changes varies across models. Greenhouse gases and tropospheric aerosols—the main human influences on climate—have increased since the preindustrial era, and observations show a detectable effect on surface air temperature, temperature of the free atmosphere and ocean temperature, as well as on sea level pressure (SLP). Gillett et al. (2003) detected influence of anthropogenic greenhouse gases and sulfates during austral summer on SLP, using combined simulations from four climate models. They found increases in SLP over the subtropical North Atlantic Ocean, southern Europe, and northern Africa and decreases in the polar regions and North Pacific Ocean, in response to human influence.

It is not yet known to what extent seasonal climate predictability will change on regional scales in a scenario of global climate change, whether it will increase (in the case of increased dryness over semiarid regions) or will diminish (e.g., in the case of increased frequency of extreme events on a warmer and more humid atmosphere) as consequence of climate change, both natural and anthropogenic. In any case, the prospects of regional climate change are robust enough to justify a continuous scientific undertaking to improving the models and monitoring the environment to help society to learn to adapt to a changing climate.

4. The state of the art of climate prediction and predictability over South America

The potentially predictable component of atmospheric interannual variability is assumed to be that due to oceanic forcing, together with an unpredictable internal component. Rowell (1998) concluded that the model-based predictability estimate has large variations throughout the annual cycle. The highest predictability occurs over the tropical oceans, particularly the Atlantic and Pacific, for which a better knowledge of the influence of SST on diabatic heating is important for understanding the variability of teleconnected regions. Land areas displaying high predictability tend to support existing empirical studies, such as the Amazon Basin, while others do not exhibit such a high degree of predictability as in the South American monsoon region (Marengo et al. 2003). Servain et al. (2000) identify two interannual modes of variability that have the same physics as the annual variability does, which is related to the latitudinal displacement of the ITCZ. Furthermore, it is suggested that ocean dynamics (as opposed to the thermodynamic processes) is the principal cause of climate variability in the region, and this works also at decadal time scales. The observed decadal changes in the Pacific, detected as changes in the frequency of intensity of ENSO events during the middle 1940s and 1970s (Houghton et al. 2001), and decadal changes identified in the tropical Atlantic also show a possible change in predictability on decadal time scales.

A number of studies have reported the existence of decadal and longer time-scale variability in South American rainfall and river discharge, related to ocean surface changes in those time scales in both the Pacific and Atlantic Oceans (Zhou and Lau 1998; Robertson and Mechoso 1998; Wagner 1996; Mehta 1998; Marengo 2004). Decadal time scales for the Pacific and Atlantic Oceans have been linked to variations of rainfall in the Amazon and Nordeste regions (Wagner 1996; Nobre and Shukla 1996; Mehta 1998; Robertson and Mechoso 1998). Mehta (1998) suggested a distinct decadal time scale (12–13 yr) of SST variations in the tropical South Atlantic, whereas no distinct time scale was found in the tropical North Atlantic SST variations. Previously, Mehta and Delworth (1995) identified in the observations and the GFDL model a multidecadal variability in the SST time series with approximately opposite phases between the tropical North and South Atlantic, exhibiting an interhemispheric gradient of SST anomalies. Dommenget and Latif (2000) found that the decadal variability in both the tropical North and South Atlantic are uncorrelated and that this variability of the upper-tropical Atlantic Ocean is forced by the atmosphere, while dynamic feedbacks are less important.

The role of the ocean in tropical Atlantic decadal variability was investigated by Seager et al. (2001). They suggest that the tropical Atlantic is largely passive and damping and that SST anomalies are largely stationary in the deep Tropics. Previously, Carton et al. (1996) suggested that decadal time-scale variability in the tropical Atlantic is controlled by latent heat flux anomalies and is primarily responsible for SST anomalies off the equator. Ruiz-Barradas et al. (2000) examine the connection between the tropical Atlantic and other basins. They found that ENSO events cause patterns of winds, heating, and SST resembling the interhemispheric gradient of anomalous SST and dipole pattern of atmospheric heating.

In southern Brazil and northern Argentina, recent studies (Camilloni 2005a,b) have detected increased rainfall and river discharge in the region since the mid-1970s. These increases are linked to changes in the regional circulation, that is, the southward displacement of the subtropical Atlantic high. Robertson and Mechoso (1998) suggested some predictability on decadal time scales in the southern Brazil region associated with a near-decadal oscillation in SST along southeastern South America.

