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ORIGINAL PAPER

Assessment of regional seasonal predictability using the PRECIS regional climate modeling system over South America

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Abstract The purpose of this study was to evaluate the accuracy and skill of the UK Met Office Hadley Center Regional Climate Model (HadRM3P) in describing the seasonal variability of the main climatological features over South America and adjacent oceans, in long-term simulations (30 years, 1961–1990). The analysis was performed using seasonal averages from observed and simulated precipitation, temperature, and lower- and upper-level circulation. Precipitation and temperature patterns as well as the main general circulation features, including details captured by the model at finer scales than those resolved by the global model, were simulated by the model. However, in the regional model, there are still systematic errors which might be related to the physics of the model (convective schemes, topography, and land-surface processes) and the lateral boundary conditions and possible biases inherited from the global model.

1 Introduction

Global models have allowed for a better scientific understanding of anthropogenic global climate change and this has brought commensurate developments in mitigation strategies. However, at the regional scale, there remains an urgent need for relevant, targeted projections of regional climate change. Furthermore, adaptation, as opposed to mitigation, is inherently a local and regional-scale issue, and is limited by the measure of confidence in the projected changes at these scales. Demand for regional climate change scenarios has generated increased interest in the downscaling of global climate model simulations. These downscaling methods can be statistical, using empirical transfer functions, or dynamical, using Regional Climate Models (RCM).

Although the ability of coupled models to simulate large-scale climate variability—including ENSO—in space and time has improved substantially, the results of long-term multimodel simulations must still be treated with caution as they do not capture the detail required for regional impact assessments, due in part to the coarse resolution in both the atmosphere and oceans of the majority of the models used. This is particularly true for heterogeneous regions, such as South America, where the distributions of surface variables such as temperature and rainfall are often influenced by local effects of topography, and thermal contrasts, which have a significant effect on the climate (Tanajura 1996; Hudson and Jones 2002; Fernandez et al. 2006; Seth et al. 2007).

Many studies around the world have carried out simulations of present and future climates (see reviews in Meehl et al. 2007). There is a consensus that for impacts or vulnerability applications, dynamic downscaling using RCMs is the most appropriate option. The hypothesis behind the use of high-resolution RCMs is that they can provide meaningful small-scale features over a limited region at affordable computational cost compared to high-resolution AOGCM simulations. The value-added information that is expected from RCMs should come not only from the spatial details but also from better-simulated temporal variability. This variability aspect is often a weakness in GCMs (Giorgi 1990; Giorgi and Mearns 1999; Wang et al. 2004).

Regional climate modeling has become an important tool for the prediction of climate variability and change.

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Dynamical downscaling in South America has been developed for better understanding of the physical processes in the atmosphere, as well as in weather and climate forecasting (Seluchi and Chou 2001; Nobre et al. 2001; Nicolini et al. 2002; Chou et al. 2002; Seth and Rojas 2003; Misra et al. 2003; Chou et al. 2004; Sun et al. 2005, Silvestri et al. 2007). However, there have been a few longer RCM simulation studies carried out over South America. In one of these, Sun et al. (2005) used the *Regional Spectral Model* (RSM) over a period of 30 years and demonstrated that the regional model can simulate the interannual variability and the probability density function distribution of daily rainfall over Northeast of Brazil, better than the AGCM in which it was nested. More recently, results of long-term integrations, as in Silvestri et al. (2007), are important to provide the MPI atmospheric limited area model, REMO, climatology and to perform model validation. Those 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 (2001).

High-resolution scenarios developed from regional climate model results have been obtained in various parts of the world: China (Zhang et al. 2006), Pakistan (Islam and Rehman 2007), Europe (Christensen and Christensen 2003; Frei et al. 2006), and in South America (Nuñez et al. 2006; Marengo and Ambrizzi 2006, Ambrizzi et al. 2007; Marengo et al. 2007, 2009; Solman et al. 2007).

During the last decade, several national and international researches in regional climate modeling has demonstrated that RCMs is a useful downscaling tool for providing climate information at the scale appropriate for societal use (see reviews on international projects using regional climate change scenarios in Marengo et al. 2009). All these have all followed a standard experimental design of using one or more GCMs to drive various regional models from meteorological services and research institutions in the regions to provide dynamically downscaled regional climate projections. Typically, present-day climate (e.g., 1961–1990) and future climate (2070–2100) time slices are simulated to calculate changes in relevant climatic variables.

A similar initiative has been recently implemented in South America, called CREAS (*Regional Climate Change Scenarios for South America* – Marengo and Ambrizzi 2006; Marengo et al. 2009). It aims to provide high-resolution climate change scenarios in South America for raising awareness among governments and policy makers in assessing climate change impacts, vulnerability, and in designing adaptation measures. CREAS runs three regional models nested in HadAM3P (a GCM used in PRUDENCE): Eta for Climate Change Studies—Eta CCS—(Pisnitchenko and Tarasova 2007), RegCM3 (Ambrizzi et

