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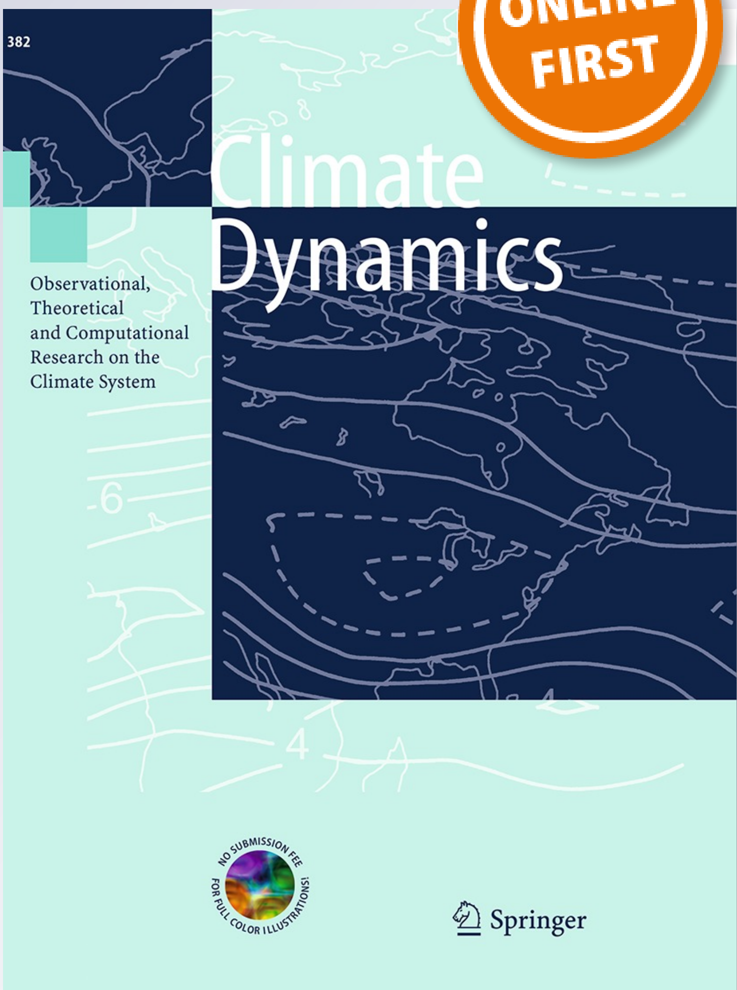

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Regional climate modelling in CLARIS-LPB: a concerted approach towards twentyfirst century projections of regional temperature and precipitation over South America

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Abstract The results of an ensemble of regional climate model (RCM) simulations over South America are presented. This is the first coordinated exercise of regional climate modelling studies over the continent, as part of the CLARIS-LPB EU FP7 project. The results of different future periods, with the main focus on (2071–2100) is shown, when forced by several global climate models, all using the A1B greenhouse gases emissions scenario. The analysis is focused on the mean climate conditions for both temperature and precipitation. The common climate change signals show an overall increase of temperature for all the seasons and regions, generally larger for the austral winter season. Future climate shows a precipitation decrease over the tropical region, and an increase over the subtropical areas. These climate change signals arise independently of the driving global model and the RCM. The internal variability of the driving global models introduces a very small level of uncertainty, compared with that due to the choice of the driving model and the RCM. Moreover, the level of uncertainty is larger for longer horizon projections for both temperature and precipitation. The uncertainty in the temperature changes is larger for the subtropical than for the tropical ones. The current analysis allows identification of the common climate change signals and their associated uncertainties for several subregions within the South American continent.

Keywords Regional climate modelling · Climate change · South America

1 Introduction

The development of climate change projections at regional scales performed with regional climate models (RCM) is

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currently a very active area of research. One of the reasons is the need of reliable information at high-resolution required by the impact community. However, the most outstanding motivation is that as long as the resolution is increased, the regional scale forcings are better captured and consequently the regional climate features, forced by both the large scale and regional scale circulation, are better represented. The improvement of our understanding of the key climatic processes for both present and future conditions on these more detailed scales, compared with those from a global climate model (GCM), can be very relevant when dealing with impact studies on human or natural systems. Moreover, information at fine scales allows improving the strategies related to risk management and adaptation (Jones et al. 2011). The relevance of using high-resolution products to add regional detail to the global climate simulations was clearly shown (Giorgi et al. 2001) and recognized by (Christensen et al. 2007b) in the 2007 Report of the Intergovernmental Panel on Climate Change (IPCC).

The most recent 2013 IPCC report (Flato et al. 2013) shows that the number of regional climate modelling studies over different continental areas of the world has increased during the last decade. Moreover, during recent years, the regional climate modelling community recognized the need for coordinated efforts in order to explore the uncertainty of RCM products. Hence, the use of several of RCMs, driven by different GCMs under a set of greenhouse gases emissions scenarios has become the common methodology to characterize the climate change signal and the associated uncertainty at the regional scales. Coordinated RCM experiments have been developed over Europe (Jacob et al. 2007; Christensen and Christensen 2007; der Linden and Mitchell 2009; Déqué et al. 2012), North America (Mearns et al. 2012, 2013) or Africa (Ruti et al. 2011), among other regions. The criteria for designing the ensemble of RCMs allows for characterize different sources of uncertainties: the driving GCM, the forcing scenario, the RCM itself and the internal variability (Giorgi and Francisco 2000; Déqué et al. 2007; Christensen and Christensen 2007; Christensen et al. 2007a; Jacob et al. 2007; Castro et al. 2007; Kjellström et al. 2010; Marengo et al. 2010; Solman and Pessacg 2012; Reboita et al. 2014), among others. The most important sources of uncertainty in climate change projections usually come from the GCM and the emissions scenario, specially on longer timescales and global basis. At regional scales, the internal variability becomes an important source of uncertainty (Hawkins and Sutton 2009, 2011). However, when using a RCM nested into a GCM to simulate the regional climate, an additional source of uncertainty arises related to the choice of the RCM. Thus, in order to characterize the full range of uncertainties in regional climate change projections, a large number of simulations is needed (multiple GCMs, multiple RCMs and different emission scenarios). Due to the complexity of including all these elements, several studies have used a reduced dimension of the full matrix of experiments to focus only on some of these uncertainties. For example, Kjellström et al. (2010), Reboita et al. (2014) focused on the uncertainty due to the emissions scenarios and driving GCMs, using only one RCM, and Marengo et al. (2010) with three RCMs. Another strategy employed in the PRUDENCE Project (Christensen and Christensen 2007; Christensen et al. 2007a; Jacob et al. 2007; Déqué et al. 2007; Castro et al. 2007) used a single GCM to force several RCMs. Yet another approach was followed by Kendon et al. (2010), Kjellström et al. (2011), Déqué et al. (2012) who used a combination of GCMs and RCMs for a single emission scenario to characterize the uncertainty in the regional climate change projections over Europe.

The success of having a large multi-dimensional matrix, with different RCMs, different GCMs and different emission scenarios depends on the extent to which a set of coordinated experiments can be designed. The CORDEX international initiative has been developed since 2009 to fill this gap. CORDEX provided a framework to build such a complex matrix, with an initial focus on the African continent (Giorgi et al. 2009; Jones et al. 2011). Several modelling centers already performed the so-called CORDEX simulations for several regions in the world (Jacob et al. 2012; Teichmann et al. 2013; Giorgi 2014).

Though many regional modelling studies have been performed for the South American continent within the last decade, most of them have been isolated efforts, as discussed in Solman (2013). The first collaborative effort for producing ensembles of RCM simulations over South America (SA) has been developed under the EU-FP6 CLARIS project in which several coordinated multi-RCM simulations were performed for relatively short periods (Boulanger et al. 2010; Menéndez et al. 2010; Carril et al. 2012). Recently, under the support of the EU-FP7, 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) was designed, among other objectives, to provide high-resolution climate change simulations over SA and its underlying uncertainty. To that end, a coordinated modelling strategy was designed, following the CORDEX framework so as to contribute also to the CORDEX initiative for the SA region. As a first step, an evaluation framework was defined in which a set of seven RCMs driven by the ERA-Interim reanalysis were used to simulate the current climate conditions for the period 1990–2008. These simulations allowed evaluating the capability of the state-of-the-art RCMs in reproducing the main SA climate features, but also characterizing the uncertainty associated with the variety of RCMs. The main results of this collaborative effort are described in Solman

Table 1 Matrix of RCM/GCM simulations and periods covered, with either 30-year periods or continuous run

RCM	GCM	1961–1990	2011–2040	2071–2100	1961–2100
REMO	EC5OM-R3				X
RegCM3	EC5OM-R1	X	X	X	
RegCM3	HadCM3-Q0	X	X	X	
RCA	EC5OM-R1				X
RCA	EC5OM-R2				X
RCA	EC5OM-R3				X
PROMES	HadCM3-Q0				X
LMDZ	EC5OM-R3	X	X	X	
LMDZ	IPSLA1B				X
Eta	HadCM3-Q0	X	X	X	

et al. (2013). As a second step, for the model projection framework, the same RCMs were used but driven by different GCMs from the Climate Model Intercomparison Project (CMIP3) ensemble under the SRES A1B emission scenario for the twentyfirst century (see details on Methodology section). The analysis of this unprecedented set of simulations, hereafter referred to as the CLARIS-LPB ensemble, is the major focus of this study.

Therefore, the main objective here is to analyze the basic features of the CLARIS-LPB ensemble in order to: first, characterize the capability of the ensemble in reproducing the main features of the present climate conditions when the RCMs are driven by GCMs and, second, identify the climate change signal and characterize the associated uncertainty. In the 2013-IPCC report (Christensen et al. 2013), some very basic results of this ensemble (see their Figure 14.21) were already shown. In addition to a first validation analysis, the main part of the work will examine how these RCMs simulate future climate conditions, during the twentyfirst century, particularly for the 2071–2100 period. The methodology section describes the combination of RCM/GCM simulations available, together with some metrics and indices used for the analysis of the climate change signal. The results section discusses both present and future climate results, and finally a discussion of the main findings, including an analysis of the uncertainty is presented. The focus here will be on the main climatic features, as in Solman et al. (2013), however, several on-going and future studies based on this ensemble are expected to address other features, such as extreme events or patterns of variability, with the expectation that they will help us to improve our understanding on the reliability and uncertainty of the regional climate change signal over the SA continent.