For the Amazon Basin, Marengo (2004) identified decadal variations of rainfall in both northern and southern Amazonia, with shifts in the mid-1940s and 1970s. After 1975–76, northern Amazonia received less rainfall than before 1975. Changes in the circulation and oceanic fields after 1975 suggest an important role of the warming of the tropical central and eastern Pacific on the decreasing rainfall in northern Amazonia due to more frequent and intense El Niño events during the relatively dry period 1975–98.

In northeast Brazil, Folland et al. (2001) study the predictability of rainfall using the HadAM2b model and they demonstrate a relatively high degree of predictability, with its sources lying mostly in the tropical Atlantic and Pacific SST. In this region, the SST gradient between the northern and southern tropical Atlantic appears to be the most important influence, though El Niño can be dominant when it is strong. This high predictability is the basis of empirical predictions in that region, as the forecasts by Greischar and Hastenrath (2000). Their method used the 1921–57 period for the analysis, and the performance was validated on the independent record 1958–89. The forecasts were in close agreement with the observed rainfall during the 1990s, with exception of the extreme El Niño 1998. A possible cause of this failure is seen in the lack of comparably extreme Pacific warm events within the training period 1921–57 and is related to the frequency of intense El Niños that changed from the middle 1970s. This conclusion on predictability can be also applicable to the Amazon Basin. So, the notion of a rapidly changing climate represents a major quest for the predictability of climate variations on interannual time scales because most methods and models, both statistical and dynamical, are based on the presumption of stationarity of the mean-state statistics considerably longer than the time span of the predictions.

a. Dynamical downscaling of regional climate predictions

The disadvantage of using AGCMs for regional climate predictions on intraseasonal to interannual and longer time scales is the inability of present-day models to resolve subgrid atmospheric processes of fundamental importance (e.g., clouds and regional-scale inhomogeneities of surface fluxes), which are likely to play a determining role in climate statistics. In interannual climate prediction, for instance, the use of regional atmospheric models has suggested that it might be possible to predict higher statistics of the regional climate like the probability density function (pdf) distribution of daily rainfall over a region. Nobre et al. (2001) obtained encouraging results using the National Centers for Environmental Prediction (NCEP's) Regional Spectral Model (RSM: Juang and Kanamitsu 1994) nested on the outputs of the ECHAM4.5 AGCM to predict the daily rainfall pdf and the spatial distribution of dry spells over the Nordeste during its rainy season (February to May 1999). Sun et al. (2004) used essentially the same dynamical downscaling technique of Nobre et al. (2001), but over a period of 30 yr, and demonstrated that the regional model can simulate the interannual variability of daily rainfall pdf over the Nordeste better than the AGCM in which it was nested. These results represent a milestone for seasonal climate prediction, as they point to the possibility of climate predictions beyond seasonal averages of atmospheric variables, first suggested by Shukla (1981).

Using a Markov model to downscale rainfall GCM simulations over specific rain gauge stations over the Nordeste, Robertson et al. (2004) were able to capture interannual changes in daily rainfall occurrence and 10-day dry spell frequencies at some individual stations. Their results suggest that stochastic models may provide a useful tool to understanding the statistics of daily rainfall at the station level in terms of large-scale atmospheric patterns and to generate rainfall scenarios at station scale for input into hydrological and crop model applications.

However, notwithstanding the encouraging results of dynamical downscaling of seasonal rainfall predictions over the Nordeste, one must keep in mind the need to correctly resolve the diurnal cycle of rainfall in the models. Current research on the topic (Misra and Kanamitsu 2004) suggests that the inability of present-day AGCMs to reproduce intraseasonal oscillations like the MJO are in part due to the skewed diurnal cycle of precipitation in the models.

b. Seasonal climate predictions over South America

Presently, there are various centers in South America and other parts of the world that issue regular seasonal climate assessments and outlooks for South America. The majority of these centers use a two-tier approach to generate the predictions: first using various methods to reach the "best estimate" of global Tropics SST prediction for the following four to six months and then using the SST forecasts to force AGCMs to generate ensembles of individual predictions starting from slightly different atmospheric initial conditions. A detailed explanation of this type of methodology can be found in Goddard et al. (2003) and Marengo et al. (2003), for example.