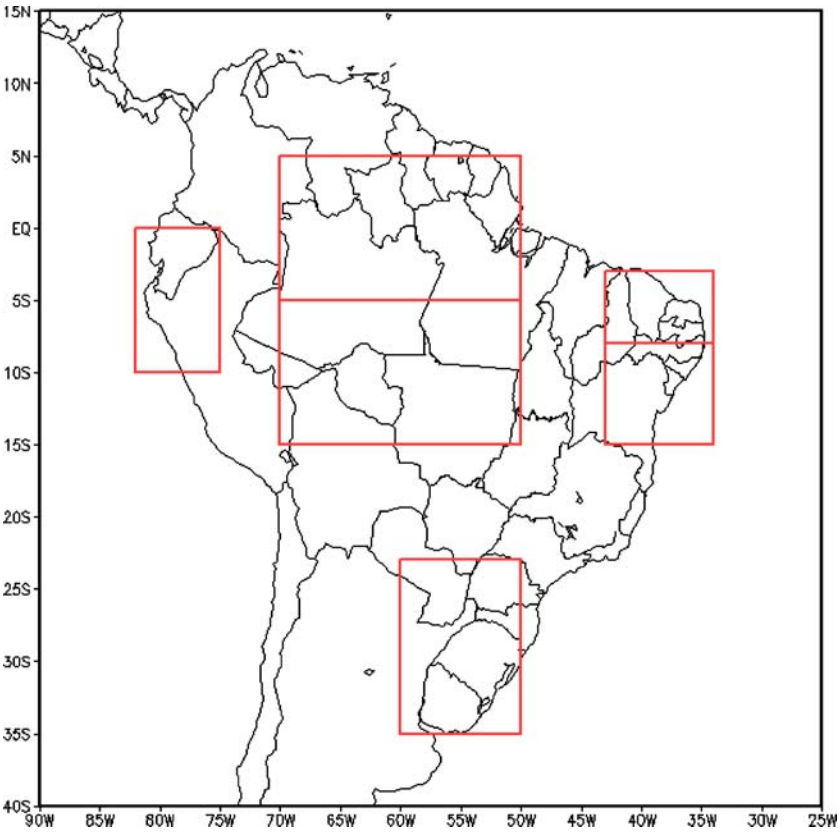


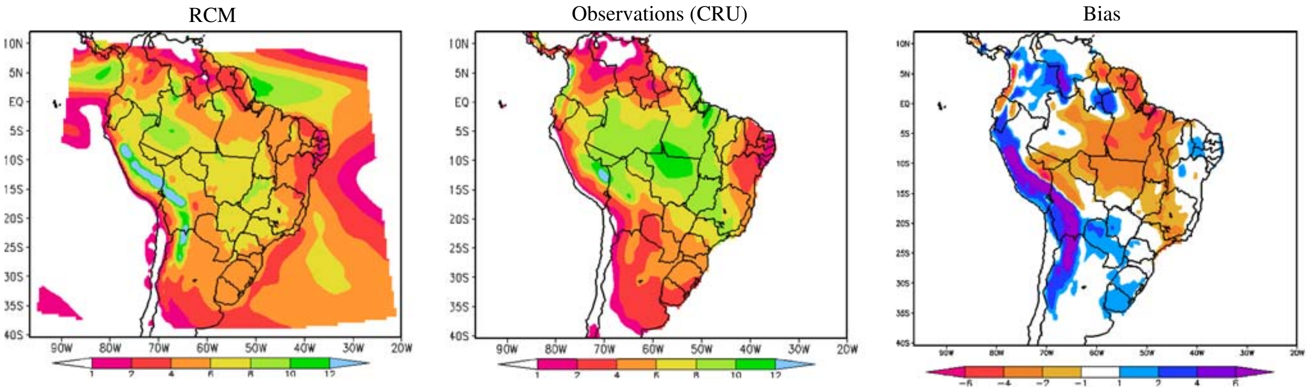
Fig. 1 *Red boxes* indicate the Amazon, Northeast Brazil, Northwest Peru and Southern Brazil regions used in area average calculations discussed in the results

al. 2007), and HadRM3P (Jones et al. 2004; Marengo and Ambrizzi 2006). CREAS explores issues such as: the challenge of using regional climate projections to develop plausible scenarios for future changes at daily time scales for extreme events; an assessment of current methods of scenario development for regions where data is available; assessments of vulnerability in regions and key sectors in South America.

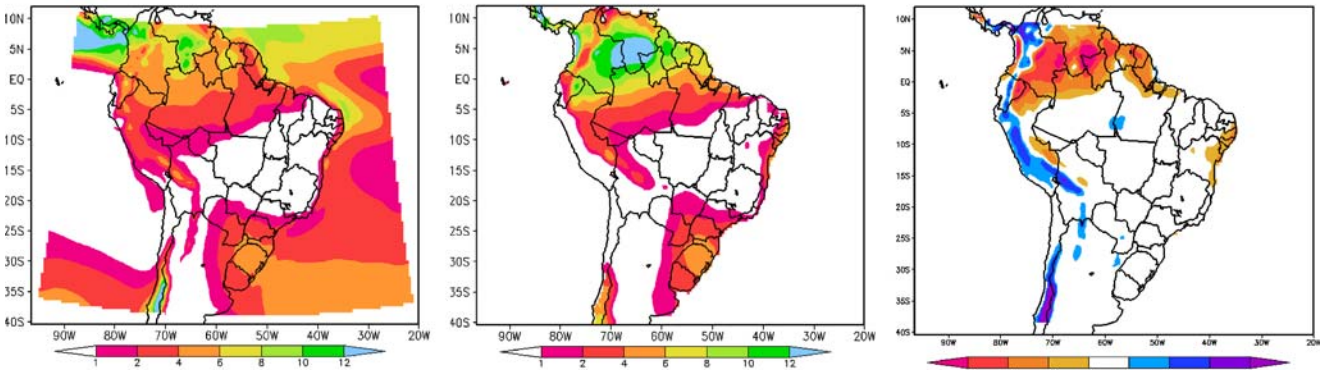
In this study, we focus on the analysis of a 30-year simulation, 1961–1990 (referred to as “present-day”), from the HadRM3P regional model, part of the PRECIS (*Providing Regional Climates for Impacts Studies*) modeling system (Jones et al. 2004) which has been used to develop regional climate change scenarios worldwide (Hudson and Jones 2002; Xu et al. 2006; Zhang et al. 2006). The HadRM3P simulations have been driven with boundary conditions from HadAM3P (the GCM on which the CREAS simulations are based) and are run at 40 km resolution. The analysis provides an opportunity to examine the behavior of the PRECIS model in simulating the mean climatological features of South America, drawing attention to possible systematic errors and biases in the simulation.

2 Model, data, and methodology

PRECIS is a regional climate modeling system developed by the UK Met Office Hadley Center. It includes a RCM (HadRM3P) that may be run over any area of the globe (see Jones et al. 2004 which also includes a detailed description of HadRM3P). It uses relatively high horizontal resolution (0.44° latitude by 0.44° longitude in rotation coordinates), which allows it to be run at reasonable computational cost over a domain covering most of South America. The model has 19 vertical levels in the atmosphere, which are based on a hybrid vertical coordinate (Simmons and Burridge 1981) and runs at a time step of 5 min. The lateral boundary conditions for HadRM3P are available from a range of model(s) and observationally based sources and in this study are obtained from the global atmospheric GCM, HadAM3P, which has a spatial resolution of 1.25° latitude by 1.875° longitude. The model formulation is the same as HadRM3P, an experimental setup which promotes consistency of the high-resolution climate change projections from the RCM with those from the global model. The experimental design of the driving HadAM3P experiment is described by Rowell (2005). The sea-surface boundary



(a) summer – DJF



(b) winter - JJA

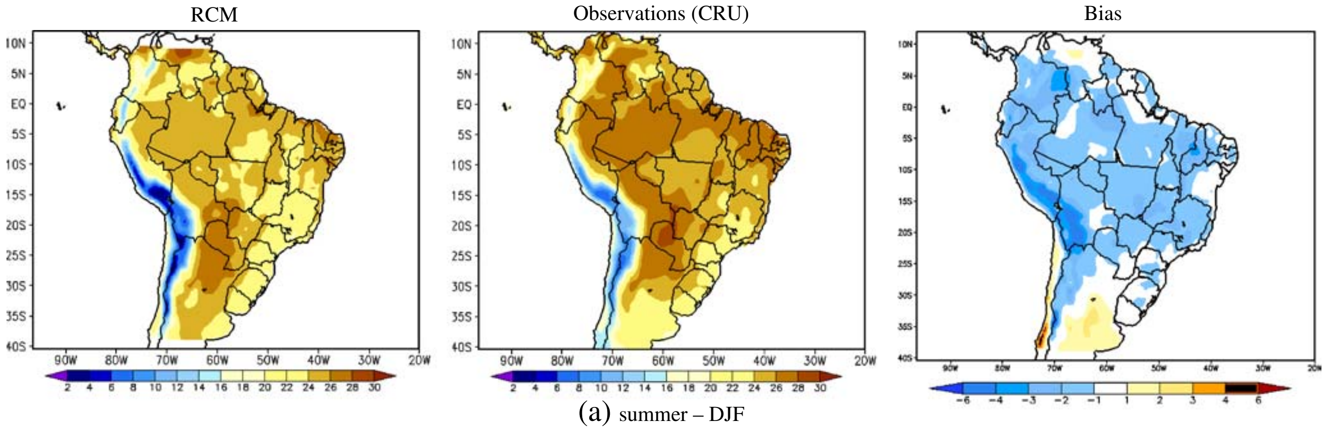
Fig. 2 Climatological precipitation (mm/day): **a** summer (*DJF*); **b** winter (*JJA*) in HadRM3P simulations (*left*), observations (*CRU*, *center*). Bias (difference between model and observations, *right*) conditions are derived from the HadISST1 dataset (Rayner et al. 2003). In the HadRM3P, the surface physics calculations were performed using the four-layer soil model MOSES I (Met Office Surface Exchange Scheme, Cox et al. 1999).

