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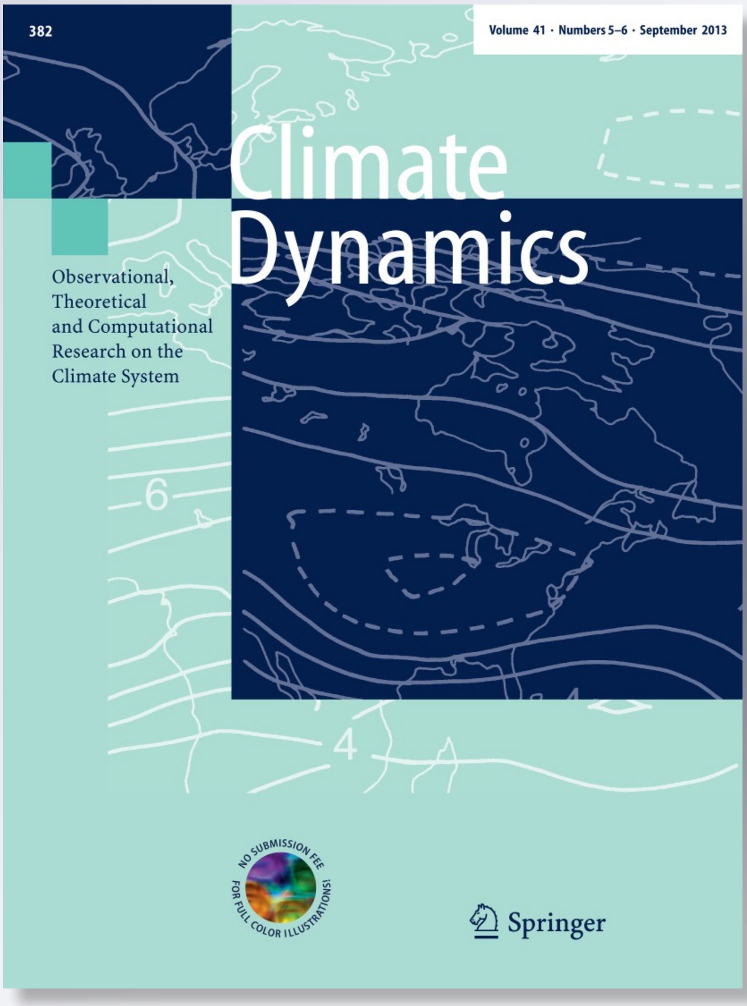
Climate Dynamics
Observational, Theoretical and Computational Research on the Climate System

ISSN 0930-7575
Volume 41
Combined 5-6

Clim Dyn (2013) 41:1139-1157
DOI 10.1007/s00382-013-1667-2



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Evaluation of an ensemble of regional climate model simulations over South America driven by the ERA-Interim reanalysis: model performance and uncertainties

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Received: 12 May 2012 / Accepted: 8 January 2013 / Published online: 22 January 2013
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Abstract The capability of a set of 7 coordinated regional climate model simulations performed in the framework of the CLARIS-LPB Project in reproducing the mean climate conditions over the South American continent has been evaluated. The model simulations were forced by the ERA-Interim reanalysis dataset for the period 1990–2008 on a grid resolution of 50 km, following the CORDEX protocol. The analysis was focused on evaluating the reliability of simulating mean precipitation and surface air temperature, which are the variables most commonly used for impact studies. Both the common features and the differences among individual models have been evaluated and compared against several observational datasets. In this study the ensemble bias and the degree of agreement among individual models have been quantified. The evaluation was focused on the seasonal means, the area-averaged annual cycles and the frequency distributions of monthly means over target subregions. Results show that the Regional Climate Model ensemble reproduces adequately well these features, with biases mostly within ±2 °C and ±20 % for temperature and precipitation, respectively. However, the multi-model

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ensemble depicts larger biases and larger uncertainty (as defined by the standard deviation of the models) over tropical regions compared with subtropical regions. Though some systematic biases were detected particularly over the La Plata Basin region, such as underestimation of rainfall during winter months and overestimation of temperature during summer months, every model shares a similar behavior and, consequently, the uncertainty in simulating current climate conditions is low. Every model is able to capture the variety in the shape of the frequency distribution for both temperature and precipitation along the South American continent. Differences among individual models and observations revealed the nature of individual model biases, showing either a shift in the distribution or an overestimation or underestimation of the range of variability.

Keywords Regional climate models · Mean climate · South America · CORDEX · Uncertainty

1 Introduction

Recent observational and climate modeling studies have highlighted the South American region as a region of particular vulnerability to climate change (Magrín et al. 2007). In recent years there has been an increasing demand from the impact community of climate change projections for designing adaptation strategies of sustainable development for the region. Although Global Climate Models (GCMs) are able to provide such information, the lack of fine-scale details limits the applicability of their results.

At present time, there has been a number of efforts for providing high-resolution climate change information at the regional level using Regional Climate Models (RCMs) over South America (Nuñez et al. 2009; Marengo et al. 2009, 2012; Urrutia and Vuille 2009; Kitoh et al. 2011). However, results are based on a single model realization, either using one driving GCM or one RCM. These studies are insufficient in providing a measure of uncertainty needed for a comprehensive evaluation of potential climate change. Lessons learned from previous studies suggest that ensembles of RCMs provide improved information at the regional level (Jacob et al. 2007 for Europe; Rinke et al. 2006 for the Arctic region, Mearns et al. 2009 for North America, Marengo et al. 2010 for South America among others). Within the context of the CLARIS-LPB Project (A Europe-South America Network for Climate Change Assessment and Impact studies in La Plata Basin; http://www.claris-eu-org), a framework for a coordinated experiment using different RCMs has been organized. The goal of this project is to provide an ensemble of climate change projections over South America (hereafter SA) and their underlying uncertainties. The first step before providing high-resolution climate change projections includes a detailed evaluation of the capability of the RCMs for simulating present-day regional climate and an assessment of the level of uncertainty of such simulations. In this regard, a set of seven RCMs simulations; driven by the ERA-Interim reanalysis (Simmons et al. 2007) for the period 1990–2008 have been performed, which covers the whole South American continent and adheres to the CORDEX framework (Giorgi et al. 2009).

The foci of this study are twofold. First, we aim to evaluate the capability of the RCM ensemble to represent observed climate over SA, which includes the identification of the main strengths and shortcomings of the state-of-the-art dynamical downscaling tool for the region. This evaluation will serve as a basis for possible model improvement. Second, we aim to characterize the uncertainty in simulating the South American climate. The uncertainty will be evaluated in terms of the spread among different RCMs, which allows identifying the degree of agreement or disagreement among models and therefore a measure of the confidence level among the current South American climate simulations.

In this paper, an overall evaluation of the RCM's ensemble is performed, which focuses mainly on the seasonal mean precipitation and near-surface temperature. Consequently, the annual cycles and empirical frequency distributions over particular sub-regions within the South American continent are analyzed. These variables have been selected for this overview because they are useful for impact studies.

The participating models and experimental design are described in Sect. 2, including the observational datasets used to evaluate each model performance. Results of the evaluation are presented in Sect. 3 for both 2-meter temperature and precipitation for the seasonal mean spatial patterns, mean annual cycles and frequency distribution of monthly means over key sub-regions. Section 4 presents a discussion on main shortcomings, strengths, uncertainties and the main conclusions.

2 Models, experimental design and data

2.1 Models and experimental design

This study includes simulations of seven RCMs from institutions participating in the coordinated experiment within the CLARIS-LPB Project. The experimental set up follows the CORDEX protocol Phase I (http://wcrp.ipsl.jussieu.fr/SF_RCD_CORDEX.html, Giorgi et al. 2009). Each model has been configured to cover the South American domain bounded by 60°S–15°N and 90°W–20°W.

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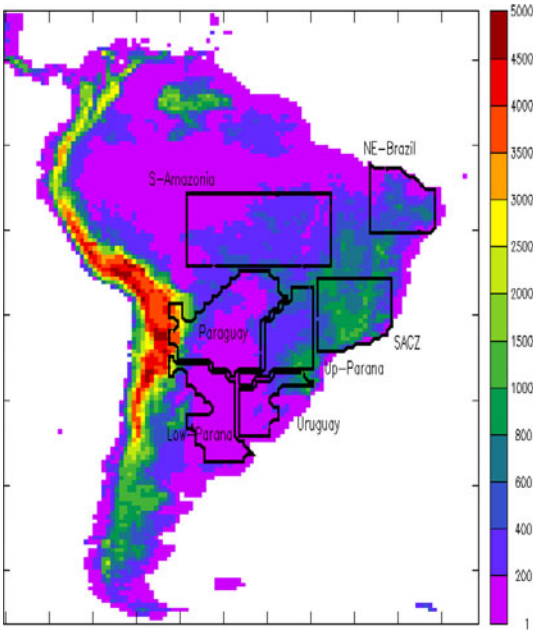

Fig. 1 Model domain and topography (*shaded* with units in m). Seven bounded regions for further statistics (e.g., area averages) are depicted: South Amazon (S-Amazonia), Northeast Brazil (NE-Brazil), Paraguay, Uruguay, Upper (Up-Parana) and Lower (Low-Parana) Paraná

Figure 1 shows the domain and topography. Seven bounded regions for further statistics (e.g., area averages) are depicted: South Amazon (S-Amazonia), Northeast Brazil (NE-Brazil), Paraguay, Uruguay, Upper (Up-Parana) and Lower (Lo-Parana) Paraná. All models were integrated on a horizontal grid of roughly 50 km resolution (around 0.44°–0.48° lat/lon) and the initial conditions and 6-hourly lateral boundary conditions were provided by the ERA-Interim reanalysis dataset (Simmons et al. 2007; Dee et al. 2011) including the prescribed weekly sea surface temperatures (SST). The reanalysis used by the RCMs is on a 1.5° resolution, except for the MPI and the IPSL models that were forced on a 0.75° resolution. Further evaluation on using the same boundary conditions but with different resolutions has not been performed.