2 Methodology: the CLARIS-LPB ensemble

In this study the strategy for building the RCM ensemble accounts for the uncertainty due to models, both RCMs and GCMs, and the uncertainty due to the internal variability. The RCMs used for building the ensemble are the same as those analysed in Solman et al. (2013), where the models were driven by the ERA-Interim reanalysis. Details of the RCMs can be found in Table 1 of the referred article. The RCM used here are: REMO, RegCM3, RCA, PROMES, LMDZ and ETA. The GCMs from the CMIP3 ensemble used to force the RCMs are: the HadCM3 (Gordon et al. 2000), the IPSL (Hourdin et al. 2006) and three realizations of the EC5OM (Roeckner et al. 2006). All RCMs simulations were performed for the SRES A1B greenhouse gases emissions scenario (Nakicenovic and Swart 2000).

All the RCM simulations share the same configuration as in Solman et al. (2013), covering the whole South American domain at a horizontal resolution of roughly 50 km. Most of the RCMs were run for three time slices corresponding to present climate (1961–1990); near future (2011–2040); and far future (2071–2100), respectively. However, some of the models were run continuously from 1961 to the end of the twentyfirst century.

Having all the possible combinations among RCMs and GCMs was too expensive computationally; in consequence, the RCM/GCM matrix was built in order to have at least two RCMs driven by more than one GCM, several RCMs driven by the same GCM and one RCM driven by different realizations of the same GCM. This strategy allowed discussing the extent to which the uncertainty in the regional climate projection was mostly due to the GCMs, the RCMs or the internal variability.

The combination (matrix) of GCMs and RCMs together with the corresponding simulated periods is shown in Table 1. Though seven RCMs were included in Solman et al. (2013), one of the models was not available for the far future time slice and was not included in this analysis. As shown in Table 1, ten RCM simulations are available.

This study represents the first step to have an overview of model performance and climate change signals for the most widely used variables. Hence, the analysis is focused on the seasonal and annual means of the 2 m temperature and precipitation for two periods: the reference period (1961–1990) and the far future period (2071–2100).

3 Results

In this section we present the results for present conditions, compared with the CRU observational gridded database (Mitchell and Jones 2005), in order to identify patterns, magnitude and common features of models biases. Then future changes, computed as the difference of the 30-year means for the two periods, and the associated uncertainties are discussed. Annual cycles and monthly frequency distribution functions over some selected sub-regions already defined in Solman et al. (2013) are examined. Finally, combined (delta) changes in seasonal temperature and precipitation over each sub-region are discussed.

We present several metrics (annual cycles, frequency distribution functions, timeseries) based on monthly means of temperature and precipitation for both present conditions and future changes. Results from the driving GCMs are also presented when showing the mean annual fields, to allow for a more accurate discussion of the similarities and differences between RCMs and their corresponding GCM, and therefore also a inspection of the potential added value of RCMs.

3.1 Annual spatial fields

3.1.1 Present climate (1961–1990)

The reliability of the RCMs described in the previous section is evaluated here in terms of their performance when describing mean present climatic features. Solman et al. (2013) evaluated the same ensemble of RCMs but driven by the ERA-Interim reanalysis, describing the main performance characteristics. Their conclusion was that the models were able to reproduce the spatial distribution of the seasonal mean temperature and precipitation for both winter and summer, despite some biases and large spreads among models over certain regions. They also found that no single model produced systematic worse or better results over every region and season, and the ensemble systematically reduced the bias when compared with observations.

The analysis starts examining each individual RCM. For the sake of brevity only annual fields are discussed. To put model biases in context, results from the driving GCMs have also been included. Figures 1 and 2 show the annual mean temperature and total precipitation biases as depicted by driving GCMs and the ten regional climate simulations, calculated with respect to observations from the CRU gridded dataset. The first relevant feature to note from Fig. 1 is that most of the driving GCMs display a similar pattern for the annual mean temperature bias among them, with colder conditions over the southern tip of South America and warmer conditions over subtropical and tropical areas. Just IPSL does not show the same behaviour. For any given driving GCM, the biases in the RCMs mostly agree with the biases in the GCM, but the regional models introduce additional errors. The magnitude of the biases in the RCMs are usually smaller than those in the driving GCMs, although some cases exhibit larger biases (PROMES, or REMO for EC50Mr3). Systematic errors from both GCMs and RCMs are the warmer conditions over the La Plata basin area and colder conditions over north eastern Brazil and Patagonia. With exception of some RCMs, the biases range from 2 to 2 °C. Comparing the ensembles of GCMs and RCMs, it is noted that the latter several times displays smaller biases over the whole South American continent, although it is not always the case, such as over NE-Brazil or La Plata Basin. Therefore, no systematic improvement can be noted from every individual RCM with respect to the driving GCM. Model behaviour over regions with complex orography is always improved in the RCMs compared with the GCMs.

The biases for the annual mean precipitation field displayed in Fig. 2 suggest that the GCMs systematically underestimate the amount of precipitation over the Amazon and La Plata basins. Positive biases are generally found over regions of complex topography, a typical behaviour of climate models in any region of the world where topography interacts with the flow and triggers topographic precipitation. Note also a slight overestimation of the precipitation amount over northeastern Brazil. The biases in the RCMs combine the biases in the driving GCM with the biases introduced by the regional model. For some RCM/GCM combinations these sources of systematic errors compensate each other but for some regions the error in the regional simulation is even larger than that in the global model simulation. This behaviour is apparent over the LPB area, where the RCMs amplify the dry bias and over northeastern Brazil, where the RCMs amplify the wet bias. The ensemble of RCMs has less bias compared with the ensemble of GCMs, particularly over tropical regions. This is mostly due to the compensation of errors of individual RCMs.

The biases in the RCMs displayed in Figs. 1 and 2 are comparable with those found when the RCMs are driven by the ERA-Interim reanalysis (Solman et al. 2013), suggesting that the spatial distribution and the sign of the bias for each individual RCM depends more on the regional model itself than on the driving global model. Accordingly, the RCMs introduce additional systematic errors that may either compensate or increase the errors from the driving GCMs. In terms of added value, Figs. 1 and 2 suggest that only some RCMs are able to improve the quality of the simulated climate when compared with the driving GCM based on the annual mean fields.

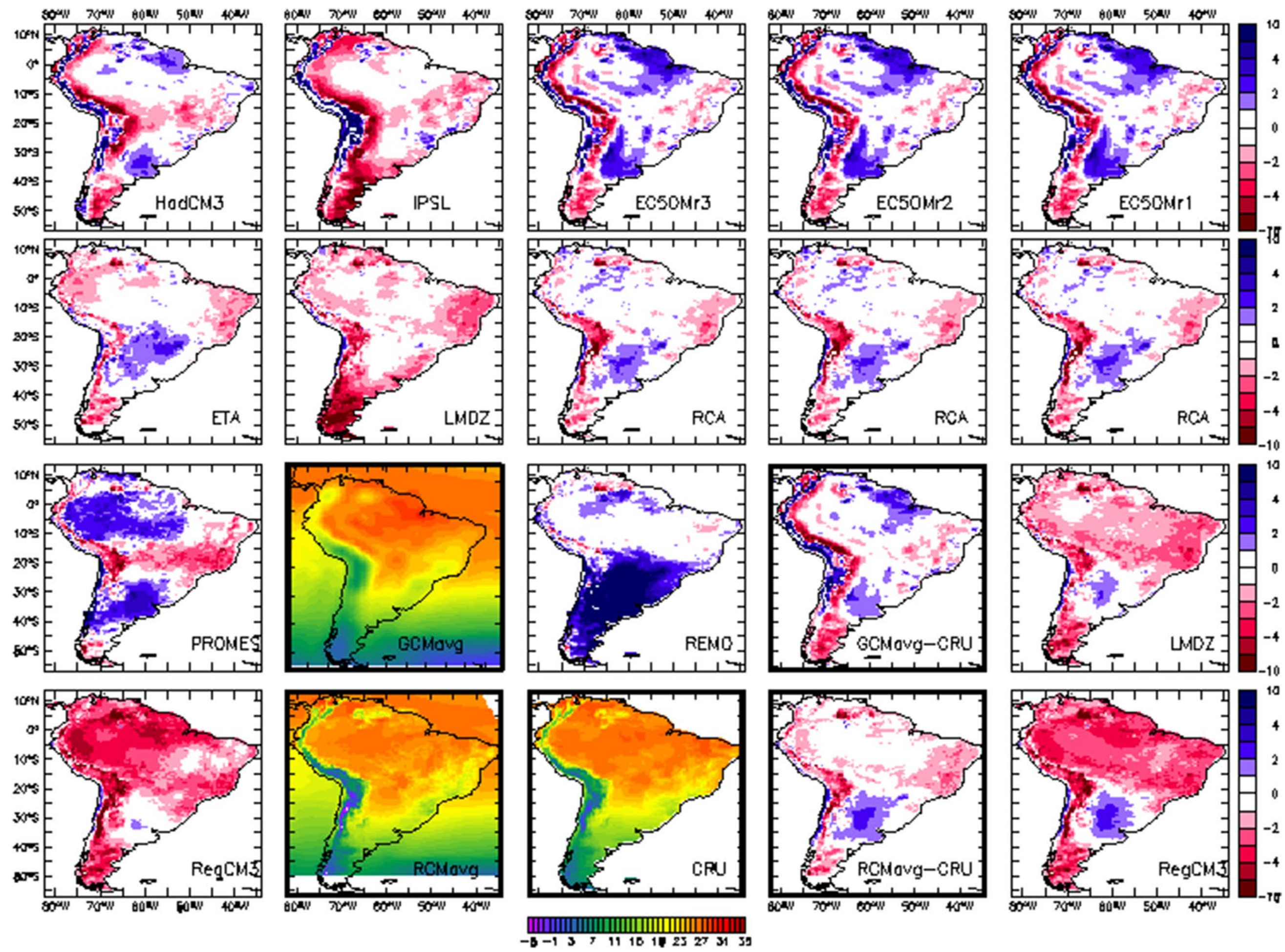

Fig. 1 Annual mean temperature biases (model minus CRU observations, in °C) simulations over the (1961–1990) period for the whole South America domain. *Upper row* shows GCM forcing fields results. On *each column* below each GCM result, RCM models forced by that corresponding GCM are plotted, following the GCM/RCM matrix simulations described on Table 1. CRU observational database results is also shown on the *bottom central figure*, together with the mean average of both all the RCM and GCM simulations and their biases against CRU observations

The main features of the systematic model errors are important for a proper interpretation of the future climate change signals.