In the choice of an RCM domain, it is desirable to select a domain that is both large enough that the regional model can develop its own internal regional-scale circulations, but not so large that the climate of the RCM deviates significantly from the GCM in the center of the domain (Giorgi and Mearns 1999). The HadRM3P run for South America has been configured for a domain extending from about 40ºS to 10ºN and 90ºW to 25ºW.

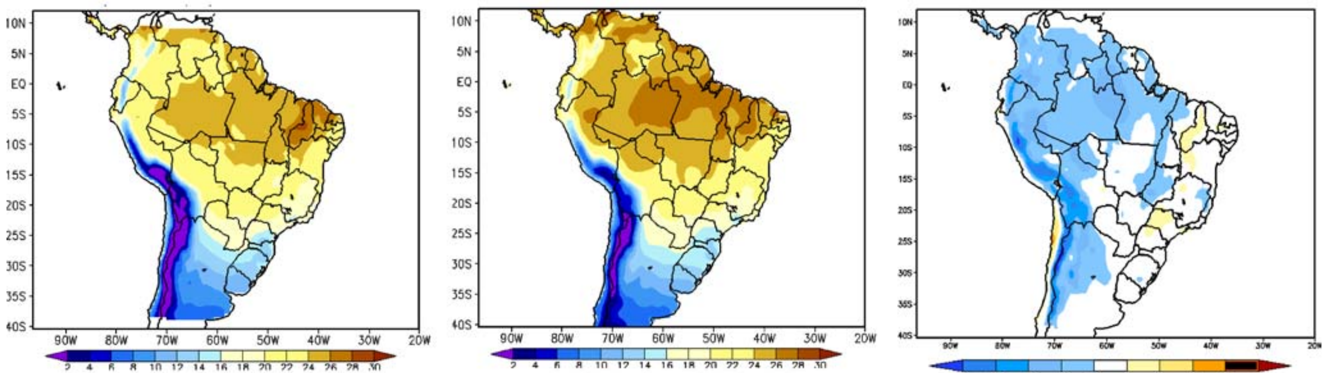
In order to simulate the present-day climate over South America, the RCM was integrated for 31 years (1960–1990) from distinct initial conditions provided by HadAM3P. Three AGCM runs were chosen to span the possible range of outcomes from the global model. The first year of each simulation was excluded in order to avoid spin-up problems. The model's seasonal and annual climatologies for the present day were obtained from the ensemble of three 30-year simulations.

There are more than a thousand stations with mean monthly climatology of surface climate over South America, mainly precipitation than temperature data, however, most of them have many missing data. Due to these deficiency and very scarce information over some areas, such as Amazônia, the fields of seasonal precipitation and temperature from the *Climatic Research Unit* (CRU) observational data sets (New et al. 1999) were used. Despite these data collation efforts, the CRU data in many regions still represent only a sub-set of the potentially available stations. The dynamical fields were compared with the *National Centers for Environment Prediction/ National Center for Atmospheric Research* (NCEP/NCAR) reanalysis product (Kalnay et al. 1996). The reanalysis data of NCEP are generated by the assimilation of data in a state-of-the art model.

We discuss the RCM ability to simulate regional seasonal variability, taking into account systematic bias and errors of the model in reproducing regional aspects of climate. In addition, we assess model predictability for seasonal rainfall anomalies in various regions of South America (shown in Fig. 1) using deterministic maps of correlation between the ensemble mean model results and the observational CRU data sets, probabilistic skill scores, such as relative operating characteristics (ROC) and the dispersion among members of the ensemble for the present day.



(a) summer – DJF



(b) winter - JJA

Fig. 3 Climatological temperature (°C): **a** summer (*DJF*); **b** winter (*JJA*). HadRM3P simulations (*left*) and observations (*CRU*, *center*). Bias (difference between model and observation, *right*)

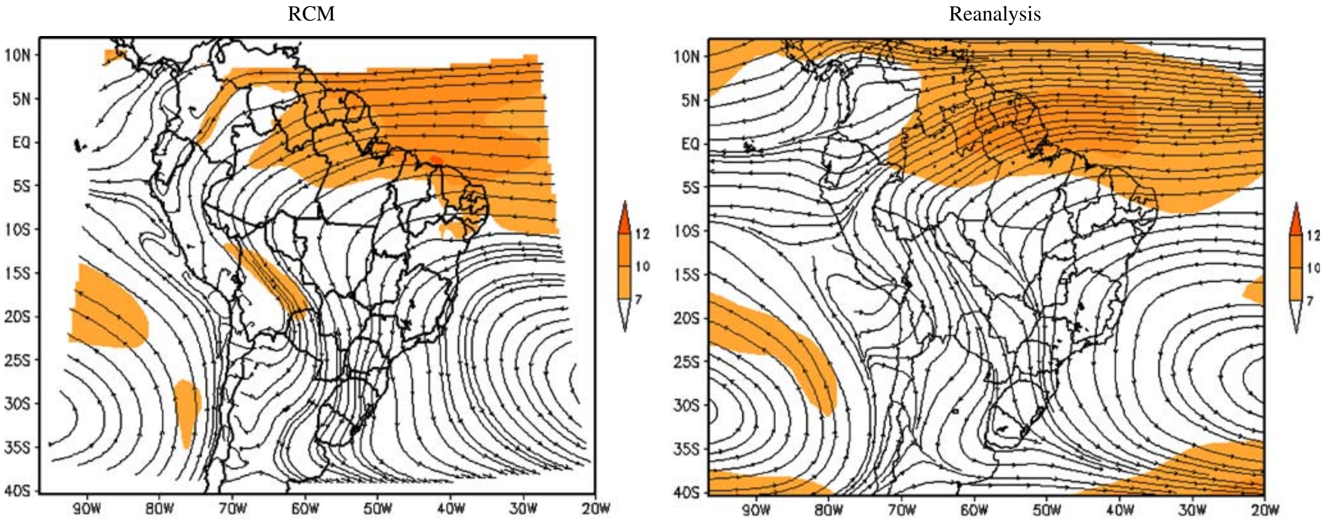
The skill of the regional model is assessed using the ROC method to represent the quality of categorical forecast. This methodology is intended to provide information on the characteristics of systems upon which management decisions can be taken, and is based on ratios that measure the proportion of events and nonevents for which warnings were provided. These ratios provide estimates of the probabilities that an event is forecast and that an incorrect warning will be issued for a nonevent.

For each of the rainy seasons in the regions indicated in Fig. 1, the 30-year observed and simulated area-averaged rainfalls were grouped into equiprobable terciles. The three categories are referred to as “below-normal”, “near-normal”, and “above-normal”. The hit and false-alarm rates, respectively, indicate the proportion of events for which a warning was provided correctly, and the proportions of nonevents for which a warning was provided incorrectly. The derivation of ROC is based on contingency tables giving the hit rate and false-alarm rate for deterministic or probabilistic forecasts. For details on the ROC, the reader is referred to Mason and Graham (1999).