In the region, CPTEC in Brazil issues seasonal climate forecasts for the entire continent since 1995, even though the focus and details are mostly for Brazil. Similar activities are being developed at the major numerical centers in the world [ECMWF, the Met Office, Max Planck Institute for Meteorology, NCAR, National Aeronautics and Space Administration (NASA), International Research Institute for Climate Prediction (IRI), etc.]. Model skill estimates based on hindcast simulations with prescribed SST are also available. CPTEC's forecasts also include statistical predictions for rainfall in northeast Brazil and southern Brazil using methods based on canonical correlations (Repelli and Nobre 2004). Since 1997, IRI has focused on global seasonal forecasts of temperature and precipitation anomalies containing an outlook for the coming 3-month season and an extended one to six months in advance. The IRI operational climate forecasts are issued every month for the globe and are based on the seasonal forecasts issued by various climate centers in the world (Goddard et al. 2003). The outlook is prepared using coupled ocean–atmosphere model predictions of tropical Pacific SST, forecasts of the tropical Atlantic and Indian Ocean using statistical models and GCM predictions of the atmospheric response to the present and predicted sea surface temperature patterns.

As made at CPTEC, the IRI seasonal outlooks provide the probability that average temperature and total accumulated precipitation fall into each of three categories. These categories are defined as the lower, middle, and upper thirds of the climatological distribution. When forecasts with probabilities for the three categories are the same, namely, a third each, they are designated as climatology. For each location and season, the terciles correspond to temperature and precipitation ranges based on a set of historical observations. Consequently, when using tercile forecasts, users need to know the ranges to which the terciles refer. The IRI seasonal precipitation probabilistic forecast for South America (Fig. 4) is based on a multimodel ensemble approach (Barnston et al. 2003). Averaging results from multiple models was found to improve estimates of the climatology and seasonal predictions of atmospheric variables.

Since December 1997, 18 Climate Outlook Fora (COF) for southeastern South America (SESA) were convened to produce seasonal climate forecasts for temperature and precipitation anomalies in the region bounded by 20°S, 40°S, the Atlantic coast, and the Andes. These COFs were organized by governmental organizations of Argentina, Brazil, Paraguay, and Uruguay. The participants were climate experts and operational forecasters, who reached a consensus forecast for the coming 3-month season (Berri et al. 2005). Also discussed at the COF are the implications of probable climate outcomes for climate-sensitive sectors. More recently, the Centro Internacional de Investigaciones sobre el Fenómeno El Niño (CIIFEN) in Guayaquil, Ecuador, coordinates COF activities in the countries on the west coast of South America, and since 2002 they have being issuing seasonal climate forecasts for this region. All of the COF estimate the probability of the seasonal mean of precipitation and temperature to be in the lower, middle, and upper thirds of the climatological distribution, as it is done at CPTEC and IRI.

5. Research and data needs

As discussed above, seasonal climate predictions over South America can partly benefit from "ocean driving" conditions of atmospheric circulation and precipitation patterns. Therefore, slowly varying ocean temperature fields like those associated with the ENSO over the equatorial Pacific and the meridional gradient of SST anomalies over the tropical Atlantic imprint seasonal predictability to the climate. However, model improvements and research-quality data are needed to both increase prediction skill and lead time. Furthermore, the evidence pointing to the dynamical limitations of using AGCMs forced by prescribed boundary conditions to predict SACZ variability is a major limitation in current prediction techniques used. Yet, due to present limitations of coupled ocean–atmosphere models to predict tropical Atlantic climate and ocean variability, the scientific puzzle ahead of us to predict the coupled variability of the tropical Atlantic basin represents a huge challenge to our ingenuity and resources: human, models, data, financial, and science wise.

Future implementations of the atmospheric component of the CPTEC coupled ocean–atmosphere model are related to improvements of physical parameterizations, new vegetation maps, and more realistic soil humidity fields. Other implementations comprise the increase of model resolution, optimization of codes, and new methods of model initialization and analyses. The consistency of the climate signal in South America pro-