Each simulation covers the 1990–2008 period including spin-up periods defined in Table 1. Note that the MM5 is the only model using nudging within the interior model domain. Due to different parameterizations among models, soil moisture and soil temperature have been initialized by each group individually. Table 1 summarizes the main characteristics of each model and its basic references.

Table 1 Basic information of the participating models

Model	Responsible institution/model version	Type of grid	Number of grid points	Number of levels	LBC, nudging zone	Spin-up period	Basic references
RCA	Rossby Centre, Swedish Meteorological and Hydrological Institute/RCA3.5	Rotated lat/lon	134 × 155	40	Davies (1976)/8 points	11 months	Samuelsson et al. (2010) Samuelsson et al. (2011)
REMO	Max-Planck-Institute for Meteorology, Hamburg/REMO2009	Rotated lat/lon	151 × 181	31	Davies, 1976)/8 points	20 years	Jacob et al. (2001) Jacob et al. (2012)
PROMES	Grupo MOMAC, Area Física de la Tierra, Facultad Ciencias Medio Ambiente, Universidad Castilla-La Mancha/PROMES2.4	Lambert conformal	145 × 163	37	Davies (1976)/10 points	12 months	Sanchez et al. (2007) Domínguez et al. (2010)
REGCM3	GrEC-USP, Departamento de Ciencias Atmosféricas, Universidade de Sao Paulo, Brail/RegCM3	Rotated Mercator	190 × 202	18	Davies (1976)/12 points	12 months	Pal et al. (2007) da Rocha et al. (2009)
MM5	Centro de Investigaciones del Mar y la Atmósfera CIMA/MM5V3.7	Mercator	150 × 203	23	Nudging of the winds above PBL (Stauffer and Seaman 1990)/8 points	2 months	Grell et al. (1993) Solman and Pessacg (2012a)
LMDZ	IPSL, Institute Pierre-Simon Laplace/LMDZ4	Irregular rectangular lat/lon	184 × 180	19	Relaxation/32 points	12 months	Hourdin et al. (2009) Li (1999)
ETA	Instituto Nacional de Pesquisas Espaciais, INPE/ETA Climate change V1.0	Regular lat/lon	123 × 245	38	Mesinger (1977)/1 point	12 months	Pesquero et al. (2010) Chou et al. (2011)

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2.2 Data

Table 2 lists several gridded datasets that have been used for evaluating the model performance. Due to sparse in situ observations of both rainfall and temperature over SA, gridded products may differ from each other (Negrón Juárez et al. 2009). The use of different datasets allows the evaluation of the uncertainty in the observations, which will be further used to compare the uncertainty in the model simulations. Precipitation datasets include four gauge-based products over land: GPCC, CRU, UDEL and CPC-UNI. For temperature, two gridded datasets have been used: CRU and UDEL. The selected datasets are available on a 0.5° grid, which ensures the compatibility and spatial representativeness between models and observations.

3 Results

In this section, results of the multi-model ensemble statistics in terms of ensemble mean and inter-model spread are presented. Several questions are addressed such as the extent of each model's capability to reproduce the long-term mean climate and the similarity among the model's performance in terms of variables and regions. This analysis identifies the regions and the variables with high or low confidence from the so-called state-of-the-art RCMs. There may be a consensus among models but each model can have similar biases in reproducing the observed climate thus common problems within the models can be identified. The ensemble mean bias and the inter-model spread are measures to critically evaluate the capability of simulating South American climate and to evaluate the level of uncertainty of the simulations. Moreover, different observational datasets also display some discrepancies among each other (Negrón Juárez et al. 2009; McGlone and Vuille 2012), so the spread among these datasets are compared with the spread among models. It is interesting to put the inter-model spread in the context of the natural variability. This aims to examine whether the differences among models can be considered considerably larger or not with respect to the observed natural variability, which is largely triggered by the control exerted by the driving fields.

All models use different grid types, therefore each model's results are interpolated into a common grid for intercomparison. The interpolations have been performed on the monthly mean values for both temperature and precipitation of each model onto a regular grid with 0.5° resolution. Accordingly, the gridded observational datasets are also interpolated onto the same grid for intercomparison. The temperature variables are interpolated using a bilinear interpolation procedure. A height correction has been applied in the interpolation procedure, which takes

Table 2 List of gridded precipitation and 2-meter temperature datasets

Dataset	Frequency	Horizontal resolution	Available period	Spatial coverage	Data source	References and availability
Precipitation						
GPCC	Monthly	0.5°	1901–present	Land	Rain gauge	Rudolf and Schneider (2005) available online from http://gpcc.dwd.de
UDEL	Monthly	0.5°	1900–2008	Land	Rain gauge	Data provided by the NOAA/OAR/ESRL PSD, Boulder Colorado http://www.ersl.noaa.gov/psd/ Matsuura and Willmott (2009)
CRU	Monthly	0.5°	1901–2009	Land	Rain gauge	University of East Anglia Climate Research Unit (CRU TS3.1) available from the CLARIS-LPB data base. Mitchell and Jones (2005)
CPC-UNI	Daily	0.5°	1979–present	Land	Rain gauge	NOAA Climate Prediction Center Unified Precipitation Analysis (Chen et al. 2008). ftp.cpc.ncep.noaa/gov/precip/ CPC_UNI_PRCP
Temperature						
UDEL	Monthly	0.5°	1900–2008	Land	Station data	Data provided by the NOAA/OAR/ESRL PSD, Boulder Colorado http://www.ersl.noaa.gov/psd/ Matsuura and Willmott (2009)
CRU	Monthly	0.5°	1901–2009	Land	Station data	University of East Anglia Climate Research Unit (CRU TS3.1) available from the CLARIS-LPB data base. Mitchell and Jones (2005)

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into account the height difference between each native RCM grid and the observed regular grid. A standard lapse rate of 6.5°/km has been used. The precipitation variables are interpolated using a first order conservative remapping.

3.1 Seasonal means: multi-model ensemble performance

Figure 2 shows the spatial distribution of the seasonal mean temperature at 2-meter for austral winter (JJA) and summer (DJF) from the ensembles of observations and RCMs. The seasonal ensemble bias is also indicated and is calculated as the difference between the ensemble mean of observations and RCMs. The overall distribution of the mean temperature across the South American continent is well reproduced by the multi-model ensemble mean during both seasons in terms of temperature gradients and magnitude of the seasonal means. During JJA, observations display the highest temperatures over the Amazon region with a marked North–South temperature gradient from 10°S to 40°S and contrasting low temperatures all along the Andean region. During DJF, the warmest regions are located over western Paraguay, northern Argentina and over northeastern Brazil. The ensemble of RCMs reproduces these main features though the ensemble bias reveals a large bias over tropical regions during JJA. The ensemble mean of RCMs is about 3 °C warmer than the observations.

The mean bias over the La Plata Basin (LPB) during the austral winter season is generally less than 1 °C. During DJF, the largest bias is located over central and northeastern Argentina, which encompasses the LPB area. The values are larger than 3 °C, which indicates that the RCMs are warmer compared to the observations. The RCMs' ensemble mean also overestimates the mean temperature over tropical SA by about 1.5 °C. Note that there is a systematic underestimation of the mean temperature during both seasons over the Andean regions. Urrutia and Vuille 2009 have also found a similar behavior with the PRECIS model. It is important to note also that the quality of observational datasets over areas with complex topography is critical for evaluating model performance as pointed out by several authors (e.g., Rauscher et al. 2010; Urrutia and Vuille 2009). Consequently, the model bias over that area should be interpreted with care. Over the Patagonian region the model ensemble underestimates the temperature by about 1–2 °C during both seasons.

The seasonal mean precipitation patterns for austral winter and summer as depicted by the ensemble mean of observations and RCMs, and the bias from the ensemble are shown in Fig. 3. During JJA, the overall distribution of precipitation is reasonably well reproduced by the models' ensemble in terms of both the spatial distribution and the magnitude of the seasonal mean precipitation (Fig. 3b). However, the remarkable feature is the strong underestimation of rainfall over southern Brazil, Uruguay and northeastern Argentina by more than 40 mm/month, which is about 40 % of the observed precipitation. The maximum precipitation associated with the intertropical convergence zone (ITCZ) over the north-eastern part of the continent (over Guyana and Suriname) is also underestimated. Large overestimates are also found over the Andean slopes. Again, the reliability of the gridded observational datasets over the Andes Mountains is questionable, so verification over that region is difficult.

During DJF, the precipitation maxima over the Amazon basin extending over the South Atlantic Convergence Zone (SACZ) region, the rainfall tongue over northern Argentina and the maximum over the southern Andes are features well reproduced by the models (Fig. 3e). However, the models tend to underestimate rainfall over the Amazon (by about 20 %) and over the northern part of the continent. Over the LPB region, precipitation is slightly underestimated (around 15 %). As for winter, rainfall is overestimated over the upstream slopes of the Andes. Other modeling studies over the Andean region have also shown a systematic wet bias, in particular along the eastern Andean slope during the wet season (Urrutia and Vuille 2009).

In general, temperature and precipitation biases are negatively correlated during summer months, which may be due to the strong dependence of these two variables on model physics during that time of the year. During winter, except over the Andes Mountains, there is no clear-cut relation between temperature and precipitation biases.