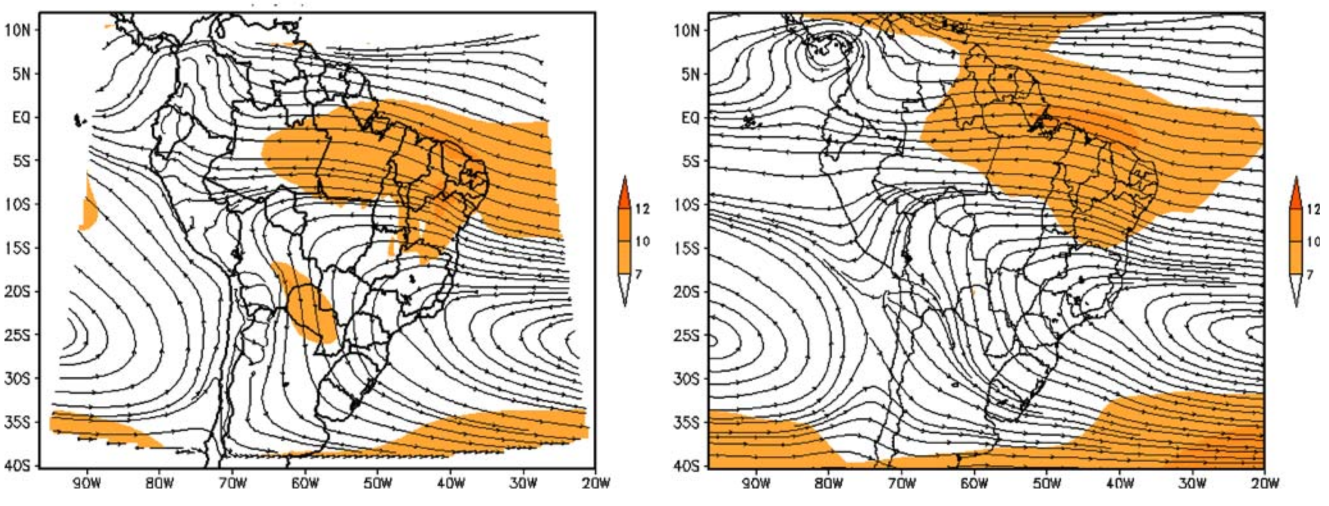
3 General characteristics of climate in South America: model versus observations

This section demonstrates fundamental model performance in reproducing global-scale climatologies of precipitation, air temperature, and circulation.

The primary feature of precipitation over South America is the well-defined annual cycle, mainly in the tropical region, with maximum precipitation occurring during



(a) summer – DJF

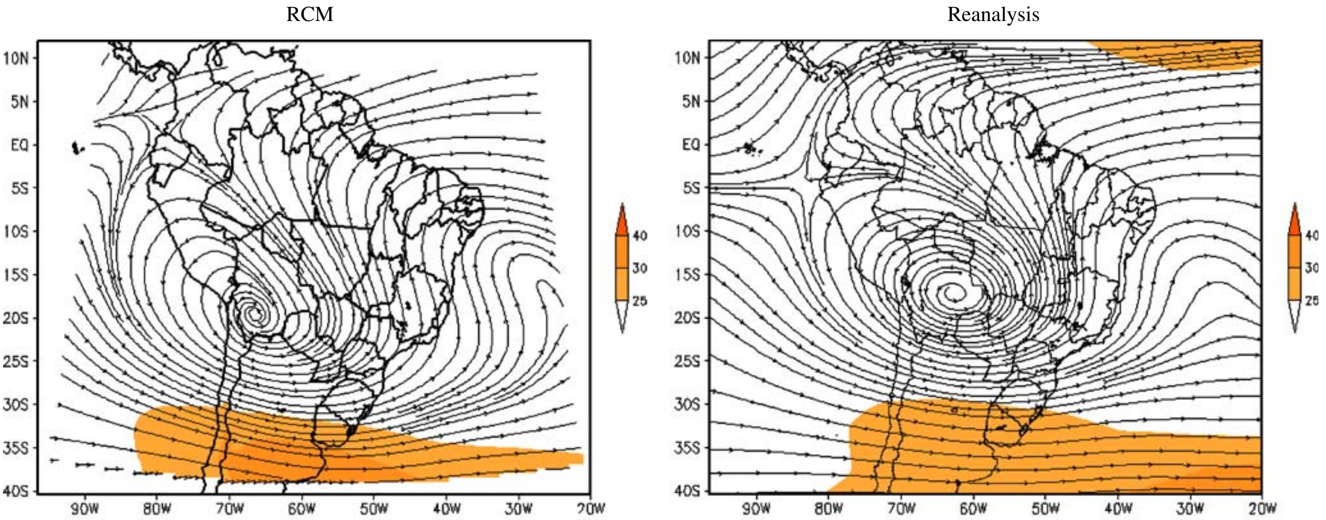


(b) winter – JJA

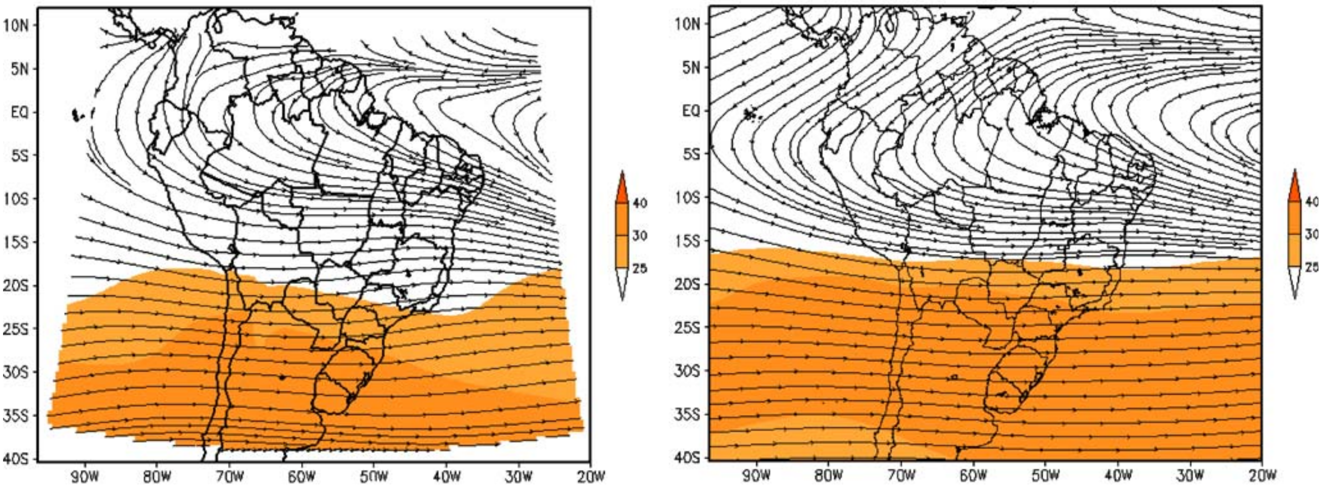
Fig. 4 Isolines and magnitude of climatological wind field (m s^{-1}) at 850 hPa simulated by RCM (*left*) and NCPE/NCAR reanalysis (*right*) for **a** summer (*DJF*) and **b** winter (*JJA*). The magnitudes are *shaded* austral summer (DJF) and minimum during austral winter (JJA) (Rao and Hada 1990). This is related to annual variations in the atmospheric circulation over South America and adjacent oceans (Satyamurty et al. 1998; Grimm et al. 2004a; Marengo and Dias 2006).

The distribution of the precipitation during summer and winter and the differences between the model and observations are shown in Fig. 2. During the summer season, the model is able to reproduce the main spatial pattern of the precipitation, correctly depicting the band of precipitation related to the South Atlantic convergence zone (SACZ), even though rainfall accumulated over it is underestimated. The dry season is also well captured by the model. Notable discrepancies between the model and observations include excessive precipitation over the Andes and a deficiency in precipitation over Amazônia and central and southeastern South America. The overestimation over the Andes, which reaches 6 mm/day, may be related to inadequacies in the representation of the topography and the associated circulation. The underestimation over Amazônia and SACZ are related to poor representation of some components of the hydrological cycle (soil moisture, surface fluxes, and vegetation types) or the convective parameterization. This same type of error over the Amazon and Andes mountains was also found in other RCMs and GCMs, such as Eta (Fernandez et al. 2006), MM5 (Solman et al. 2007), ECMWF (Brankovic and Molteni 1997), CPTEC/COLA, and the GISS GCM (Marengo et al. 2003; Cavalcanti et al. 2002).