3.1.2 Future climate (2071–2100) projections

The projected temperature changes during DJF and JJA seasons based on individual RCMs including the driving GCMs for 2071–2100 relative to 1961–1990 are shown in Figs. 3 and 4, respectively. Comparing the spatial pattern of GCMs during austral summer (Fig. 3 first row), IPSL and EC5OM simulations have similar regions of warming especially over the east of the central Andes while HadCM3 tend to have maximum warming over the Amazon Basin. During austral winter (Fig. 4 first row), the regions of maximum are similar to Fig. 3 but with a pronounced warming over the tropics. In these two figures, temperature increases are similar for the RCM and their forcing GCM, although for example, RegCM3 driven by HadCM3 there is an enhancement of the temperature increase pattern. This behaviour has been already highlighted in previous studies, such as Teichmann et al. (2013) and Marengo et al. (2014), among others. RCMs tend to exhibit this pronounced higher warming during austral summer (Fig. 3) than during austral winter (Fig. 4), compared to the driving GCMs. In addition, RCMs produce a detailed spatial pattern of warming in areas with complex orography, such as over the Andes and also over coastal areas.

The seasonal spatial pattern of the projected precipitation change illustrates complexities compared to the projected temperature change as shown in Figs. 5 and 6. During austral summer, the IPSL and HadCM3 GCMs have regions of opposite signal while the EC5OM simulations have an overall tendency of regions becoming wet except

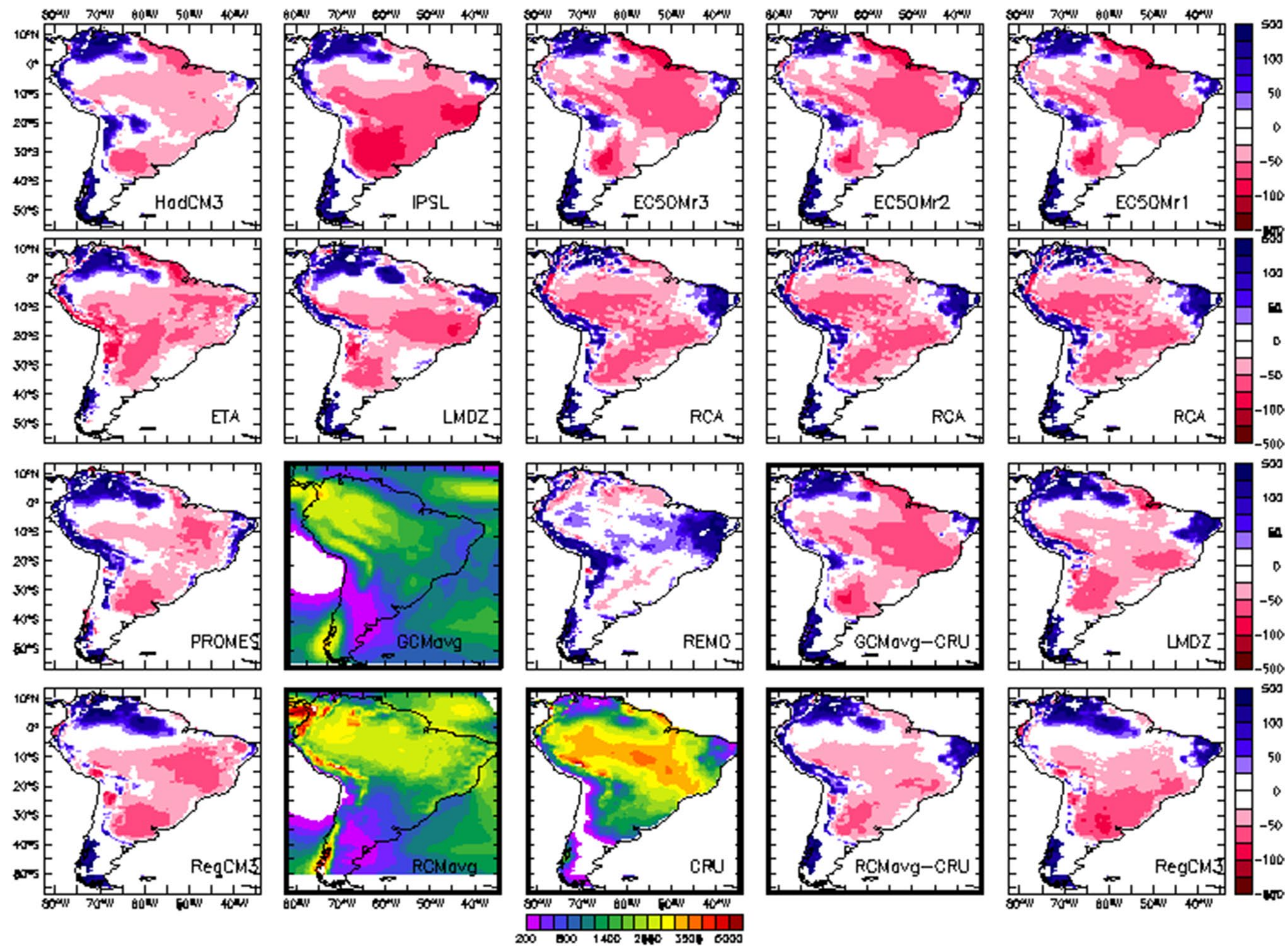

Fig. 2 As in Fig. 1, but for total annual precipitation amount biases (in %)

in southern Chile (Fig. 5 first row). During austral winter, similar behaviour can be observed between HadCM3 and IPSL, except over northern SA, while EC5OM tends to have drier regions in the tropics and wetter regions over La Plata Basin in the future A1B scenario. However, the projected precipitation changes simulated by the RCMs are rather uniform compared to the GCMs, i.e., regions getting wetter over La Plata Basin and drier in the central part of the domain during summer (Fig. 5). These changes are also shown in the ensemble mean of RCMs, which is outlined with thick black line. The projected precipitation change resulting from almost every RCM resembles the main patterns of rainfall variability at the intraseasonal and interannual time-scales, with a dipole structure with opposite signs at the La Plata Basin and the South Atlantic Convergence Zone (SACZ) (Paegle et al. 2000; Grimm and Zilli 2009). During winter, the ensemble mean of RCMs shows the future dry regions over south of Chile and close to the equator and the future wet regions over the La Plata Basin, with a considerable agreement among individual RCMs.

The spatial patterns of the RCMs and their corresponding driving GCMs have large differences not only on the intensity of climate change signal but even in the sign, i.e., in the case of the simulated drying regions of the central part of South America in the RCMs that use the EC5OM simulations. It must be taken into account that even GCMs comparison exhibits large differences (Vera et al. 2006; Vera and Silvestri 2009; Torres and Marengo 2013; Marengo et al. 2014). However, from Figs. 5 and 6, RCMs seem to present an overall agreement on the rainfall signal. Nevertheless, some differences can also be seen, as around 10–20 S dry conditions obtained on the second-row RCM projections, that are not seen when looking at other RCMs. The differences of the projected changes among the simulations with the same RCM but driven by different realizations of a single GCM (i.e., the internal variability) are smaller than the difference among different combinations of both regional and global models.

It is interesting to inspect regions where RCMs show a better or worse agreement in the climate change signal of

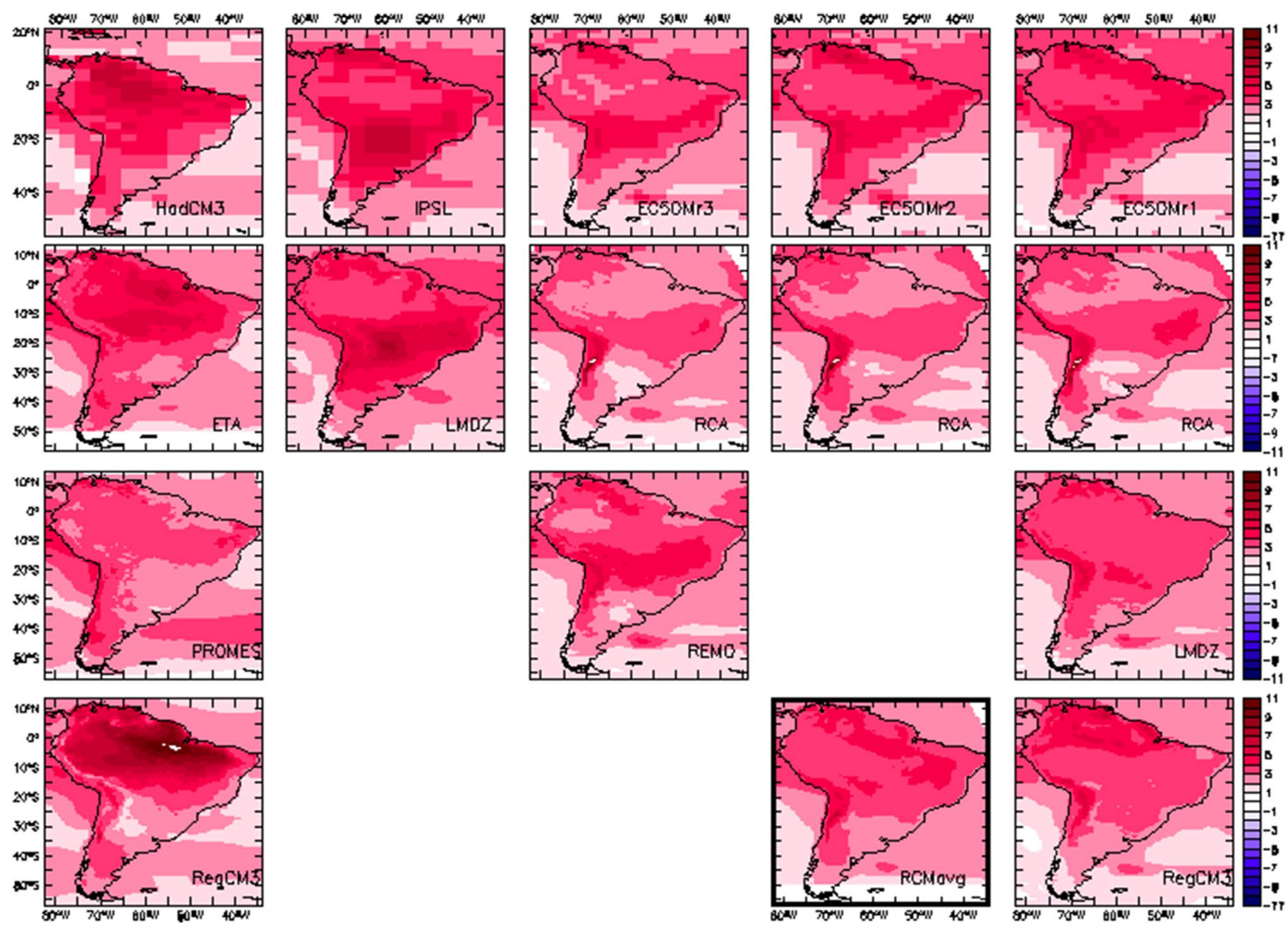

Fig. 3 As in Fig. 1, but for DJF temperature projections change from (1961–1990) to (2071–2100) period

precipitation for austral summer and winter (Fig. 7). Considering that the value of ten indicates that all the RCMs agree in the sign, most models agree on an increase in precipitation over Southern SA, and a decrease in precipitation over Chile and NE-Brazil during both JJA and DJF seasons. In addition, consistent drying patterns over most of the Amazon basin during austral summer (Fig. 7, upper panel) is apparent.