3.2 Seasonal means: inter-model spread

The biases discussed for both temperature and rainfall are based on the ensemble mean of the RCMs. In order to evaluate common shortcomings and strengths of RCMs and to identify the level of uncertainty in the simulations, the spread among RCMs is examined. The spread among models is calculated as the standard deviation of the 19-year mean of each individual model with respect to the model ensemble mean. Moreover, in order to put the inter-model spread into context, the spread among observational datasets and the ratio between the inter-model spread and the interannual variability are also analyzed. The spread among observational datasets is calculated in the same way as for the models. Note that the spread of the observations for temperature is calculated using two datasets only. The interannual variability is computed as the standard deviation of monthly values with respect to the climatological monthly mean. The mean interannual variability is calculated as the average of the variability of each individual observational data set. Ratios smaller than 1 indicate that

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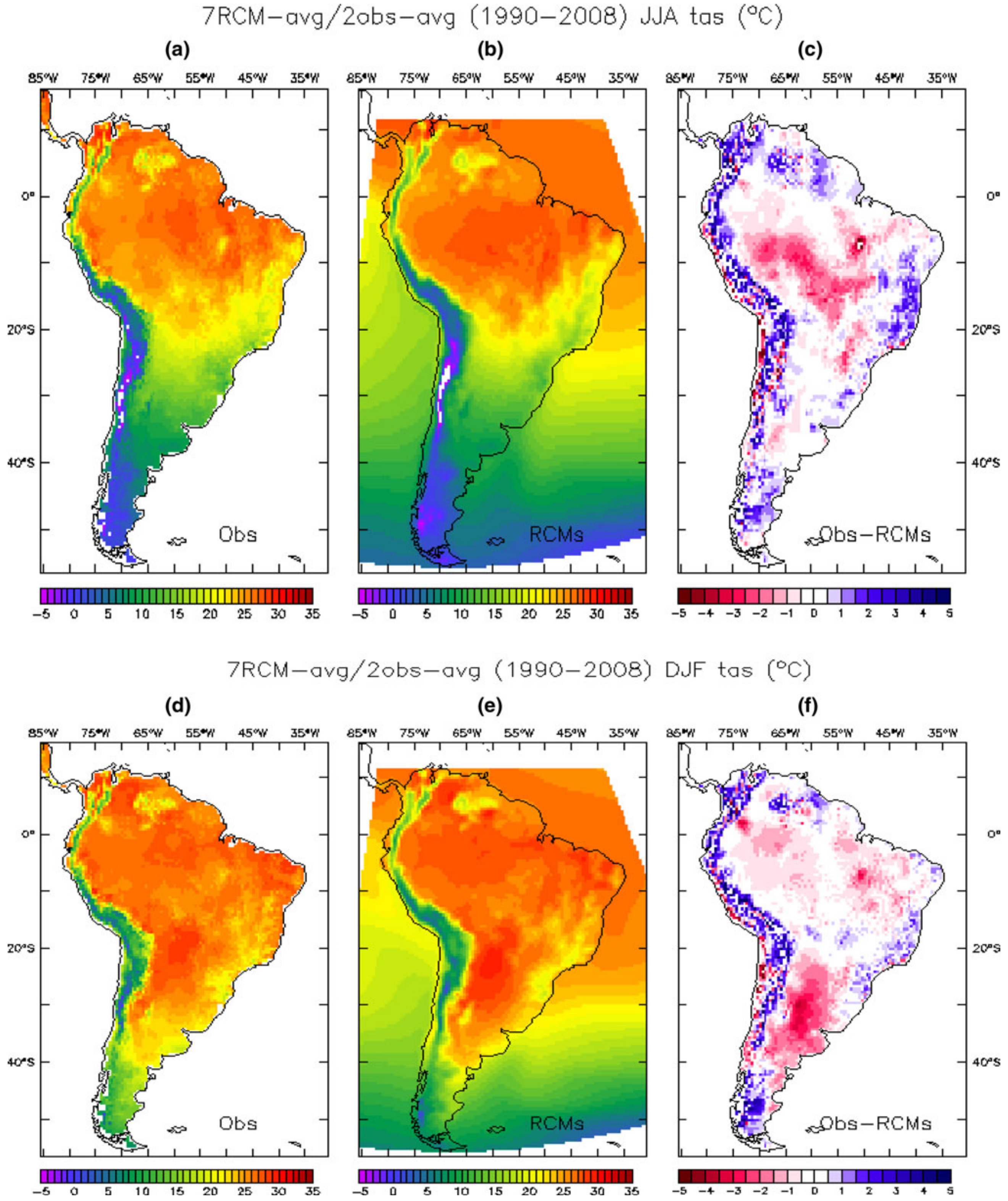

Fig. 2 The seasonal mean temperature for JJA (*top panel*) and DJF (*bottom panel*). The units of the mean ensemble of observations (**a**, **d**) and RCMs (**b**, **d**) and the bias of the two ensemble means (**c**, **f**) are in °C. For the bias, *red* (*blue*) *shading* indicates that the model ensemble is warmer (colder) than the observed values

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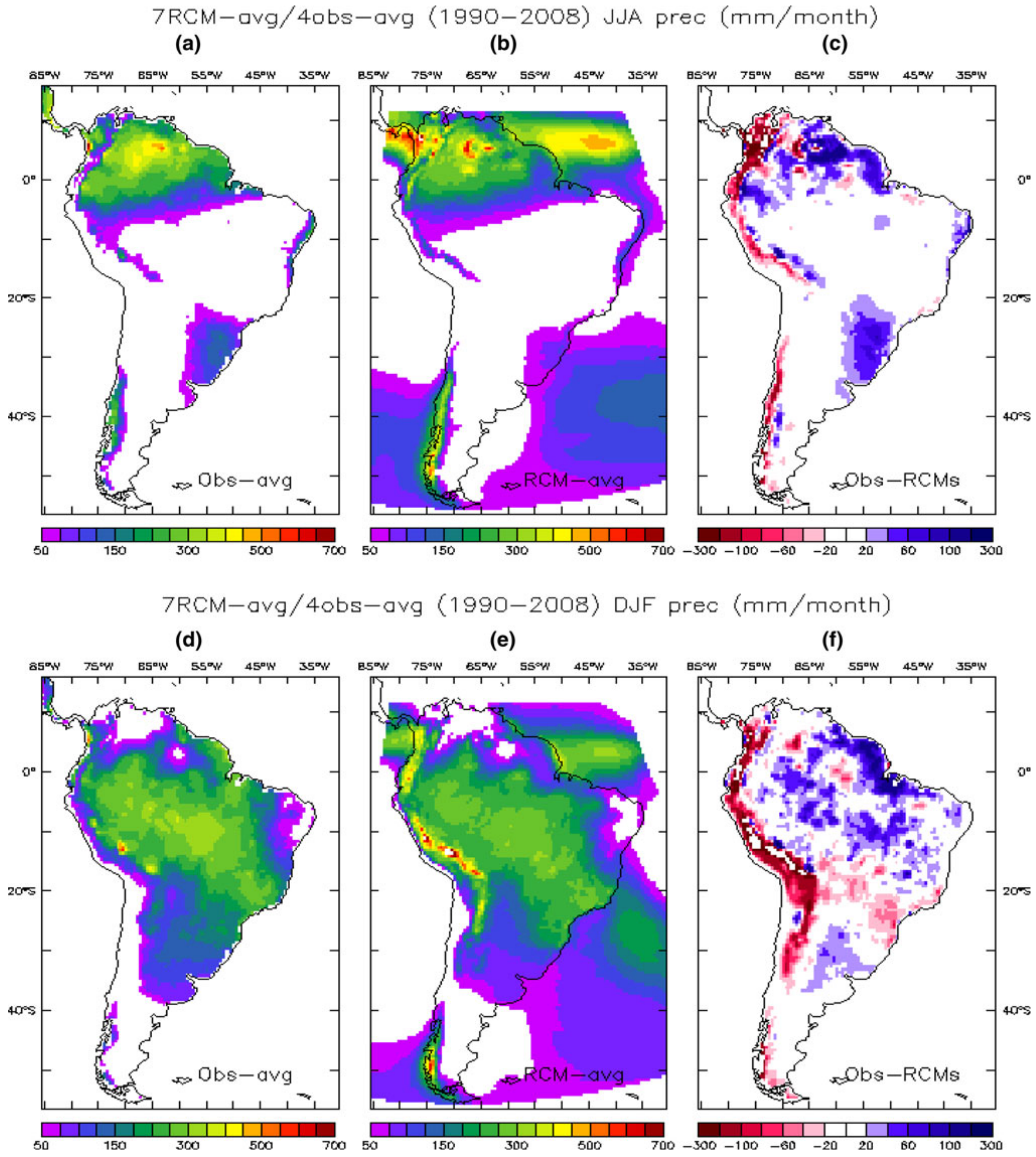

Fig. 3 Same as Fig. 2 but for precipitation. Units are mm/month. For the bias, *red* (*blue*) *shading* indicates that the model ensemble is wetter (drier) than the observed values

the scatter across models is smaller compared with the natural variability and, consequently, the uncertainty is relatively low. Ratios larger than 1 indicate that the driving fields have limited control on the simulated climate and consequently the uncertainty of the model is considerably large (Rinke et al. 2006).

Figure 4 displays the seasonal temperature spread among the observational datasets and RCMs, and the

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abovementioned ratio. During JJA (Fig. 4b), the regions with the largest spread among models, which values range from 1.6 to 3 °C, are located over the subtropical Andes, the Amazon region and southern Patagonia. Conversely, the inter-model spread over the LPB and eastern Brazil regions are generally below 1 °C. These differences in simulating temperature among different models may be due to different treatment of the key physical processes, such as the surface energy budget, which involves a variety of physical schemes for radiation, land-surface and clouds. Note that the spread among observational datasets is also large all along the Andes, with values ranging from 1 up to 3 °C. This observational dataset spread may be due to different interpolation algorithms used, which may be critical over regions of complex terrain where the number of stations available is reduced. Over the central Amazon, the observational datasets also present differences of around 1 °C, which is probably due to relatively poor coverage of observations.