Figure 3 shows seasonal averages of temperature and, as in Fig. 2, the difference between the model and observations. Overall, the model reproduces reasonably well the

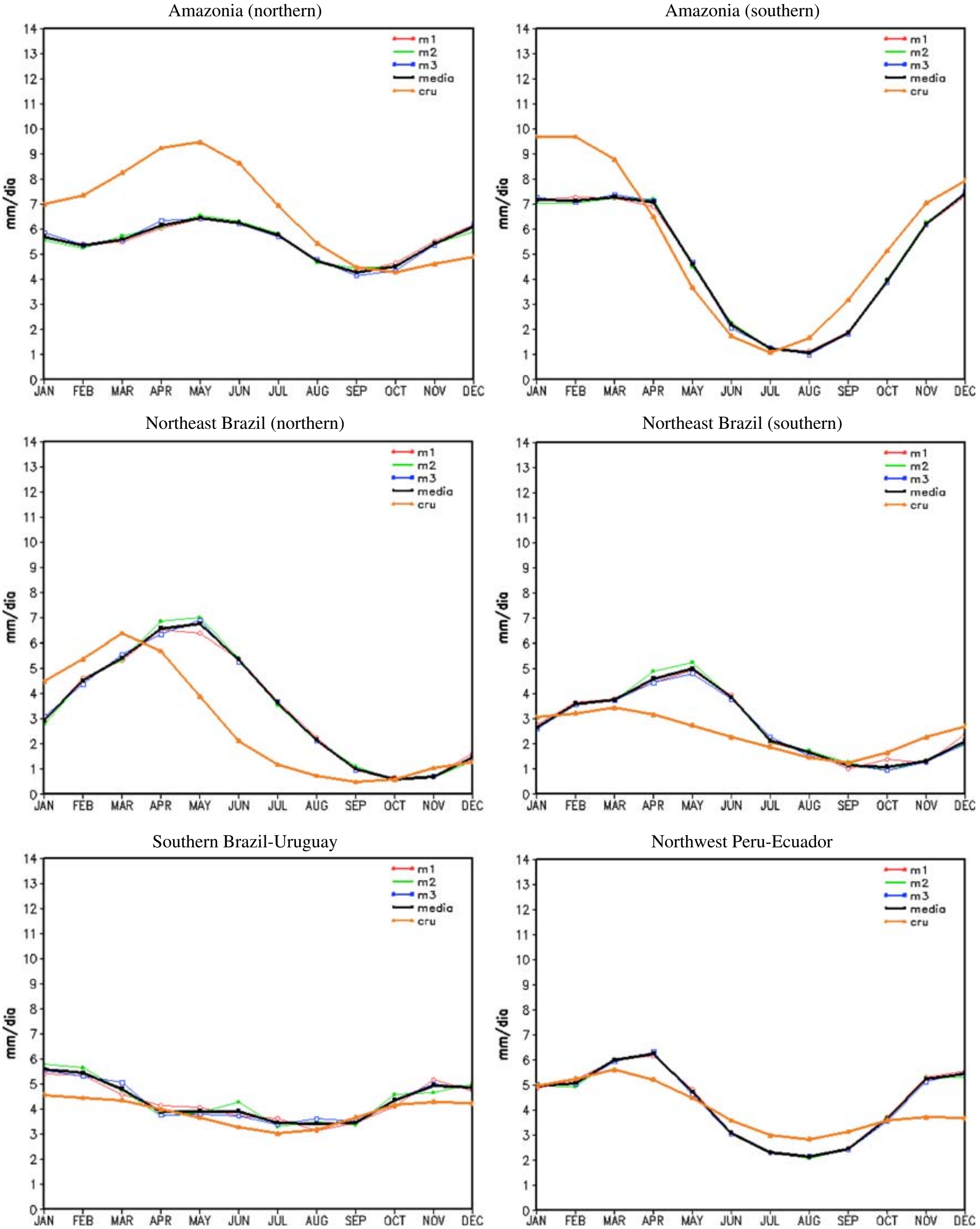


(a) summer – DJF



(b) winter – JJA

Fig. 5 Isolines and magnitude of climatological wind field (m s^{-1}) at 200 hPa simulated by RCM (*left*) and NCPE/NCAR reanalysis (*right*) for **a** summer (*DJF*) and **b** winter (*JJA*). The magnitudes are *shaded* spatial and seasonal variability of surface temperature, particularly in middle latitudes, where there is major thermal variability over the seasons, resulting from the action of cold fronts at high latitudes, especially during winter. Despite the uniformity of temperature in the equatorial region throughout the year, the model underestimates the temperature, as demonstrated in the bias maps, by around 2°C. Over the Andes, too, significant negative biases are evident. This discrepancy may be due largely to some misrepresentation in the land-surface


Amazonia (northern)

Amazonia (southern)

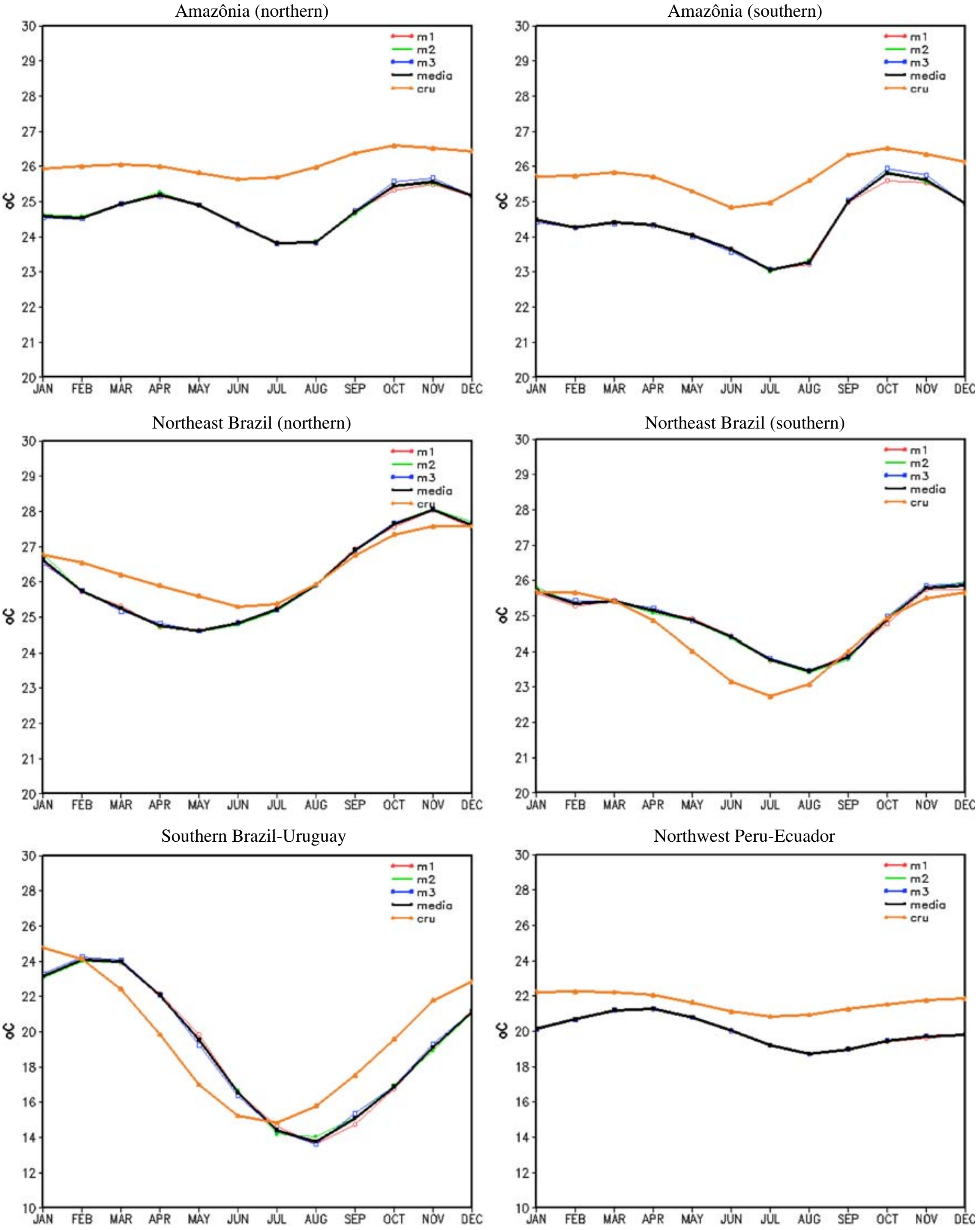
Northeast Brazil (northern)