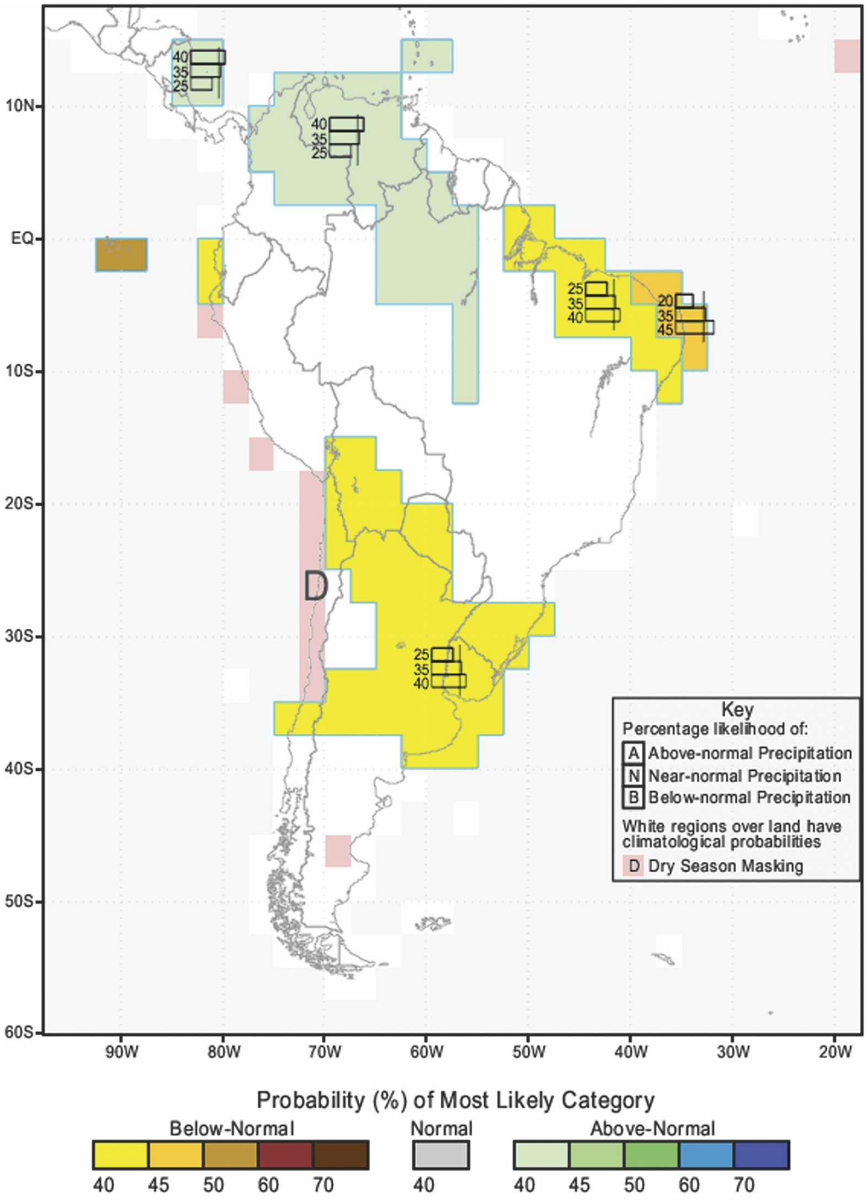

FIG. 4. Seasonal precipitation forecast issued by IRI for climate prediction for November/December 2005–anuary 2006. From http://iri.columbia.edu/.

duced by the CPTEC/COLA AGCM and the suite of models from IRI allows us to characterize high predictability, and good model skill for some regions of South America, as demonstrated by various skill scores. For other regions, where the skill is low, the weaknesses of the models used for seasonal climate predictions should not be regarded as permanent defects since the models are undergoing continuous improvement. Other factors beyond the external forcing provided by SST anomalies may be important in their year-to-year climate variability, suggesting current limitations on climate predictability over those regions.

On the observational side, Brazil is committed to contributing to the development of a comprehensive ocean–atmosphere observational network over the tropical Atlantic. The Pilot Research Array of Moored Buoys over the Tropical Atlantic (PIRATA) project of moored ATLAS buoys in the tropical Atlantic (Servain et al. 1998), in which Brazil participates with France and the United States, constitutes the embryo of such an observational network. As recently as August 2005, a southwestern extension (SWE) of the original PIRATA backbone (indicated by the blue circles in Fig. 5) has been installed to complement the original