It is interesting to note that both the inter-model spread and the ensemble bias over the subtropical Andes are larger than 2 °C (Fig. 2c). This result suggests a high uncertainty and low confidence on regional simulations over the Andean regions. A closer inspection of individual model performance (not shown) reveals that over the Amazon region, 4 (3) out of 7 RCMs overestimate (underestimate) winter temperature. In contrast, over LPB both the inter-model spread and the ensemble bias are small, which suggests that the reliability in simulating winter temperature is high and the uncertainty is low. The ratio between the ensemble spread and the interannual variability (Fig. 4c) reveals that the inter-model scatter is smaller than the natural variability over most of subtropical SA and particularly over the LPB area, which indicates that the uncertainty in simulating winter temperature is low. The uncertainty is considerably larger compared with the natural variability over the Amazon, Northeastern Brazil and subtropical Andes.

During DJF (Fig. 4e), the uncertainty of the observational datasets remains similar to that of JJA. The areas where the temperature spread among models is larger (around 3 °C) are located over the Amazon basin, northeast Brazil and north-western Patagonia. However, over these areas, the ensemble bias is small (Fig. 2f) due to compensation of positive and negative biases of individual RCMs. Over the LPB and central Argentina, the inter-model scatter is smaller than 1 °C, except over some particular regions where the inter-model scatter is slightly larger. However, the ensemble bias is large (more than 2 °C), which indicates that the models agree with each other and share similar biases. The ratio between the inter-model spread and the natural variability (Fig. 4f) is larger than 1 over most of SA, indicating that the uncertainty in simulating summer temperature is considerably high, particularly over tropical SA.

The observational and inter-model spread for precipitation together with the ratio between the inter-model spread and the interannual variability during JJA and DJF are displayed in Fig. 5. During JJA, the uncertainty in the observational datasets is close to 18 % over northern SA, LPB and southern Andes. The largest values of inter-model spread are located over the same regions with values close to 30 % and are larger than the observational uncertainty, which is expected. Moreover, areas with the largest inter-model spread are also areas with the largest ensemble bias (Fig. 3c). A closer look at the individual model biases (not shown) reveals that individual model behavior is very different from each other over northern SA with some models either overestimating or underestimating. A similar behavior is found over the subtropical Andes region; however, this behavior may be attributed to the different model orography, which is then spatially interpolated to a common grid. Over the LPB region, though large values of inter-model spread are found, each individual model underestimates rainfall at different magnitudes. Consequently, the underestimation of wintertime precipitation over LPB seems to be a systematic shortcoming of each RCM. This result is not only given by other authors using RCMs but also based on simulation results from GCMs (Solman et al. 2008; Chou et al. 2011; Carril et al. 2012, Vera et al. 2006). Wintertime precipitation over this area is mainly due to synoptic scale activity. South-eastern South America is one of the regions in the Southern Hemisphere where the largest cyclogenetic activity occurs (Gan and Rao 1991; Reboita et al. 2010; Mendes et al. 2010). Though the reasons for this systematic model shortcoming are not clear, it is possible that the models are not able to capture the amplitude of this synoptic activity. This hypothesis is being evaluated in a separate study. Despite these systematic and non-systematic biases, the ratio between the inter-model spread and the interannual variability (Fig. 5c) remains smaller than 1 over most of the continent, which indicates that the RCMs' uncertainty is low except over the Andes.

During DJF, the observational uncertainty for precipitation is largest (about 10 %) over tropical areas of SA, and is smallest over the LPB region (Fig. 5d). The inter-model spread over tropical SA is around 60 mm/month, close to 15 % of the summertime precipitation, but some areas with larger spread are found over northern Amazonia and the SACZ region. The Andes region is also affected by a large spread among models. The inter-model scatter over LPB is smaller compared with that over tropical SA (around 30 mm/month) although it accounts for 30 % of the summertime precipitation. As during JJA, the areas with the

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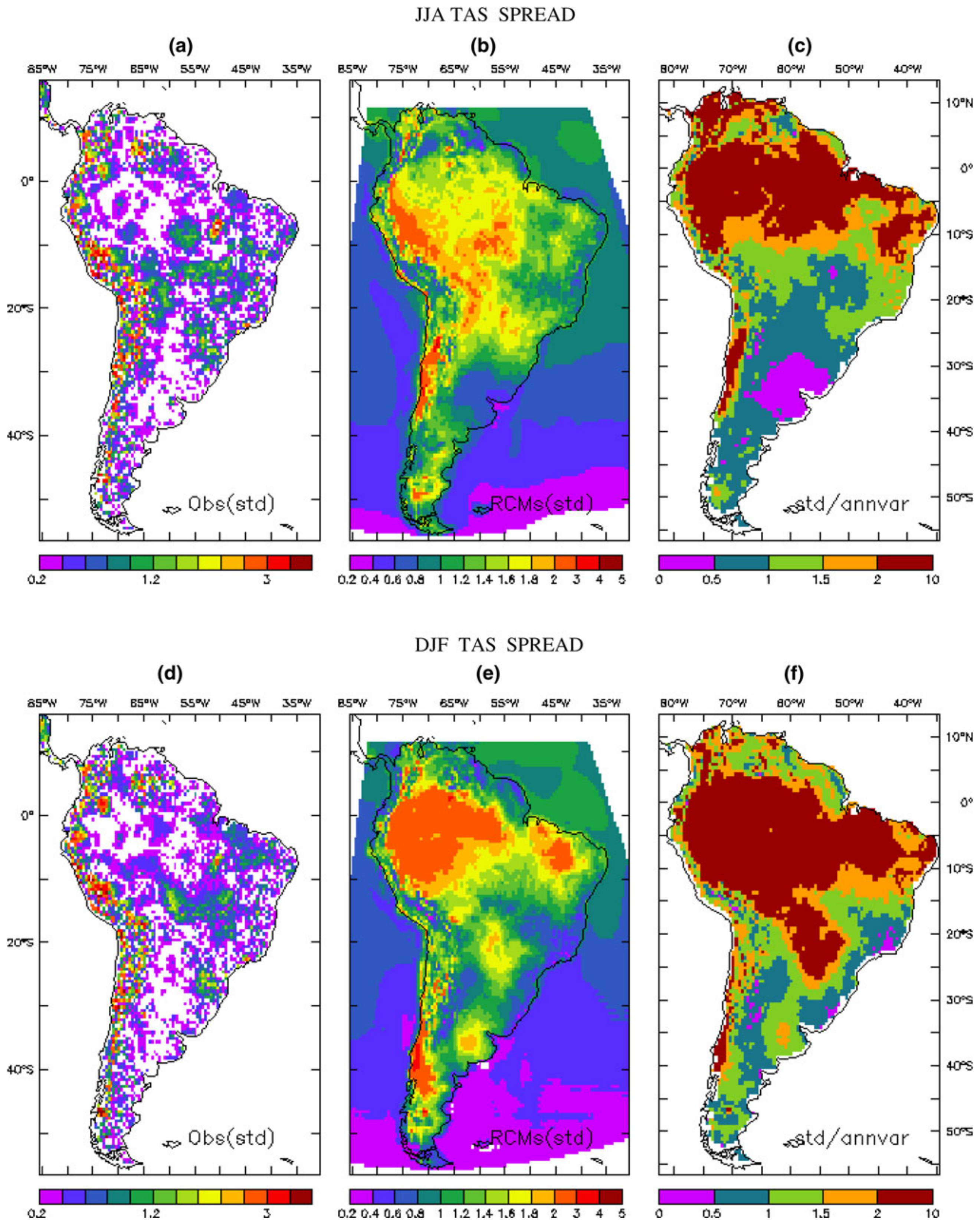

Fig. 4 Seasonal spread for austral winter (*top panel*) and summer (*bottom panel*). Spread among observational datasets (**a**, **d**) and among individual RCMs with respect to the ensemble mean for temperature (**b**, **e**). Units are in °C. The ratio between inter-model spread and interannual variability from observations (**c**, **f**) are unitless

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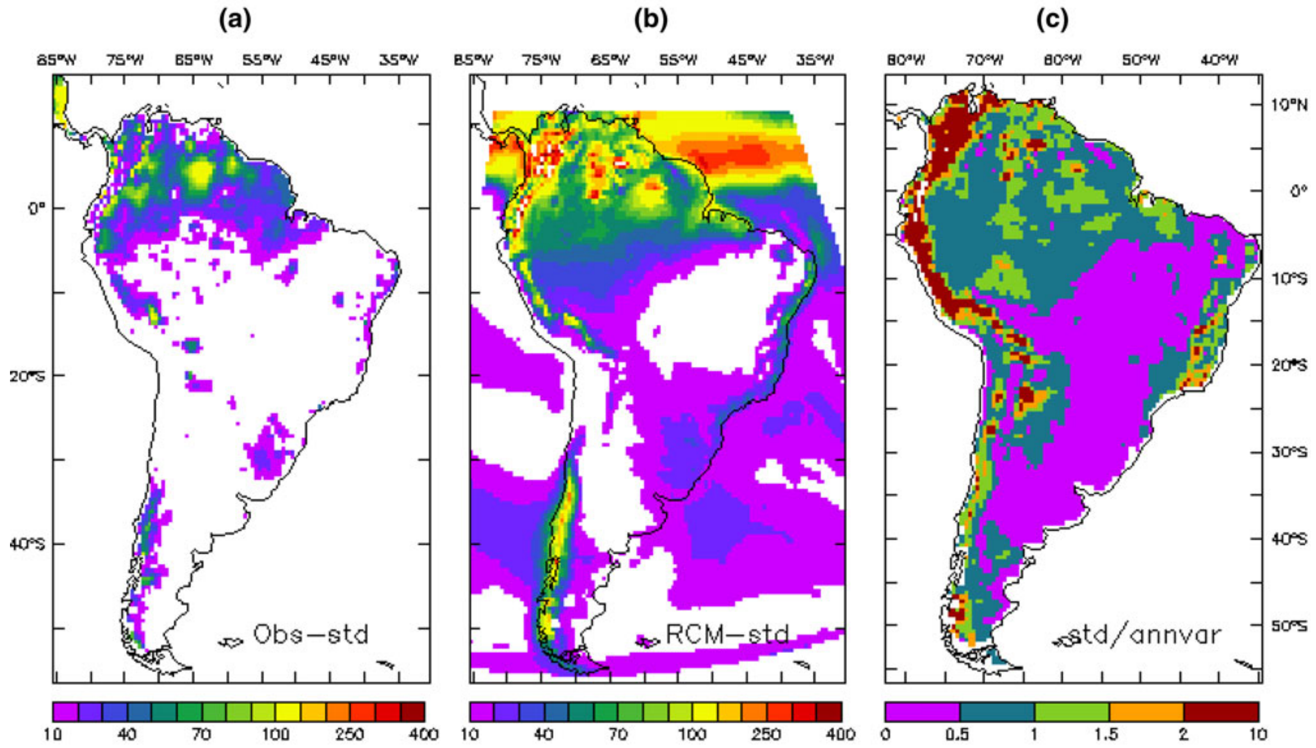
JJA Precipitation SPREAD