Northeast Brazil (southern)

Southern Brazil-Uruguay

Northwest Peru-Ecuador

Fig. 6 Annual cycle of observed and modeled rainfall in several regions of South America (mm/day). The *thick orange line* shows the observed rainfall. The *thick black line* represents the mean rainfall from the model ensemble. Thin *red/green/blue lines* represent each member of the ensemble processes and interactions. Thus, it is expected that this would introduce a change in energy to the surface and the water balance, leading to a cooling through a reduction in the amount of long-wave radiation. Another explanation, this time linked to possible problems in the observed temperature fields, is that the number of stations with temperature data is smaller than the number of rainfall stations, especially in tropical South America, and interpolation has been relied upon to fill the many gaps in those regions.


Amazônia (northern)

Amazônia (southern)

Northeast Brazil (northern)

Northeast Brazil (southern)

Southern Brazil-Uruguay

Northwest Peru-Ecuador

Fig. 7 Annual cycle of observed and modeled temperature in several regions of South America (°C). The *thick orange line* shows the observed temperature. The *thick black line* represents the mean temperature from the model ensemble. Thin *red/green/blue lines* represent each member of the ensemble

In order to explore the reasons behind the biases in the modeled precipitation and temperature fields, it is important to analyze the low- and high-level circulation field. The mean seasonal circulation at 850 and 200 hPa simulated and reanalysis during the summer and winter are illustrated in Figs. 4 and 5, respectively. One of the main characteristics of the low-level circulation in the South America region is the subtropical highs over the oceans. The cores of the subtropical highs are well represented by the model; for example, the largest influence of the South Atlantic High (SAH) over South America is in winter, when the circulation center is closer to the continent. The seasonal changes, which are simulated well by the model, have implications for the precipitation of some regions, such as in the northern part of the northeast region of South America. The southeastward displacement of the SAH in DJF and the change in the direction of the trade winds in the tropical region are related to the southward displacement of the tropical confluence zone, which has an influence on the position of the ITCZ. These features are well simulated by the model. The model also captures the role of the Andes in deflecting the northeast trades, and the tropical flux of the northwesterly flow along the east side of the Andes, especially in summer. The model captures reasonably well the structure of the northwesterly flow east of the Andes during winter, but not relates to the summer trades that flow from Amazônia but to the west flank of the SAH, that is closer to the continent. This northwesterly flow that reaches southeastern South America during this season transports the moisture coming from the South Atlantic into northern Argentina, Paraguay, Uruguay, and southern Brazil. In JJA, the winds are almost parallel to the north coast of Brazil. The manner in which the model represents this circulation feature, as compared to the NCEP reanalyses, has a strong impact on its simulation of precipitation over southern Brazil and Uruguay.

In the same view, the 200-hPa circulation field (Fig. 5) suggests that the model simulates the main climatological features of the upper-level circulation, such as the zonal patterns, stronger wintertime subtropical jet streams, the anticyclonic circulation over Bolivia associated with summertime deep convection, and the Northeast trough. However, the principal differences between the model and reanalysis are related to the position and intensity of these systems. During summer, the trough seems to be slightly weaker in the model and the Bolivian high is displaced a little towards the east, relative to the reanalyses. During winter, the subtropical westerly jet seems to be more intensity and positioned further north in the model.

Quantitative estimates of the model's precipitation biases and a more detailed analysis of its mean annual cycle can be observed in Fig. 6, which show simulated and observed precipitation averaged over several sub-regions defined in Fig. 1. First, the analysis shows that the simulations exhibit only a slight or negligible dispersion among individual members. This implies good skill in simulating the annual cycle of precipitation in those regions. The interesting feature in the annual cycle simulated by the model, considering the local characteristics of each region, is the agreement with the observational annual cycle in almost all the chosen regions. The annual cycle in some regions seem to be well simulated for some regions, with some under or over estimations, and also with a 1-month difference between model and observations.

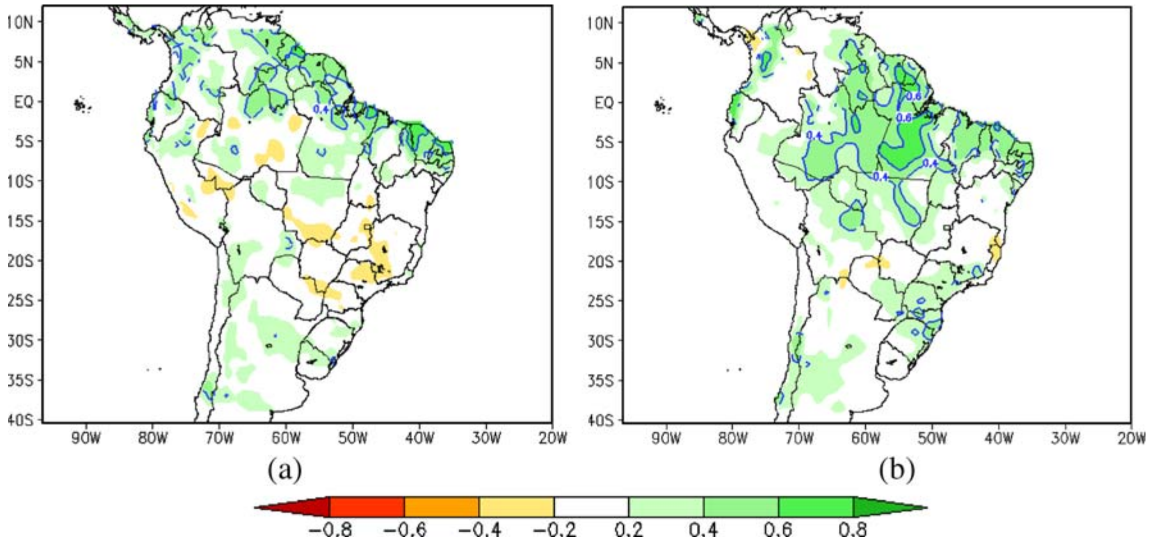


Fig. 8 Correlation coefficients between model anomalies (ensemble mean) and observed anomalies of rainfall: **a** DJF and **b** JJA. *Color scale* shows the values of the correlations. *Area inside blue line* represents regions where the correlation coefficients are significant at the 95% level