3.2 Annual cycles

A more detailed analysis of both the ability of the models to represent the annual cycle of temperature and precipitation, and their projected changes for future climate conditions, is further discussed. The results for several selected regions are displayed in Figs. 8 and 9. The definition of the regions, based on the location of key river basins over the South American continent, was already displayed in Figure 1 of Solman et al. (2013). The temperature biases for each individual RCM are similar to those found when the models were driven by ERA-Interim (Solman et al. 2013), in their Figure 6). However, as expected, the spread among models is slightly larger compared with the ERA-interim driven simulations.

Changes for future conditions normally indicate a similar increase of temperature (Fig. 8) along the year, although September-October-November period tends to show a larger increment of temperature. This is specially the case over the S-Amazonia region, where larger spread among models is obtained. The IPSL–LMDZ model tends to give larger temperature increases, in correspondence with its forcing GCM, as in Christensen et al. (2007b).

When looking at the annual cycles of precipitation (Fig. 9), the RCMs reproduce the features of the observed (current) climate but the errors of each individual model are amplified over some regions, particularly over NE-Brazil and Uruguay, compared with the errors in the ERA-Interim driven simulations (not shown). As for temperature, the spread among regional climate simulations driven by global models is larger when compared with the spread among the same RCM driven by reanalysis. This behaviour suggests that the uncertainty in the simulated climate is amplified due to the uncertainty introduced by both the regional and global models.

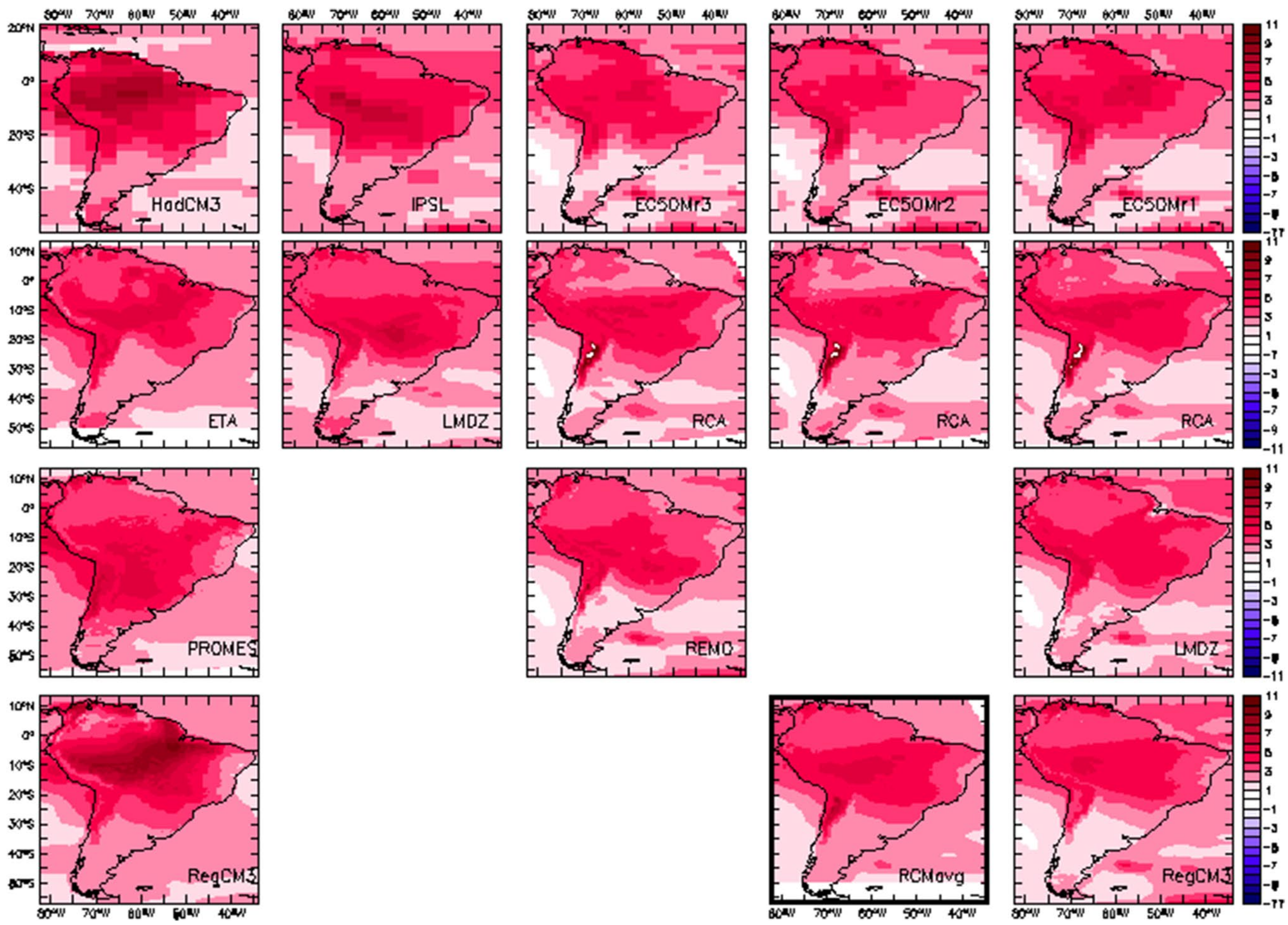

Fig. 4 As in Fig. 1, but for JJA temperature projections change from (1961–1990) to (2071–2100) period

Future conditions present large dispersion among models. The uncertainty due to both the RCM and the driving GCM is translated into diverse climate change signals, even of opposite signs over some regions. However, common features arise such as increases over southern regions (Uruguay, Low-Paraná, Up-Paraná) and decreases over S-Amazonia, SACZ and NE-Brazil, particularly during SON season, as already noted from the analysis of Fig. 7.

3.3 Monthly frequency distribution functions

In order to better interpret the climate change signal discussed above, the empirical frequency distribution for the ensemble of regional climate simulations is analysed. We have grouped the RCM results into an averaged frequency distribution function (FDF) for each of the regions. Results for temperature and precipitation for each sub-region are displayed in Figs. 10 and 11, respectively.

It is remarkable how the RCM ensemble for present conditions is able to reproduce the large variety FDF temperature distributions over the different selected regions. Shapes ranges from areas where the distribution is quite flat for a large interval of values (such as at Low-Paraná or Uruguay), to others with a narrow maximum frequency together with an asymmetric distribution towards low temperatures (Paraguay, Up-Paraná or SACZ), and finally those with a more symmetric shape (S-Amazonia or NE-Brazil). Nevertheless, some relevant differences are also seen when compared present climate distribution of the model ensemble against CRU observations. Model temperature FDFs tend to give a wider distribution over the tropical regions, where temperatures are not very different along the year, indicated by the very narrow distribution from CRU database. The ensemble overestimates the frequencies of both high and low temperature extremes over S-Amazonia, and overestimates the frequencies of the lower tail over NE-Brazil and SACZ, explaining the cold bias noted in Fig. 1. Over the regions within the La Plata Basin, the RCM overestimates the temperature variability mainly due to the overestimation of the frequencies of warm extremes compared with the observations, explaining the warm bias. The lower tail of the distribution agrees with the observations.