DJF Precipitation SPREAD

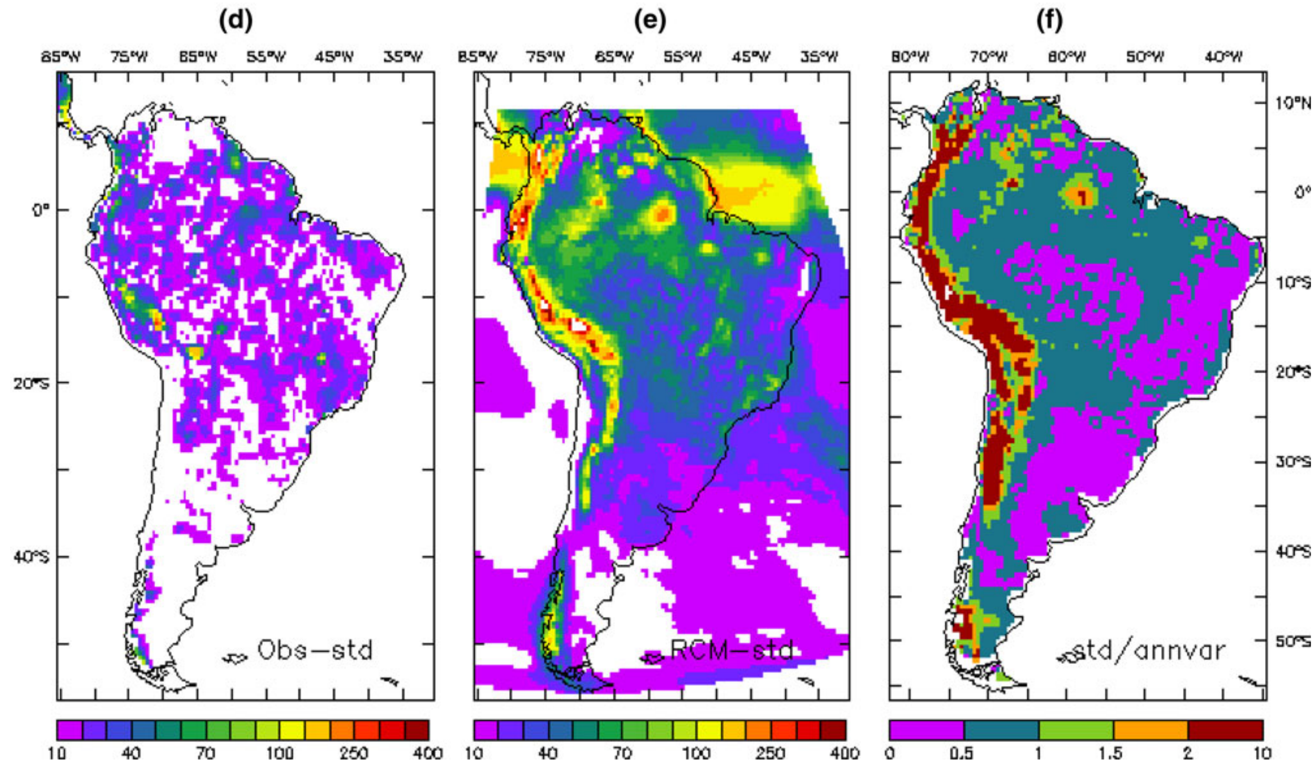


Fig. 5 Same as Fig. 4 but for precipitation. Units are in mm/month

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largest uncertainty are also areas with the largest absolute ensemble bias. Moreover, individual model biases are very diverse over tropical areas due to the strong influence of individual physics on summertime precipitation. As for JJA, every model has negative bias during DJF over LPB, which again suggests a common deficiency in simulating the region's summertime precipitation of each model. Each model overestimates precipitation on the upstream slope of the southern Andes, which is in agreement with other modeling studies where orographic precipitation is always larger compared with observations (Walker and Diffenbaugh 2009; Lucas-Picher et al. 2012). As for JJA, the ratio between the inter model spread and the interannual variability (Fig. 5f) is smaller than 1 over most of the continent, indicating that uncertainty in simulating DJF precipitation is low over most of the continent except over the Andes.

Summarizing the main findings, the LPB region is characterized by systematic biases in both temperature and precipitation but the uncertainty is low. Consequently, the reliability of the RCMs simulations is high and a bias correction methodology may be applied in order to improve models' accuracy. Over tropical regions of SA, large uncertainty and large bias suggest low reliability and limited capability in reproducing observed climate conditions.

3.3 Annual cycle of temperature and precipitation

The annual cycles of temperature and precipitation have been calculated for several sub-regions shown in Fig. 1, which have been defined in terms of their distinctive hydroclimatic characteristics. For each region, area averages of monthly temperature and precipitation are computed considering land-only grid points. Results are shown in Figs. 6 and 7 for temperature and precipitation, respectively. Individual model results are displayed together with the ensemble mean and the discussion is not intended to evaluate the ability of each individual model, but to understand the agreement or disagreement among them.

Over S-Amazonia, which comprises the South American Monsoon region, most of the models follow the observed annual cycle of temperature, which reaches a maximum in October and a minimum in July. The timing of the maximum and minimum is fairly well reproduced in the models but the amplitude does not exactly fit the observations. The spread among models is large from August to December (up to 9 °C for September and October), which is larger than the amplitude of the observed annual cycle itself. The relevance of surface processes and the way that the surface energy and water budgets are treated in each model may explain the large uncertainty during this part of the year. Moreover, the treatment of clouds could also have an effect on temperature. The ensemble mean of the models accounts for a compensation of individual model biases and reproduces the annual cycle better than the individual members of the ensemble.

Over NE-Brazil, each model reproduces the correct timing and amplitude of the annual cycle. The spread among models ranges from 3 to 4 °C all year long, which is larger than the amplitude of the annual cycle. This spread suggests that although the uncertainty in reproducing the seasonal evolution of temperature is smaller than over S-Amazonia, it is still considerably large. However, the models' ensemble mean is able to capture both the amplitude and the timing of the observed annual cycle due to compensation of individual model biases. Over the SACZ region, each model reproduces fairly well the main features of the annual cycle and the ensemble mean of the models is close to the observations throughout the year. The discrepancy between the two observational datasets ranges from 1 to 2 °C with maximum values during winter months. The spread among models varies from 2 to 4 °C with the largest discrepancies during spring.

Over the sub-regions within the LPB, the models capture quite well the seasonal evolution of temperature. Over the northern part of the basin (Paraguay and Up-Paraná) the inter-model spread is larger than over the southern part of the basin (Low-Paraná and Uruguay) and individual model biases are diverse. For each region within the LPB area, the spread among the models is smaller than the range of seasonal variation while larger spreads are still found during the warmest months. The warm bias identified in Fig. 2 during DJF is systematic only over the Low-Paraná region from October to March, which reaches up to 5 °C.

By comparing individual model behavior within the selected sub-regions, it is evident that no single model outperforms the others over the entire South American domain. Some models reproduce the observed climatology better than others in some regions but not all. Figure 6 also highlights that during the monsoon season from October to April, the uncertainty in simulating the observed temperature over most of SA is larger and the ability of the models deteriorates over regions located in tropical latitudes. In other regions such as the LPB and SACZ, the RCMs are able to reproduce the annual cycle of temperature with small biases and with low uncertainty. Note that the uncertainty is smaller compared with the natural interannual and seasonal variability. In order to understand the major shortcomings of RCMs in simulating temperature, it is worth examining the ability of the models in reproducing the annual cycle of precipitation. In most of the regions the precipitation bias and the temperature bias are strongly correlated.