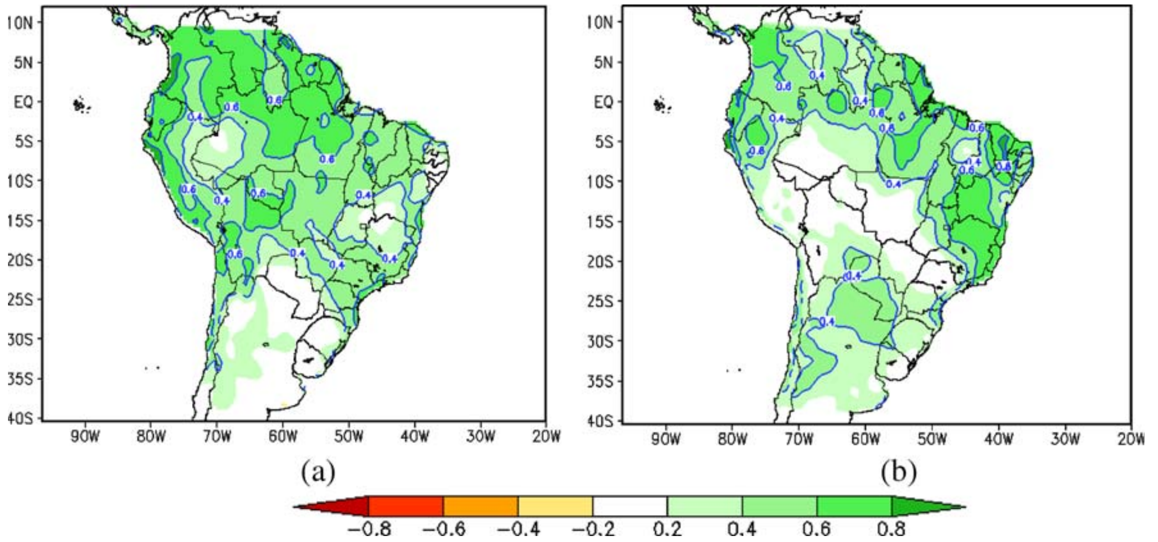


Fig. 9 Correlation coefficients between model anomalies (ensemble mean) and observed anomalies of temperature: **a** DJF and **b** JJA. Color scale shows the values of the correlations. *Area inside blue line* represents regions where the correlation coefficients are significant at the 95% level

In Amazônia, the RCM simulates well the timing of the peak rainfall season, although the amounts are underestimated by about 37%. In northern Northeast Brazil, the simulated peak in May occurs almost 2 months after the mean observed peak, while in the southern Northeast, the agreement between models and observations is not so good. In southern Brazil–Uruguay, and northwestern Peru–Ecuador, the RCM does not capture the observed annual cycle.

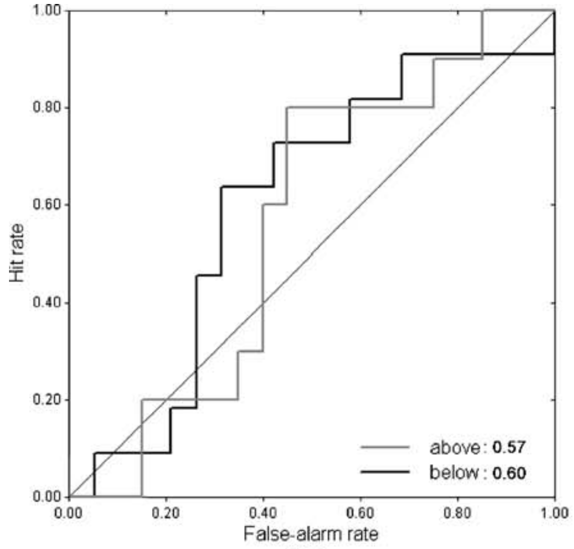
The figures of the annual cycle of temperature (Fig. 7) show a better agreement in all regions with observations, where temperature reaches its maximum during summer and its minimum during winter, especially over southern Brazil and Uruguay, where the temporal variability is more evident. Similar to the annual cycle of precipitation, these figures show that there is only a small degree of dispersion between members. The major shortcoming of the regional model in other regions is the systematic underestimation of temperature in almost all months. It is important to remark that due to inadequate coverage of observing stations in these regions, these results should be examined with caution. The under- or overestimation shown in Fig. 7 reflects either the small number of stations reporting temperature in the CRU data set in some regions of Brazil, or the representation of physical processes in the mode. This under or overestimation in temperature is also observed in various global models (Cavalcanti et al. 2002; Marengo et al. 2003).

4 RCM skill assessments

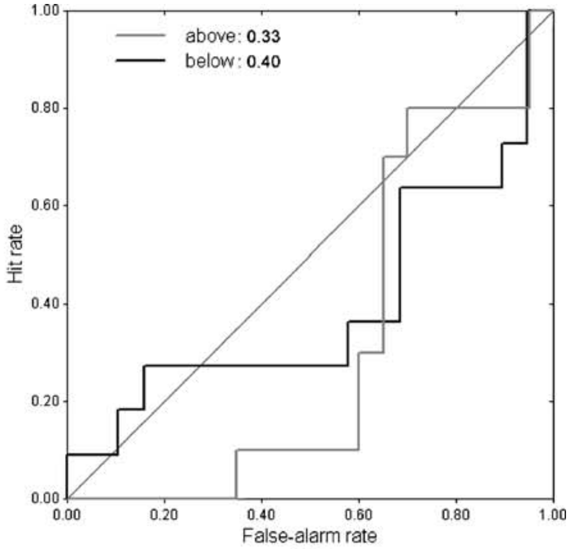
Using deterministic scores, Figs. 8 and 9 show the seasonal anomaly correlation coefficients derived from the model results and the CRU rainfall and temperature data sets, respectively. The correlation is high (>0.4) over northern South America, including northwest Peru–Ecuador, northern Amazônia, and Northeast Brazil during austral summer and winter. The correlations reach statistical significance at the 95% level based on a *t* test, in regions where the RCM has proven relatively good skill: northern Amazônia, Northeast Brazil, southern Brazil, and the northwest coast of Peru–Ecuador. In the monsoon region of South America, the negative correlations during DJF (the rainy season) indicate the inability of the model to simulate rainfall variability in these regions, in agreement with the assessments shown in Fig. 2, and with some other studies using global models (Marengo et al. 2003; Meehl et al. 2007). In general, the correlations of temperature reach values over 0.8 in northern Brazil, while in southern Brazil, the values are larger than 0.4 during DJF and JJA.

Figure 10 shows the ROC curves for seasonal rainfall for selected regions. Buizza et al. (1999) suggest that an area under the ROC curve of more than 0.80 is an indication of a good prediction system, and an area of 0.70 is the limit for a useful prediction system. Considering that for a skillful forecast system, the ROC curve should bends

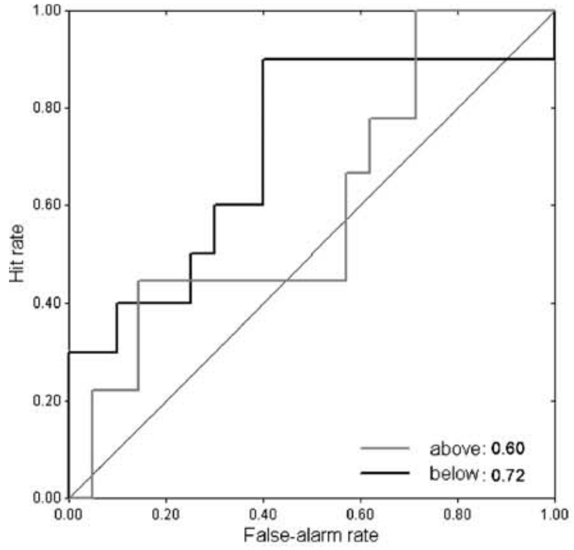
Fig. 10 Hit rates versus false-alarm rates for seasonal area-averaged rainfall at the peak season for selected regions (same regions as Fig. 1). **a** Amazônia (northern), **b** Amazônia (southern), **c** Northeast Brazil (northern), **d** Northeast Brazil (southern), **e** Southern Brazil–Uruguay, **f** Northwest Peru–Ecuador. The hit and false-alarm rates were calculated using rainfall simulated by the regional model forced with observed SST and using three members. Results are shown for the simulation of rainfall above the normal (*gray line*) and below the normal (*black line*). The *area beneath the ROC curves* is indicated also for above- and below-normal precipitation ▶