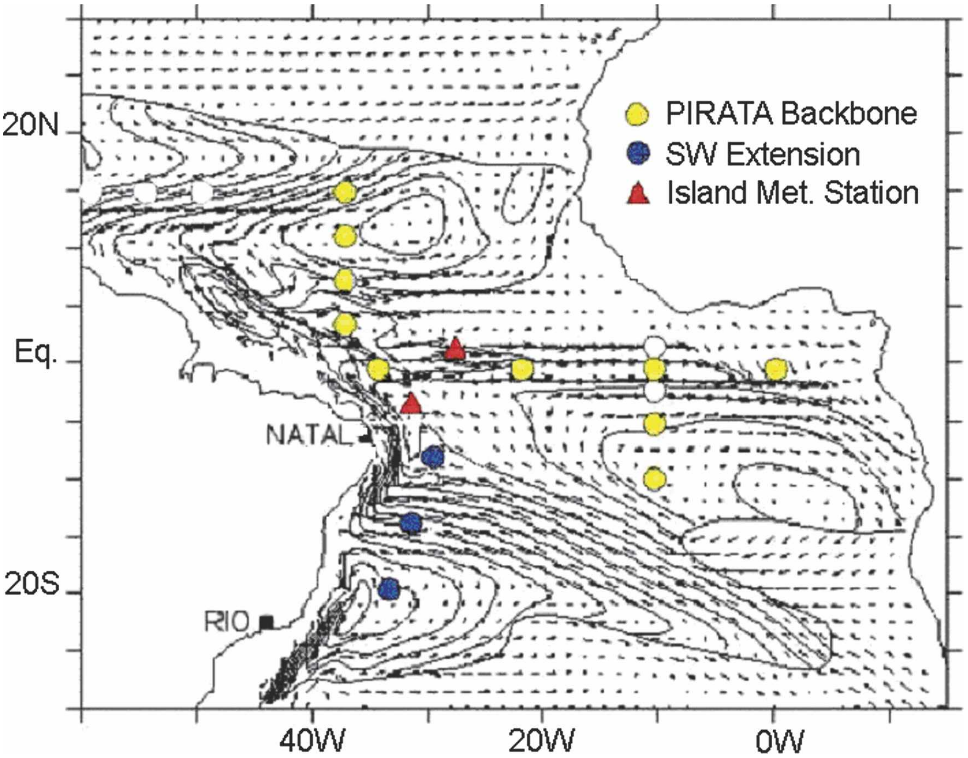

FIG. 5. PIRATA array of moored buoys over the tropical Atlantic (circles: yellow—active; white—inactive; blue—SWE: active; moored August 2005) and island meteorological stations (red triangles). Background map shows simulated currents by Lazar et al. (2002).

PIRATA array. The PIRATA SWE is aimed at studying three major phenomena over the South Atlantic and their impact on regional climate variability and predictability: (i) the formation of a southern branch of the ITCZ during the months of June to August, (ii) the impact of temperature–salinity anomalies advected by the South Equatorial Current (SEC) on the local storage of heat on the upper ocean, and (iii) surface and upper ocean heat fluxes related to the SACZ variability.

One of the major problems detected in climate modeling and in the depiction of circulation patterns such the SACZ, the ITCZ, or the South American low level jet (SALLJ) is representation of the diurnal cycle. The discrepancy between the diurnal cycle derived from the surface/upper-air observations and the NCEP reanalyses or climate models indicates the need for more observations, and a more accurate evaluation of the diurnal cycle will be accomplished through a dense network of observations at least 4–6 times per day. This has been one of the major objectives of field experiment programs in South America. Among them the South American Low Level Jet Experiment (SALLJEX), which took place during the austral summer 2002–03, as part of the Climate Variability and Predictability Study (CLIVAR)–Variability of South American Monsoon Systems (VAMOS), and the reference sites (flux towers) implemented in the Amazon Basin since the 1990s as part of the Global Energy and Water Cycle Experiment (GEWEX)–Large-Scale Biosphere–Atmosphere Experiment in Amazonia (LBA). These data started being used for calibration of models in the Amazon and the South American monsoon region, and the future implementation of the GEWEX–La Plata Basin (LPB) will extend this monitoring to the Paraná–La Plata Basin in southeastern South America.

6. Conclusions

This paper has highlighted that seasonal predictability over South America varies highly. The high predictability of Nordeste seasonal rainfall, and to some extent over southern Brazil, by AGCMs contrasts with the low reproducibility of seasonal rainfall over southeastern Brazil, indicating that different processes are operating to modulate rainfall variability on seasonal time scales over those regions. It is speculated that coupled ocean–atmosphere interactions play an important role in the dynamics and thermodynamics of SACZ. According to the literature reviewed in this article, seasonal climate prediction over South America presents two major challenges: first, for the regions in which the mean state of the atmosphere is modulated by external forcing, like SST, effective forecasting tools are needed to predict the future state of the oceans and, second, for phenomena that cannot be reproduced by the "ocean forcing" paradigm of climate variability, it is necessary to develop coupled models that include not only the ocean and the atmosphere, but also land surface feedbacks, which are not well represented in most of the global climate models used in seasonal climate predictions.

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