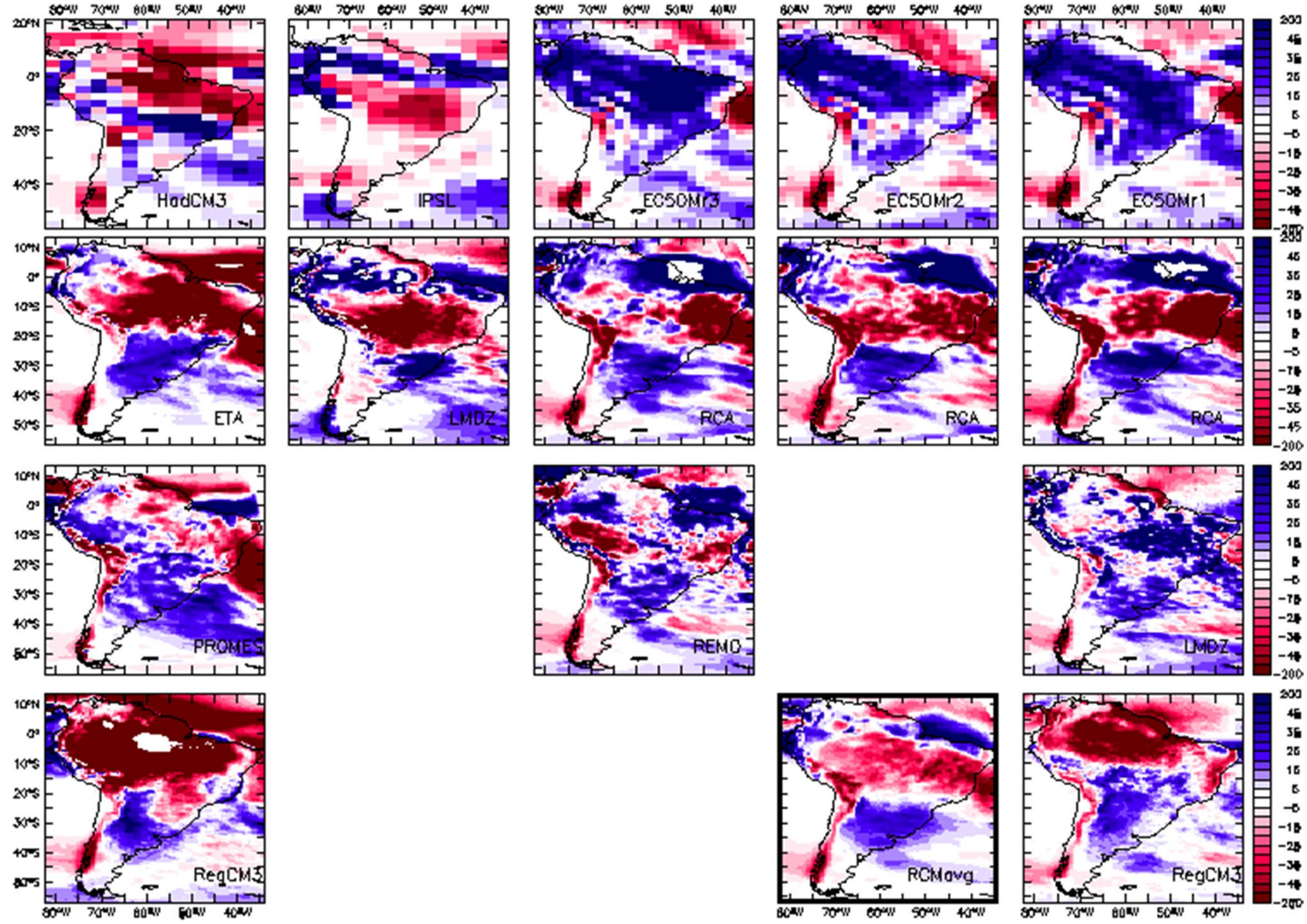

Fig. 5 As in Fig. 1, but for DJF precipitation projections absolute change from (1961–1990) to (2071–2100) period

The FDF curves seem to mainly be displaced towards larger values, without any relevant change in their shape for most of the regions for the future climate conditions. Nevertheless, a slight decrease in the normalized frequency of the maximum value is apparent indicating that the distribution becomes wider, i.e., the range of variability is increased in the future climate. Within the LPB region, the northern areas (Paraguay and Upper-Paraná) show stronger increase of warm extremes and a weaker decrease of cold extremes. For the southern areas within LPB (Low-Paraná and Uruguay), characterized by a bi-modal distribution, the projected distribution shows not only a shift toward higher temperatures but also higher frequencies for the warmer maximum, suggesting that both warm extremes and moderate warm events may increase for the future climate. This can be interpreted as warmer transition seasons.

The FDFs for precipitation show that all the regions are characterized by an exponential shape distribution, except Uruguay characterized by a log-normal-like or a gamma-like frequency distribution. There are just few similar studied showing monthly FDF shapes over specific subregions, such as the one of (Tapiador et al. 2007) over Europe, pointing to shape differences among closer regions similar to the ones obtained here over South America. Present climate simulations generally agree with observations, though over tropical regions there is a systematic underestimation of light to moderate precipitation intensities. Within the LPB region, the models depict a systematic overestimation of light precipitation and underestimation of moderate to heavy precipitation, in agreement with the large negative bias in the mean precipitation discussed above. It is important to highlight that this behaviour was also found for the ensemble built with the same RCMs but driven by perfect boundary conditions (Solman et al. 2013). Consequently, this behaviour is more due to RCMs imperfections rather than due to errors in the driving models. The changes in the FDFs are subtle over most of the regions, but systematic decrease in frequencies is apparent over NE-Brazil, consistent with drying conditions over that region. Over LPB, the RCM ensemble show a decrease in the frequency of light precipitation and increase in the frequency of moderate to heavy precipitation intensities, suggesting an overall

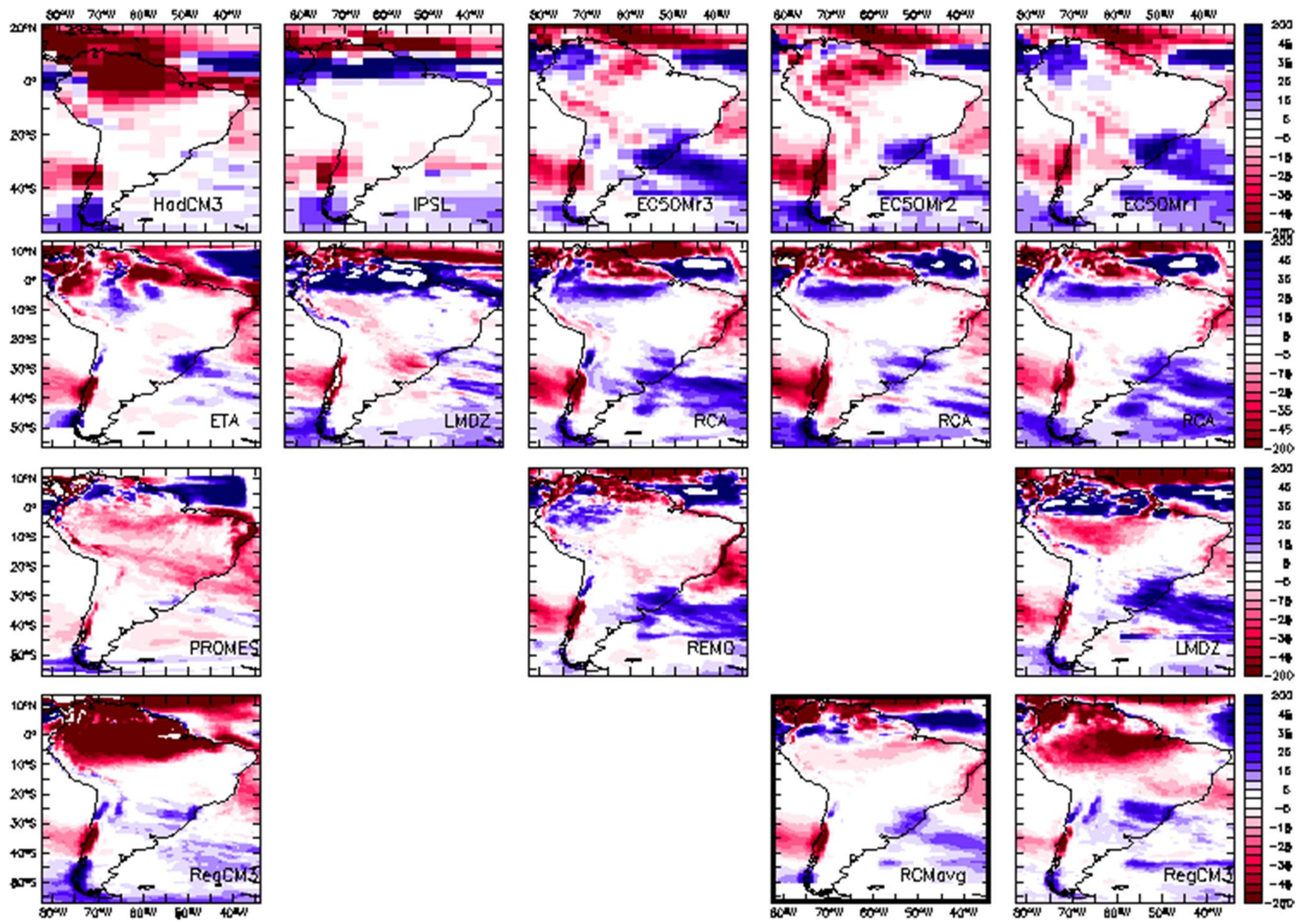

Fig. 6 As in Fig. 1, but for JJA precipitation projections absolute change from (1961–1990) to (2071–2100) period

increase of rainfall over the region, as depicted in Fig. 4. This behaviour also suggests a tendency to more frequent extreme rainfall events.

3.4 Timeseries

So far the analysis of the climate change signal has been considered as the difference between two 30-year periods. For temperature, it is usual to assume a linear increase in response to increasing greenhouse gases concentration. However, this assumption does not always hold to understand precipitation changes. The reason for this is that changes in precipitation may be related not only with global warming but interdecadal variability plays an important role. In fact, it has been discussed in the literature that rainfall over the South American continent has undergone strong interdecadal variations related with the interdecadal variability of circulation patterns (see Marengo et al. 2010). On the other hand, the idea of the scalability of the climate change signal, assumes that changes in regional climate (generally both temperature and precipitation) can be estimated for any scenario and any temporal horizon by simply scaling the changes assuming that the regional response of a climatic variable is linearly related to the global mean temperature change (Cabré et al. 2010). This, of course, does not account for any interdecadal signal. In this context, it is worth to explore the temporal evolution of both temperature and precipitation by individual RCMs in order to identify whether the climate change signal characterized so far is associated with a linear trend or it is affected by interdecadal variations. Moreover, this analysis also allows characterizing the spread among models and evaluating whether the uncertainty in the climate change signal for both temperature and precipitation remains unaltered or increases with time.