Hit rate
False-alarm rate
0.00
0.20
0.40
0.60
0.80
1.00
above : 0.57
below : 0.60

(a)


Hit rate
False-alarm rate
0.00
0.20
0.40
0.60
0.80
1.00
above : 0.33
below : 0.40

(b)


Hit rate
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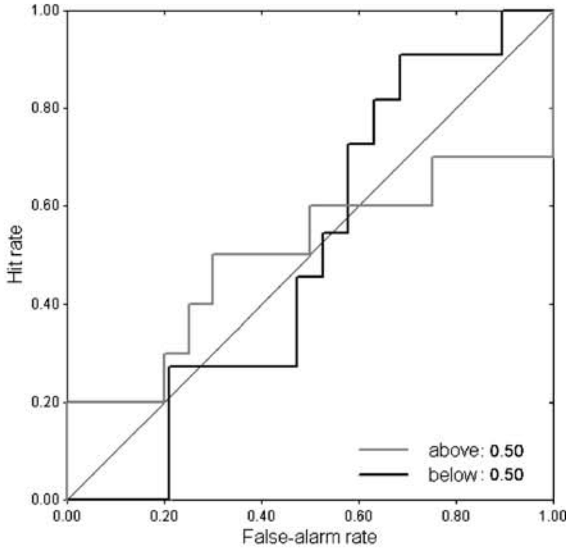
0.20
0.40
0.60
0.80
1.00
above: 0.60
below : 0.72

(c)


Hit rate
False-alarm rate
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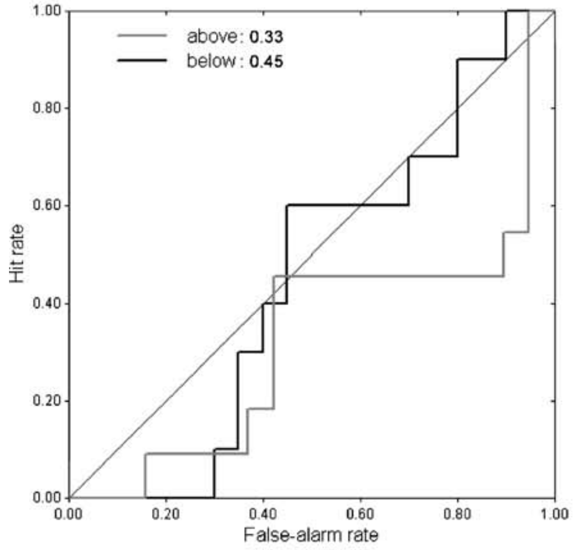
0.20
0.40
0.60
0.80
1.00
above: 0.50
below : 0.50

(d)


Hit rate
False-alarm rate
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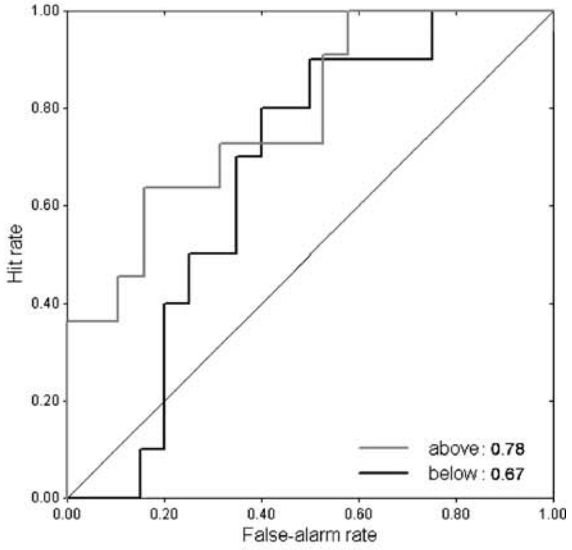
0.20
0.40
0.60
0.80
1.00
above : 0.33
below : 0.45

(e)


Hit rate
False-alarm rate
0.00
0.20
0.40
0.60
0.80
1.00
above : 0.78
below : 0.67

(f)

toward the top left, where hit rates are larger than false alarms, it is observed that northern Amazônia (Fig. 10a), Northeast Brazil (Fig. 10c), and northwest Peru–Ecuador (Fig. 10f) exhibit this tendency. Southern Amazônia (Fig. 10b) exhibit negative skill. For the other selected regions, the curve lies close to the diagonal, indicating that the forecast system does not provide useful information. Similar to the results presented by Marengo et al. (2003) the area under the ROC curve shows that the model is able to predict about 70% of the below-normal rainfall events and more generally about 50% of the above-normal events in all regions. In summary, the behavior of the ROC curves for regions such as Amazônia, Northeast Brazil, southern Brazil–Uruguay, and northwest Peru–Ecuador agrees with the analyses of the seasonal variability of model and observations and the deterministic score depicted by the anomaly correlation.

5 Conclusions

This study focuses on regional climate features and its seasonal variability as simulated by a three-member 30-year ensemble simulation (1961–1990) of the HadRM3P regional model forced with the boundary conditions from HadAM3P. The regional simulation reproduces reasonably well the spatial and temporal patterns of the precipitation and temperature and the main features of large-scale circulation that sometimes are not well captured by the low-resolution driving model. However, it is important to mention the systematic errors that exist in the regional simulation. For precipitation, the model shows underestimation over Amazon basin and overestimation over the Andes. Biases over regions of steep orography are due to deficiencies in the regional model itself (land-surface processes, convection scheme, and others). Overestimation of precipitation is a common behavior in regional simulations over mountainous regions (Giorgi et al. 2004; Solman et al. 2007). In spite of a better representation of the precipitation band related to the SACZ during the summer months, the regional model nevertheless fails to reproduce the observed rainfall amounts over Central Brazil.

Overall, the seasonal mean spatial patterns of the temperature agree reasonably well with observations, particularly in middle latitudes, where we observed strong thermal variability. However, some model biases have been identified, particularly over tropical regions, where a large cold bias occurs in all seasons. A cold temperature bias similarly exists over the Andes. However, it should be noted that the observed data used to evaluate model performance may also be dubious, particularly over mountainous and tropical regions where not too many stations reported data to the CRU, making it difficult to evaluate the model performance properly.

The difficulties of the regional model in representing adequately rainfall amounts and mean temperature notwithstanding, the annual cycle of precipitation, and temperature is well captured over almost all the sub-regions analyzed.

Although the results have shown that the regional model has good skill in the simulation of the present-day climate, it requires adjustments to the settings used by the model in order to correct the different systematic errors and ultimately to produce useful estimates of regional seasonal to interannual climate projections

The analysis undertaken in this study does not systematically diagnose the physical explanation of model errors but it suggests possible tracks for model improvement. The results here are encouraging, and support the use of RCMs in making future projections of climate change, then some final statement about spatial resolution and impacts studies.

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