The annual cycle of precipitation over the selected sub-regions from the models and the gridded observational datasets are displayed in Fig. 7. Over these sub-regions, the

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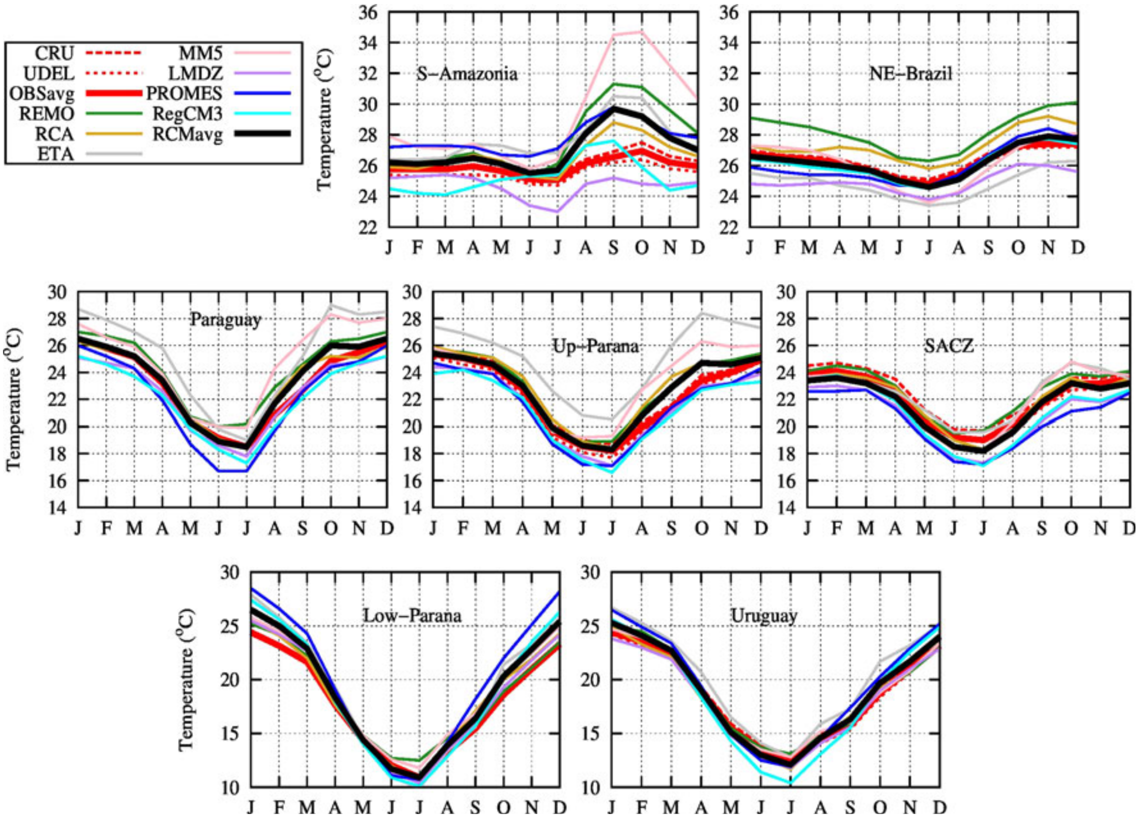

Fig. 6 Annual cycle of temperature averaged over sub-regions defined in Fig. 1. *Solid lines* indicate individual RCM and *thick black line* indicates the ensemble mean of the RCMs. *Dashed lines* are individual observational datasets and *thick red line* is the ensemble mean of the observations. Units are in °C

annual cycle of precipitation is well reproduced by most of the models in terms of the timing of the maximum and minimum precipitation, the amplitude of the annual cycle and the amount of monthly precipitation; however, some deficiencies are obvious. Over S-Amazonia, the largest discrepancies among RCMs occur during the life-cycle of the monsoon. Note that during the onset of the monsoon (October to November), some models overestimate and some models underestimate rainfall. However, almost all models showed a strong overestimation of 2-meter temperature. This may be related to the treatment of land-surface processes such as soil moisture feedbacks, which are relevant over this region.

Over NE-Brazil, two out of seven models overestimate rainfall by more than 50 % during the rainy season while the rest of the models show a strong underestimation, though the annual cycle computed from the model ensemble is close to the observations. This shortcoming could be related to the way each model represents the convection along the ITCZ. However, the timing of the maximum precipitation is well captured by every model. Note that the models overestimating (underestimating) rainfall during the rainy season underestimate (overestimate) the 2-meter temperature and the model with the largest or the smallest rainfall bias is not the same model affected by the largest or smallest temperature bias.

Over the SACZ region, the annual cycle and the amount of precipitation is closely reproduced by the members of the model ensemble except for one, which shows a systematic overestimation of 40 mm/month throughout the year (representing more than 50 %). However, it is remarkable that each member of the model ensemble is capable of reproducing the timing of the onset and decay of the monsoon.

For the northern part of the LPB basin, the amplitude and phase of the annual cycle is well reproduced over Paraguay and Up-Paraná. Most of the models tend to overestimate the amount of rainfall during the rainy season (5 out of 7 models) over Paraguay. Over Up-Paraná, a systematic dry bias is apparent from April to October. In the southern part of the basin the annual cycle is characterized by a reduced amplitude over the Low-Paraná and Uruguay regions compared to the northern part, which is properly captured by the models. The timing of the maximum rainfall during March over Low-Paraná is captured by the models, though most of them underestimate the rainfall amount. Over Uruguay, rainfall peaks in April and October. Only few models are capable of capturing this

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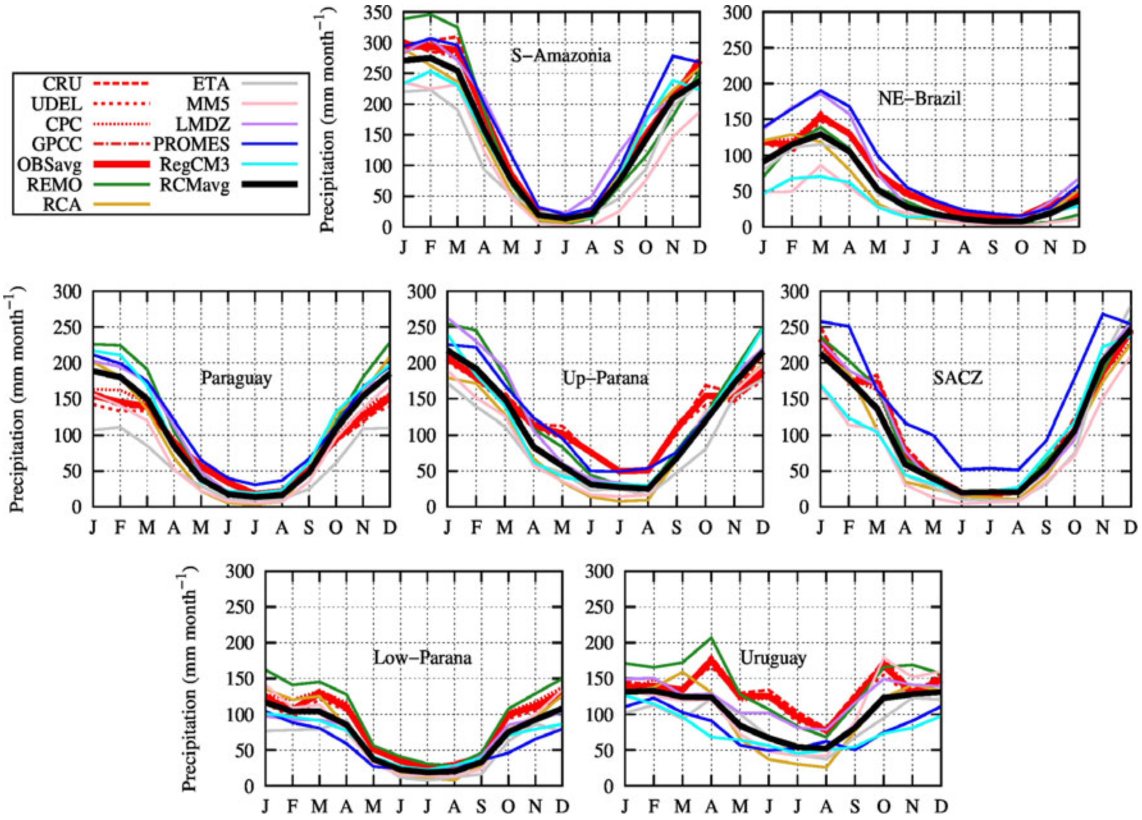

Fig. 7 Same as Fig. 6 but for precipitation. Units are in mm/month

behavior. The members of the model ensemble, except for REMO, underestimate the rainfall amount all along the year, with some of the models being 50 % drier than observations during winter months. As mentioned previously, this is a common shortcoming of RCMs and GCMs.

As for temperature, no single model outperforms over all regions. Moreover, most of the individual model biases are not uniformly distributed throughout the year or throughout the target regions. The ensemble mean of the RCMs reproduces realistically the observed mean annual cycle of rainfall due to compensation of positive and negative biases from individual models over most of the regions within the South American continent.

3.4 Frequency distribution of monthly temperature and precipitation

To this point, the evaluation of RCMs has been focused on the spatial distribution of seasonal means and climatological annual cycles of temperature and precipitation over target regions. In order to have a better understanding of the behavior and the biases of the models, the empirical frequency distributions of monthly temperature and precipitation have been calculated over the selected subregions. The evaluation of frequency distribution diagrams allows assessing the capability of the models in representing the variability of monthly temperature and precipitation. The RCMs are evaluated to describe the entire range and frequencies of rainfall intensities and temperature. In addition, it allows evaluating whether the RCMs are able to simulate the occurrence of extreme climatic events (Tapiador et al. 2007; Kjellström et al. 2010). This analysis will establish a degree of confidence in projections of climate change, particularly related to changes in the occurrence of extreme climatic events.

For each sub-region, a single monthly time series of individual models are constructed by concatenating the 19-years monthly time series of every grid-point within the region. The histograms of each individual model distribution, which are normalized by the length of the time-series, are calculated with bin widths of 0.5 °C and 3 mm/month for temperature and precipitation, respectively. The same procedure is carried out for the observational datasets. The normalized frequency distribution for the ensemble of models (observations) has been calculated by averaging individual frequency distributions for each model (observational dataset). The results are shown in Figs. 8 and 9 for temperature and precipitation, respectively.