Accordingly, timeseries of annual mean anomalies of precipitation and temperature for the period 1960–2100 are displayed in Fig. 12, including the full set of simulations described in Table 1, for each of the subregions referred above. The anomalies are calculated with respect to the mean climate corresponding to present conditions of each individual model. A 9-year running mean has been applied

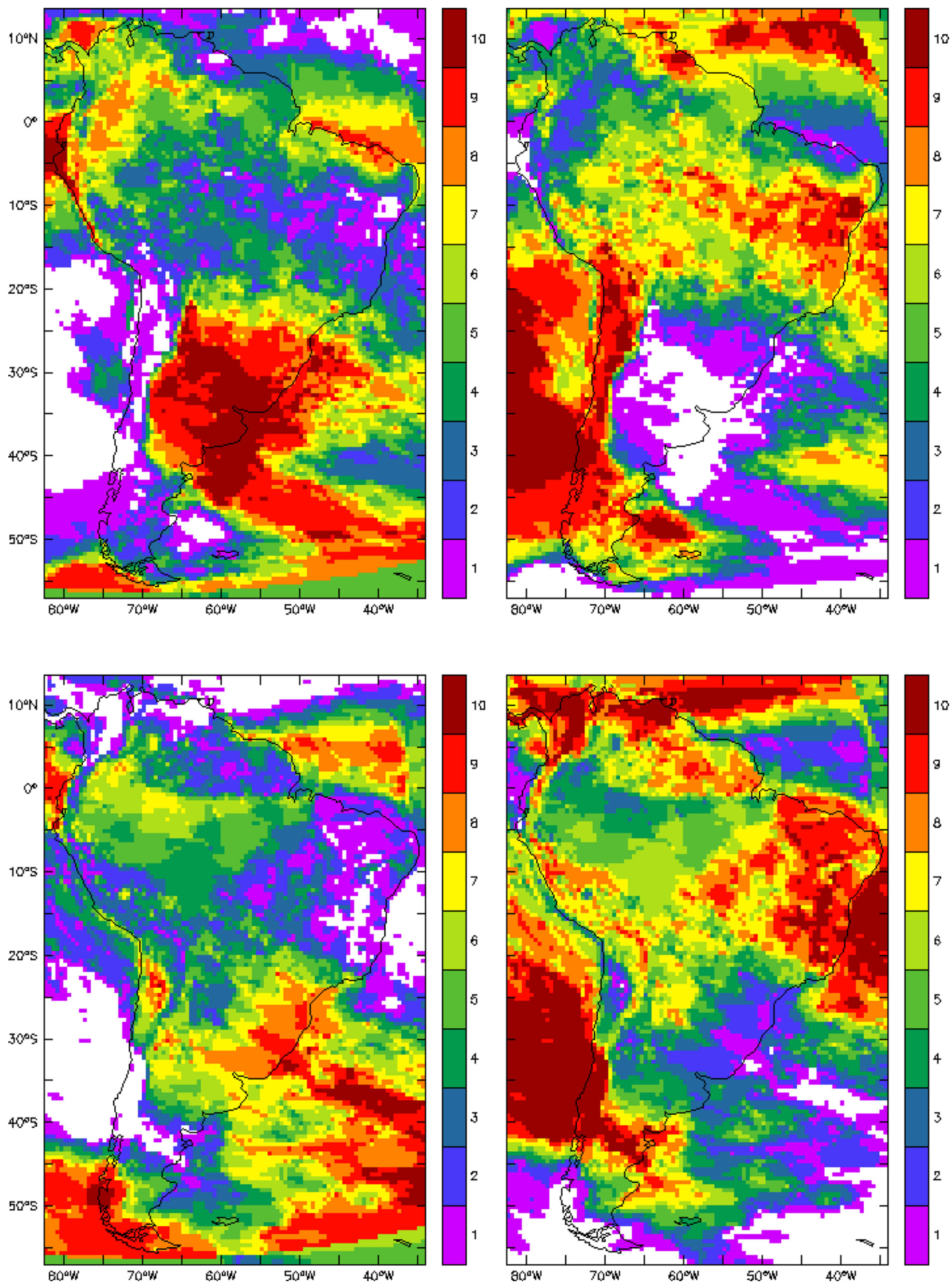

Fig. 7 Precipitation projections change agreement from (1961–1990) to (2071–2100) period among the ten RCM simulations for DJF (*on top*) and JJA (*bottom*) seasons. Positive changes (increases) are shown on *left figures*, and negative changes (decreases) on *right figures*

to filter out the interannual variability. For all subregions and all RCMs, the temporal evolution of the annual mean temperature anomalies is characterized by a quasi-linear trend; this trend is superimposed to weak interdecadal variability signal. The temperature trends seem to be larger for tropical than for subtropical regions. A visual inspection of the figure suggests that the spread among the curves for individual RCMs is larger for the southern regions (Low-Paraná and Uruguay) indicating a larger uncertainty in the climate change signal over these regions. Moreover, the spread among models seems to increase with time for every region, suggesting that the uncertainty due to models increases for projections over longer timescales.

The timeseries for the low-pass filtered annual precipitation anomalies clearly shows that the spread among models increases for longer-term projections. Large discrepancies among models are apparent, particularly over NE-Brazil, where no clear signal can be identified. All timeseries displayed in Fig. 12 suggest that precipitation is affected by a strong interdecadal variability signal, which is dependent mostly on the driving GCM. Note that for some regions the amplitude of the interdecadal variability signal is close

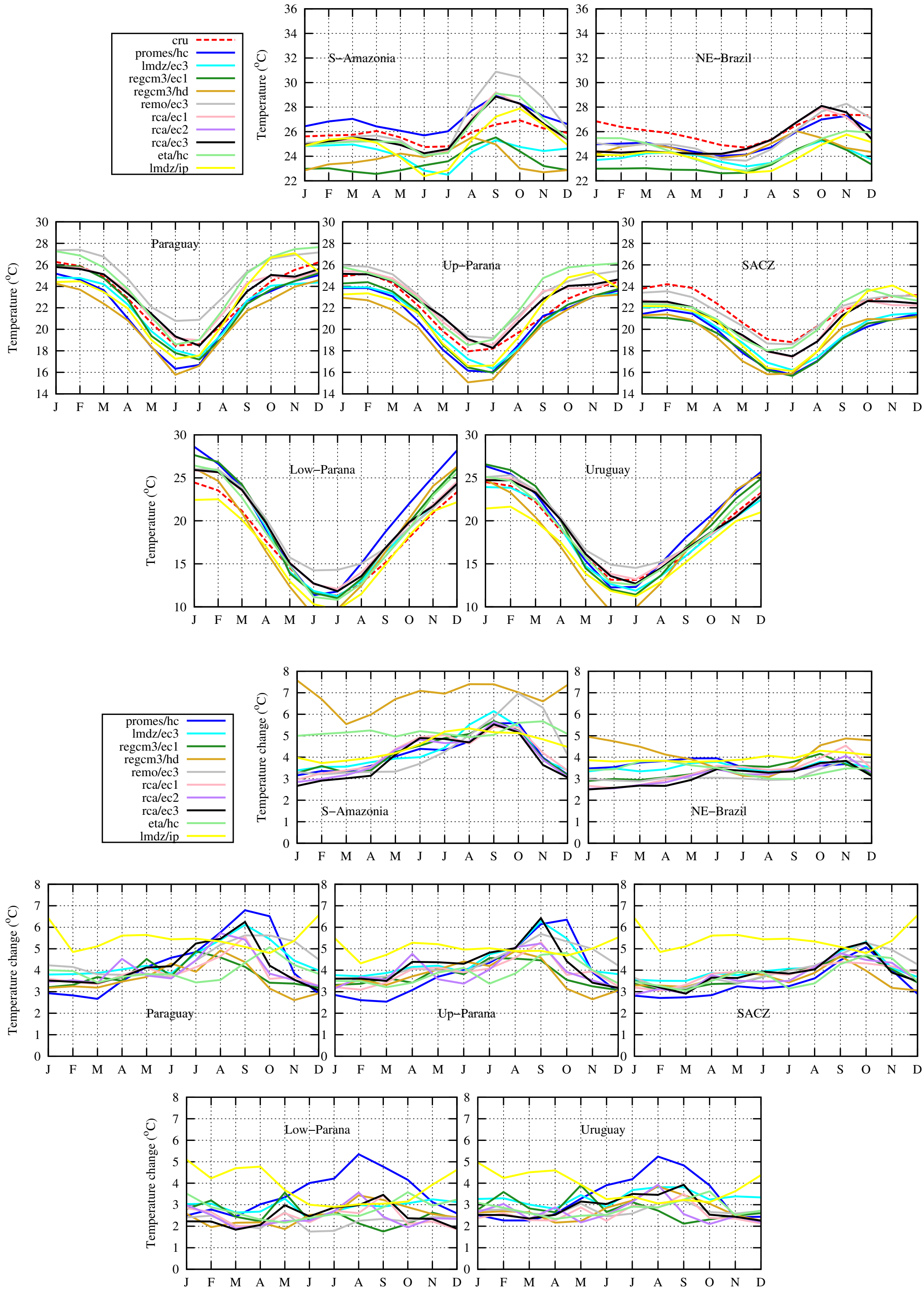

Fig. 8 Annual cycle of monthly temperature (in °C) for the seven selected subregions over the domain for present climate conditions (1961–1990) in the *upper panel*, and for the absolute change for future conditions (2071–2100) with respect to present climate (*bottom panel*)

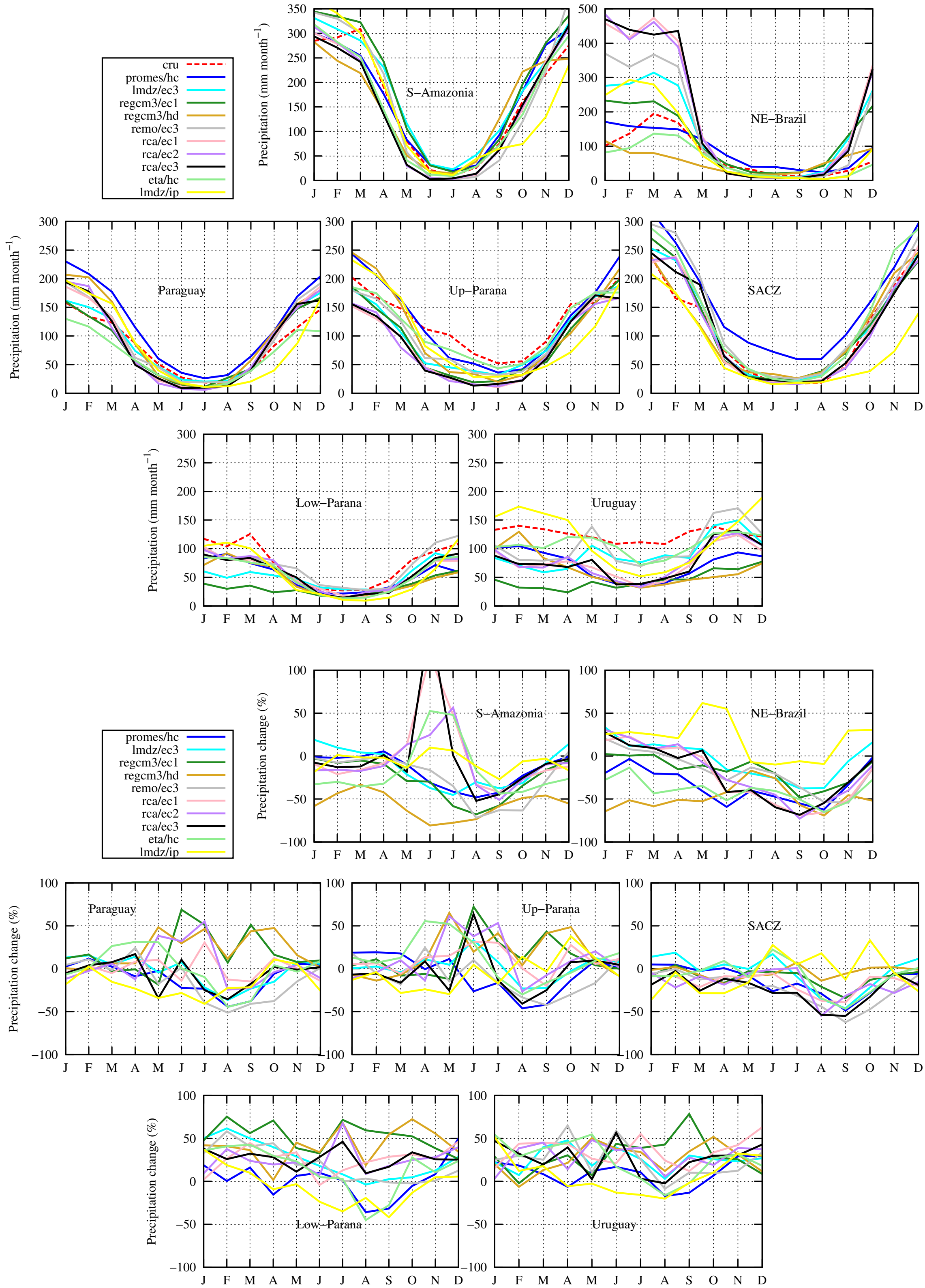

Fig. 9 As Fig. 8, but for the annual cycle of monthly precipitation (in mm month−1), and the change (in %)