In general, the normalized empirical frequency distribution diagrams for monthly temperature (Fig. 8) suggest

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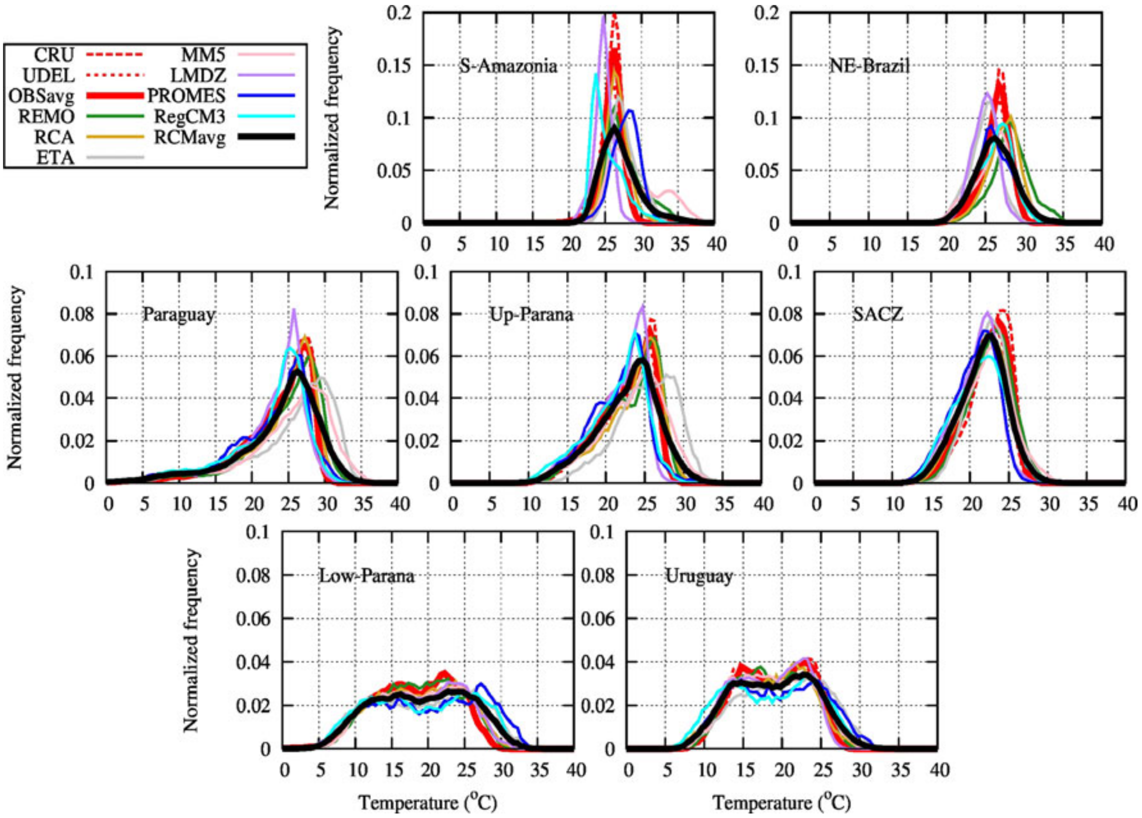

Fig. 8 Frequency distribution of monthly mean temperature over sub-regions defined in Fig. 1. *Solid lines* indicate individual RCMs and *thick black line* indicates the ensemble mean of the RCMs. *Dashed lines* are individual observational datasets and *thick red line* is the ensemble mean of the observations. Units are in °C

that the shape of the curves from both models and observations is similar. However, large discrepancies are found for tropical regions. Over S-Amazonia, the observed frequency distribution is characterized by a narrow curve with the maximum frequencies around 26 °C. All the RCMs exhibit deviations from the observed distribution with most of the models overestimating the frequencies of high temperatures (above 29 °C) and underestimating the frequencies of low temperatures (below 25 °C). These biases reflect the tendency for the models being warmer than observations as noted in Fig. 6a. Moreover, most of the models overestimate the variability of the regional time-series, indicated by longer tails of the distribution.

Despite the large spread among models, the frequency range among them encompasses the observed frequency. The LMDZ and RegCM3 models tend to shift the distribution towards lower temperatures, which explains the temperature underestimation all year long noted in Fig. 6a. Conversely, the PROMES model shows the opposite behavior. The ensemble mean of the models still captures the primary features of the observed distribution and the range of variability of the time-series, with a tendency of better representing the lower tail and overestimating the frequencies of the upper tail.

For NE-Brazil, the models show a considerable spread in their individual frequency distributions, with the distributions being completely shifted towards lower or higher temperatures compared with observations. For instance, the cold (warm) bias noted in Fig. 6b by REMO and RCA (LMDZ and ETA) models seems to be due to a shift in the overall distribution towards lower (higher) temperatures, which indicates a systematic temperature bias. The models wherein the center of the distribution agrees with the observations, overestimate both tails of the distribution. This result indicates higher occurrences of extreme temperatures. Moreover, the width of the observed frequency distribution is much smaller compared with any of the models (similar to S-Amazonia) indicating that the temperature variability is larger in models than in observations. The ensemble mean of the models overestimates the frequencies on both tails of the distribution and strongly underestimates the frequencies of the intermediate ranges of monthly temperature.

For the SACZ region, the agreement between individual models and observations is much better than in the previous region's analysis of both the center and the tails of the distribution. A systematic shift towards lower temperatures is still apparent for each model. The spread in frequency

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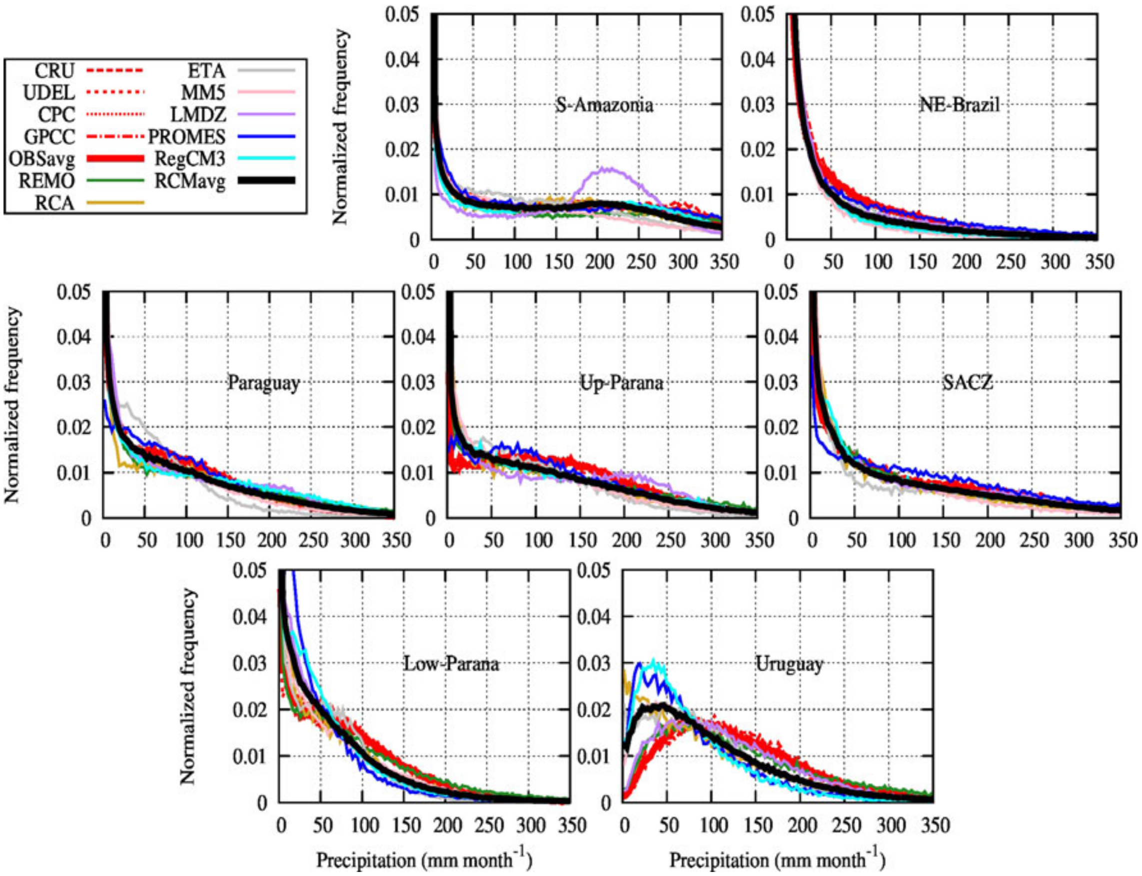

Fig. 9 Same as Fig. 8 but for precipitation. Units are in mm/month

distribution among models is relatively small. The ensemble mean of the models tends to represent better the upper tail of the distribution but overestimates the frequency of low temperatures (below 20 °C), which is translated in the cold bias noted in Fig. 6. Over the LPB region, it is interesting to note that the observed frequency distribution over the northern part of the basin (Up-Paraná and Paraguay) follows a negatively skewed shape compared to the bi-modal characteristics of the distributions over the southern part of the basin (Low-Paraná and Uruguay). The models seem to reproduce such features. For Paraguay and Up-Paraná, the lower tail of the distribution is well represented and with good agreement among the models. Substantial biases and spread are apparent towards the upper tails of individual simulated distribution that indicates less model reliability in reproducing extreme warm temperatures due to both underestimation and overestimation of the simulated frequencies.

Over Low-Paraná and Uruguay, the spread among the models is narrow and the modeled frequencies are in close agreement with observations by every model. The upper tail of the frequency distribution seems less represented than the lower tail, which is similar to the findings in the northern part of the basin. Most of the models overestimate the observed frequency in the upper tail of the distribution, which suggests that the models tend to overestimate the occurrence of warm extremes. The radiation, planetary boundary layer, microphysics and land surface schemes used in the models directly affect the modeled 2-meter temperature behavior. Consequently, the biases could be related to a misrepresentation of either clouds and/or surface fluxes. These biases should be taken into account when evaluating changes in the distribution for the analysis of scenario runs, in which the changes in the frequency of extreme events is relevant.

The frequency distribution diagrams for precipitation displayed in Fig. 9 reveal that there is an overall good agreement among models and observations over tropical regions. Sub-regions within the LPB basin have the largest discrepancies, either among models or observational datasets. The exponential shape of the frequency distributions over each sub-region except Uruguay that is characterized by a log-normal type distribution, are features well reproduced by each model. Over most of the regions, a systematic overestimation of light rainfall intensities is found together with a systematic underestimation of intermediate to heavy rainfall intensities. This is a common shortcoming of both RCMs and GCMs (Sun et al. 2006; Menéndez et al. 2010).

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Over S-Amazonia, models (MM5 and ETA) underestimating the amount of precipitation during the rainy season are found to underestimate the frequencies of intense precipitation (more than 200 mm/month). The LMDZ model seems to show a particular behavior of strong overestimation over the frequencies corresponding to intermediate precipitation intensities and underestimation of frequencies corresponding to intensities of less than 100 mm/month. This behavior is also visible but in a lesser extent over the regions of Paraguay and Up-Parana. The precise cause of this overestimation of intermediate precipitation intensities is still unclear. A strong suspicion is, however, on the convection scheme. The LMDZ model uses the Emanuel cumulus scheme, which preferentially produces mid-intensity rainfall in the monsoonal region over South America.

Over NE-Brazil, most of the models underestimate the frequencies ranging from intermediate to heavy precipitation intensities, which is in agreement with the systematic underestimation of rainfall during the rainy season (Fig. 7b). An exception is the overestimation of the frequency of heavy precipitation by the PROMES model, which suggests that either the convective scheme or the explicit microphysics scheme may be hyperactive (Held et al. 2007).

Over SACZ, the agreement among models and between models and observations is quite good except for the PROMES model for which the underestimation (overestimation) of light (heavy) rainfall intensities is larger compared with the other models. Over sub-regions within the LPB basin, a good agreement between models and observations are found in the northern part rather than the southern part. Over Uruguay, only two out of 7 models (LMDZ and REMO) are capable of reproducing the observed frequency distribution of rainfall. These models are able to simulate the winter precipitation maxima during JJA with an error of less than 10 % (not shown). The other models do not reproduce the center of the distribution and also show a strong overestimation of the frequency of light precipitation and a systematic underestimation of the frequency of intermediate and heavy rainfall intensities. These deficiencies could explain the strong underestimation of precipitation during winter months identified in Fig. 7g.

Overall, the similarity between observations and simulations builds up our confidence in the multi-model ensemble for most sub-regions. Moreover, most of the models are capable of simulating the shape of the frequency distributions of the two analyzed variables. The differences in the distribution throughout different climatological regions within the South American continent for both temperature and precipitation are also accounted for. The analysis of individual model biases based on the frequency distribution diagrams discussed above could be useful for applying suitable bias correction methodologies (Li et al. 2010; Piani et al. 2010; Amengual et al. 2012).

4 Concluding remarks

In the present study, the capability in reproducing the mean climate conditions over the South American continent has been evaluated using a set of seven coordinated RCM simulations performed in the CLARIS-LPB Project. The focus of the analysis is on evaluating the main biases and uncertainties in simulating mean precipitation and near-surface air temperature, which are the variables most commonly used for impact studies. The model simulations are forced by "perfect boundary conditions" from the ERA-Interim reanalysis dataset for the period 1990–2008 on a grid of approximately 50 km. The uncertainties due to the variety in the RCMs formulation is the only source of uncertainty considered in this study. Several gridded observational data sets are used for model evaluation in order to account for the level of uncertainty within the observations.

Results have shown that the models are able to reproduce the spatial distribution of the seasonal mean temperature and precipitation for austral summer and winter seasons. However, examination of the ensemble bias reveals that the ensemble mean tends to overestimate temperature over tropical regions during JJA and over LPB during DJF by almost 3 °C, while a systematic underestimation of around 2 °C is apparent along the Andes. The temperature bias over other regions and seasons is generally less than ±1 °C. Precipitation is underestimated all over SA, particularly over northern SA during DJF (around 20 %) and over south-eastern Brazil and Uruguay during JJA (close to 50 %). Over the Andes, the ensemble mean systematically overestimates topographically-induced rainfall. This is a common shortcoming to various simulations over SA (Chou et al. 2011; Solman et al. 2008; Carril et al. 2012, among others). Moreover, the precipitation and temperature biases in areas of complex topography are also apparent in every RCM simulation all over the world (Walker and Diffenbaugh 2009; Nikulin et al. 2011), although these biases may be artificially amplified by the lack of a dense observational station network.

Even with a homogeneous experimental design such as the one presented here, there is a considerable spread among individual models. The largest inter-model scatter is found for temperature mainly over tropical SA and the Andes regions (3 °C), which is larger compared with the interannual variability. Over the LPB, the level of uncertainty in simulating temperature is less than 1.5 °C. This value is even lower compared with the interannual

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variability. The level of uncertainty in simulating precipitation is low over most of the South American continent, except over northern SA and the Andes. These results suggest that the reliability of the RCMs simulations is high over the LPB region. Though the ensemble bias is large, each model shares similar biases which yields a low inter-model spread, suggesting a systematic shortcoming in every model. Conversely, large uncertainty and large biases over tropical SA suggest that the reliability in simulating mean climatic features is degraded.

Differences in RCMs results may be caused by different parameterizations of key physical processes such as convection, planetary boundary layer and land-surface, which are critical over regions and seasons where local forcings are relevant. However, other sources of uncertainty due to the models' configuration, such as numerical techniques, vertical resolution and treatment of lateral boundary conditions are also important sources of uncertainty which may explain differences in the simulated climate (Solman and Pessacg 2012b). In all cases, the models' uncertainty is larger than the observational uncertainty.

The evaluation of the annual cycles of temperature and precipitation over selected sub-regions reveals that the basic features of the annual cycles such as the amplitude and the timing of the maxima and minima, are reproduced by most of the models. The discrepancy between models and observations and among models in reproducing the annual cycle of temperature and precipitation reveals a seasonal dependence of the disagreement and the reliability for current climate simulations over the South American continent. In general, high (low) reliability is found for subtropical (tropical) regions during the cold (warm/monsoon) season. The influence of land-surface interaction and convective processes on near surface temperature and precipitation mainly during the warm monsoon season and the variety of schemes used in the RCMs may account for the large inter-model spread and bias.

The frequency distribution diagrams for monthly mean temperature and precipitation evaluated over several sub-regions within the South American continent reveal that the models are able to capture the shape of the distributions over each region and also the differences among different climatological regions. However, individual models show systematic biases due to either a shift in the distribution or due to an overestimation or underestimation of the range of variability. For subtropical regions, the ensemble mean tends to overestimate the frequency of extreme warm temperatures, while the occurrences of extreme low temperatures are well reproduced. Moreover, the spread among models also suggests that the reliability in reproducing the upper tail of the distribution is lower compared with the lower tail. For regions over tropical latitudes, individual model behavior is clearly less accurate.

Inspection of the frequency distribution diagrams for monthly precipitation reveals that most of the models reproduce the observed variability quite well, mainly over tropical areas. The difficulty of the models in reproducing the observed patterns mainly over Low-Parana and Uruguay regions are also highlighted where the models systematically overestimate the frequencies of light precipitation (less than 50 mm/month) and underestimate the frequencies for moderate to heavy precipitation intensity (more than 100 mm/month).

Understanding the behavior of individual models is beyond the scope of this study, as this should account for a detailed analysis of how each model is configured and how sensitive the models are to a variety of model components including the dynamics, the physical parameterizations and their interactions. Moreover, no attempt has been made to evaluate why the models agree or disagree among each other, but each model is supposed to be built after a robust evaluation concerning model performance over the region of interest (see the basic references of the models in Table 1). Besides, most of the models evaluated here have been used to perform climate simulations over Europe (e.g., Boberg et al. 2009) and it has been demonstrated that they are capable of reproducing the observed climate with some degree of accuracy. Though RCMs are supposed to be portable in the sense that they can be used to simulate the climate of any region of the world, the quality of their results depends on the regions, as discussed in Takle et al. 2007. Consequently, the analysis discussed here may be useful to improve individual models in order to increase the reliability of the simulated climate over South America.

After critically evaluating the results for the set of metrics analyzed in this study, it is evident that no single model could be identified as systematically producing worse or better results for every variable over every region. Moreover, the ensemble mean of the RCMs systematically improves the quality of the simulated climate compared with any individual model. However, large biases in the ensemble still exist, which means that before applying the simulations to any impact study, a bias correction method should be applied. The intention of this study is to document the main strengths and weaknesses of an ensemble of RCMs in simulating climate conditions over SA. Knowing the consistency of the simulated climate conditions with observations and identifying main biases and uncertainties is important for interpreting future climate projections, mainly when multi-model results are applied for assessing the impact of climate change on a broad range of climate impact studies.

Acknowledgments The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under Grant Agreement B°212492

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(CLARIS LPB A Europe-South America Network fir Climate Change Assessment and Impact Studies in La Plata Basin). This work has also been supported by UBACyT Grants X160 and Y028, Conicet Grants PIP 112-200801-00195 and PIP 112-201101-00189. Additional funding were provided by the projects Rede-CLIMA, the National Institute of Science and Technology for Climate Change (INCT-CC), from the FAPESP-Assessment of Impacts and Vulnerability to Climate Change in Brazil and strategies for Adaptation options project (Ref. 2008/58161-1). The authors wish to acknowledge two anonymous reviewers for very helpful suggestions which certainly led to an overall improvement of the paper.

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