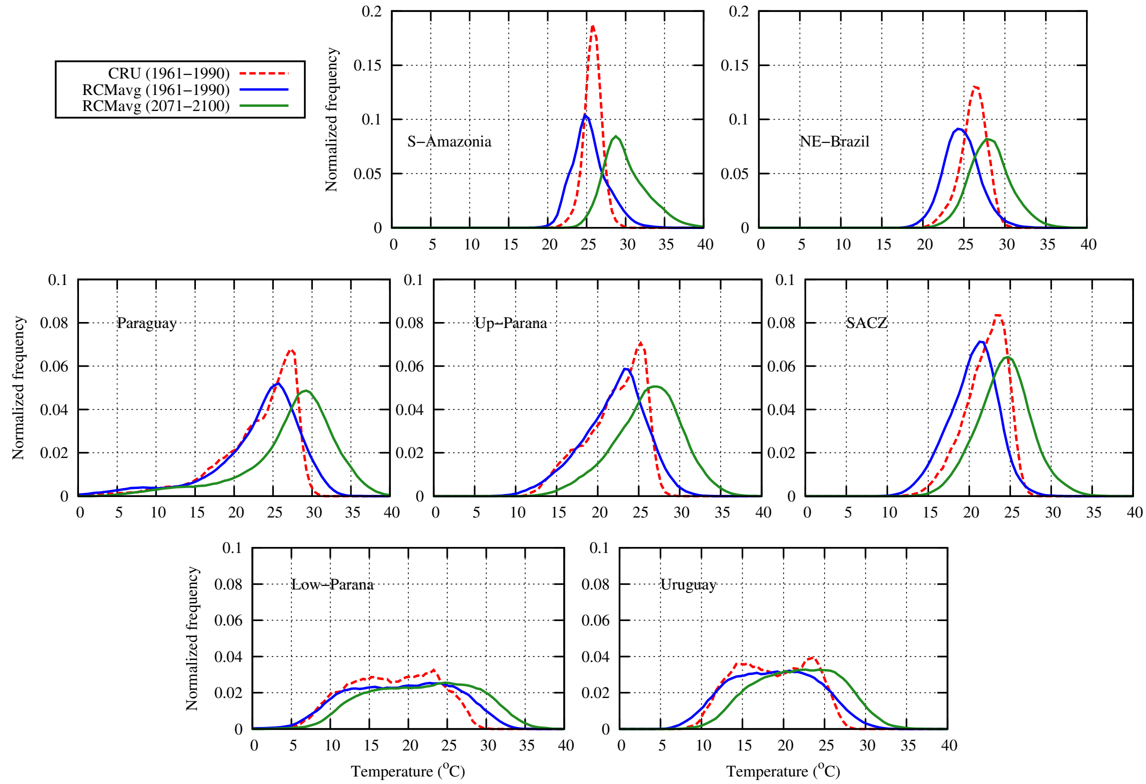

Fig. 10 Frequency distribution function of monthly mean daily temperature (in °C) for the ensemble of the RCMs over each of the seven selected subregions for present and future climate conditions, together with CRU observational database

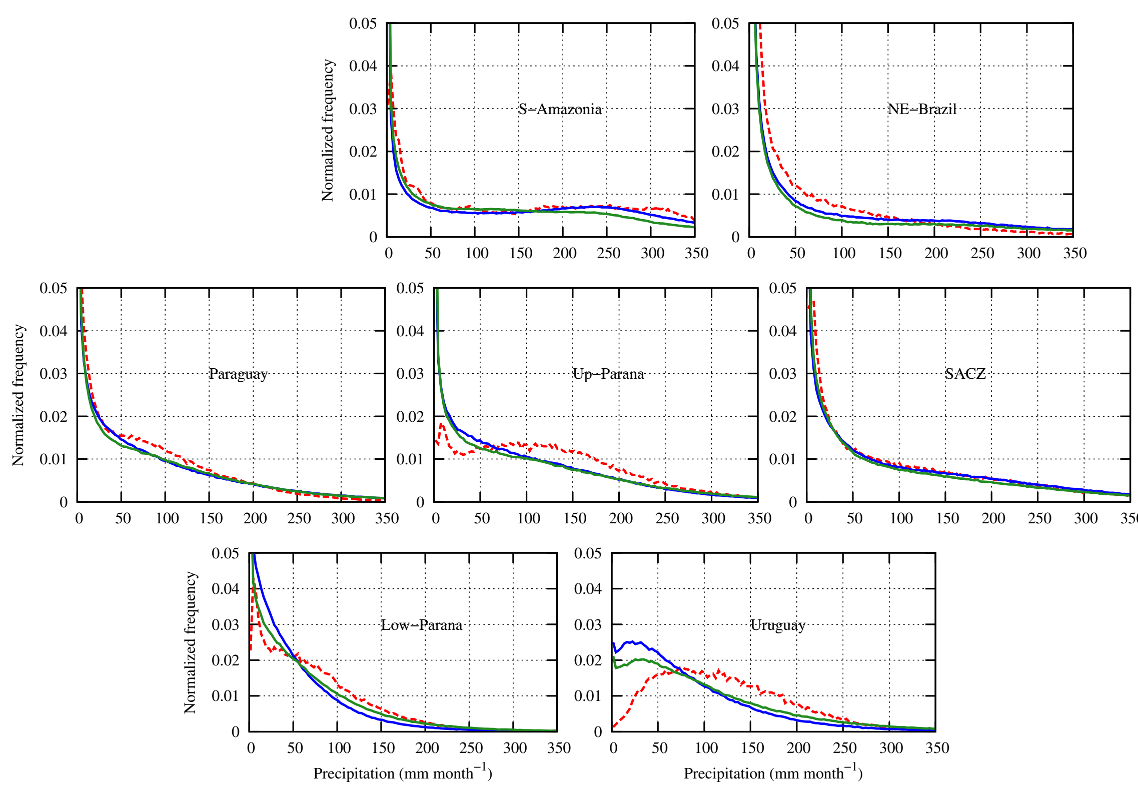

Fig. 11 As Fig. 10, but for monthly precipitation (in mm month^{-1})

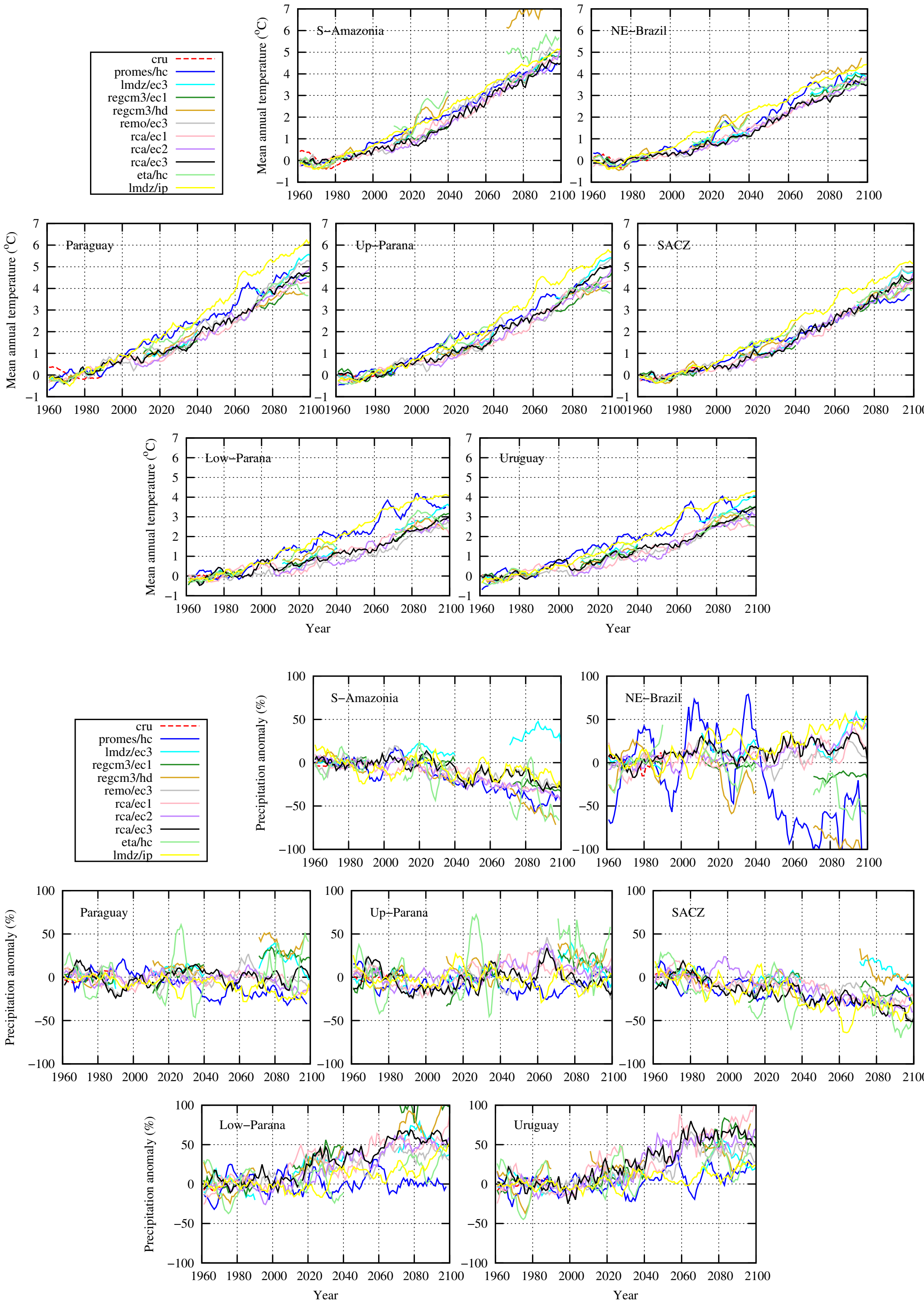

Fig. 12 Annual timeseries of daily temperature (*above*) and annual precipitation (*below*) anomalies, including the complete period from the simulations with continuous runs over the seven selected sub-regions. Anomalies are related to the average for each model for its (1961–1990) period. Precipitation anomalies are computed in % with respect to that period

to the amplitude of the climate change signal, particularly for near-term projections. However, a quasi-linear trend can be identified over some of the regions, such as negative trends over S-Amazonia and SACZ and positive trends over Low-Paraná and Uruguay. For these regions, almost every model shows agreement in the sign of the change for the long-term projections, but the magnitude of the change is characterized by a large spread. Other regions, such as Paraguay and Upper-Paraná do not display any trend in precipitation; being this behaviour shared by all the simulations, suggesting that the precipitation change has no signal for these regions.

3.5 Combined changes (deltas) of precipitation and temperature

A very interesting analysis is the combined inspection of changes in precipitation and temperature for each region for both summer and winter seasons. The agreement and dispersion among changes in these two variables from the set of RCM simulations allows identifying both the range of the climate change signal and its associated uncertainty. It is worth to note that the seven regions identified lie within (or are related to) the South American monsoon region, where rainfall occurs mostly during the warm season. In addition for the southern subregions the amount of rainfall during the cold season is also important. These results are displayed in Fig. 13.

Changes in temperature among RCMs are roughly in the range of 2–6 °C, being generally larger for JJA than for DJF in most of the regions. For precipitation the ranges are roughly 50 to 50 %. The individual model changes in temperature are well clustered together, with a dispersion of around 1 °C among individual RCMs. The changes in precipitation are more region dependent: no change for Paraguay and Up-Paraná regions; increase for Uruguay and Low-Paraná and decreases for SACZ and S-Amazonia. For NE-Brazil a decrease for JJA is also apparent. Northern regions (S-Amazonia, NE-Brazil, SACZ) relative precipitation decreases tend to be larger for JJA compared with DJF, thus increasing the amplitude of the rainfall annual cycle. On the contrary, for many of the southern regions, most of the RCMs obtain relative precipitation increases, that are usually larger for JJA than for DJF. This would lead to a reduction on the amplitude of the annual cycle there. However, this behaviour is not so clearly seen by all the RCMs over these southern regions, such as ETA/HC or LMDZ/IP over Low-Paraná, for example. The dispersion among changes in precipitation, even for those regions where the models agree on the sign of the signal, is quite large, of around 40 %, suggesting that even when the models agree on the future change there is a quite large uncertainty in the amount of the change. This behaviour may be critical for impact studies, as the impact of a increase or decrease in rainfall may depend on a threshold, which may indicate no sensitivity at all, or a large sensitivity to a given projected change, depending on the rate of the change.

Note that the regions where there is an agreement in the sign of precipitation change it is produced by different GCMs driving one or more RCMs, suggesting that the reliability of the climate change signal can be considered as high. One final comment on the delta change plot refers to the extent to which the driving GCMs exert a control on the projected change. For several regions, the sign of the precipitation change is opposite even when different RCMs share the same driving GCM. This behaviour suggests that regional scale processes play an important role in modulating the large scale signal.

4 Concluding remarks

The results of the first coordinated ensemble of regional climate model (six) climate change simulation projections (ten) over South America region for the whole twentyfirst century are presented. Simulations are based on CLARIS-LPB EU FP7 project, using the forcing of three global climate models, and A1B greenhouse gases emissions scenario. Validation of present climate conditions (1961–1990) period indicates an overall agreement of the ensemble of RCMs, despite the forcing GCM when describing the mean climate features for both temperature and precipitation: spatial structure of annual means, the annual cycle over several subregions, the frequency distribution function of monthly values or the annual timeseries for that period. This is in agreement with the previous work of Solman et al. (2013), where all these RCMs analyzed here were forced with the ERAinterim reanalysis perfect boundary conditions.

However, some relevant biases are also seen. The spatial pattern of the temperature differences between the RCMs CRU observations typically resembles that of their forcing GCM. Precipitation biases also depict an overall reduction when compared with GCM results. Nevertheless, certain RCM/GCM combinations produce reduced errors, but for some others the biases are amplified, such as over LPB for dry conditions, and NE-Brazil for wetter values. Annual cycles, annual timeseries and frequency distribution functions of temperature and precipitation for present conditions also exhibit a comparable behaviour, with more spread on RCM results over tropical areas, specifically on temperature over S-Amazonia and NE-Brazil for precipitation. Note the overestimation of high temperature values when compared with observations, and specially over LPB subregions, as shown in the higher tail of the frequency distribution function. Precipitation timeseries for present

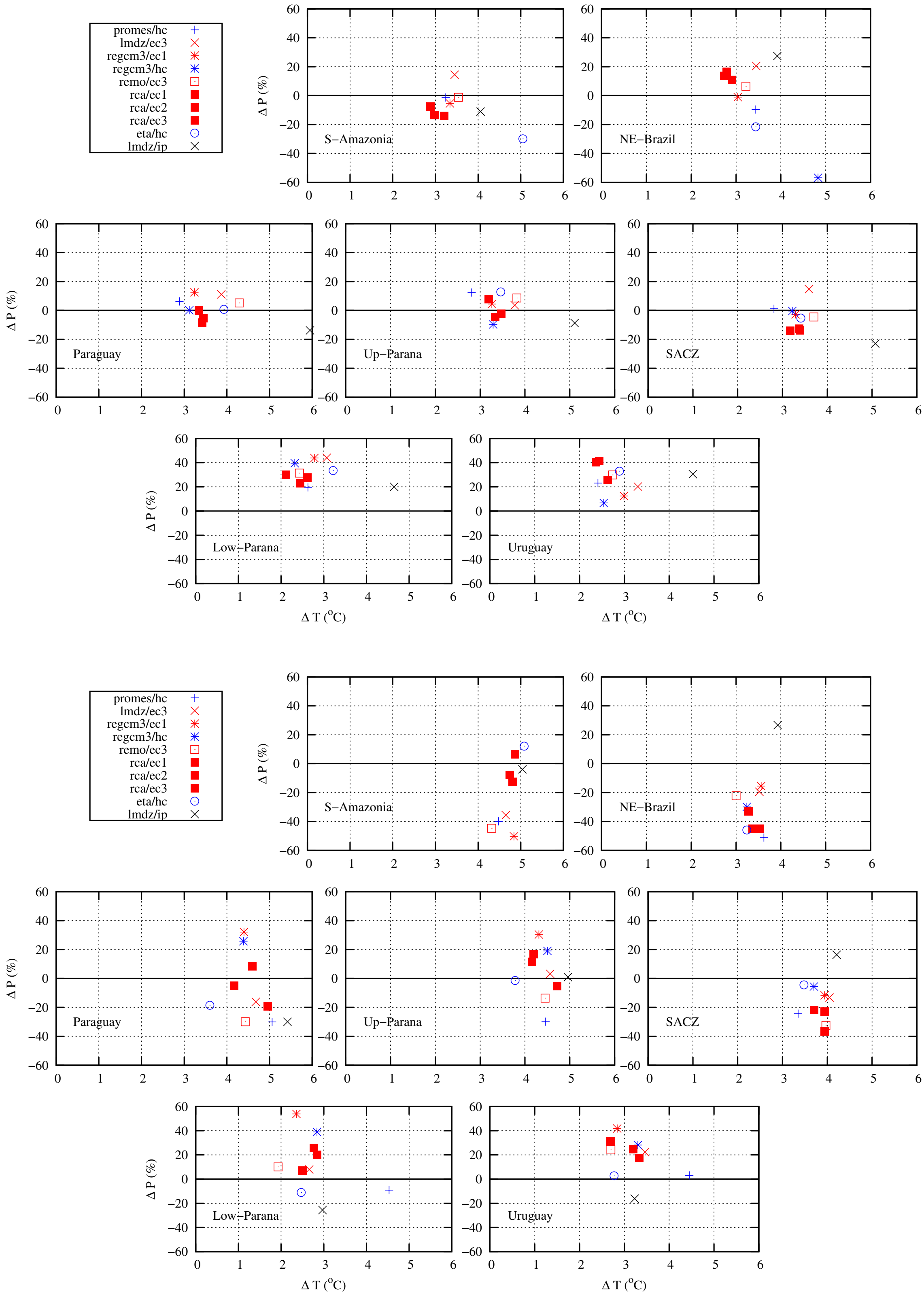

Fig. 13 Combined changes in temperature (in °C on the horizontal axis) against changes in annual precipitation (in percentage) for each of the RCMs over the seven subregions when compared future climate conditions (2071–2100) with present (1961–1990) periods, for DJF (*upper figures*) and JJA (*bottom figures*). Each RCM is presented with a *different symbol*, and each forcing GCM with a *different color* (HadCM3 in *blue*, EC5OM in *red*, and IPSL in *black*)

conditions indicate a large variability among RCMs around the values of CRU observations.

Once present climate simulations are described, the main focus and objective of this work are to analyze main climate change features for both temperature and precipitation. Mean temperature changes indicate an overall increase of temperature for all the seasons and regions, generally larger for the austral winter season. The potential added value of RCMs can be seen over regions with complex orography, such as over the Andes or coastal areas. Related to precipitation patterns, a decrease over the tropical region and an increase over the subtropical areas is obtained. These climate change features are common to any driving global model and the RCM. Nevertheless, large differences, even sometimes in the sign of the change are shown on the forcing GCMs, and therefore, in the RCM projections. Among the common features shown by the RCM results, it can be pointed the dipole structure between LPB and SACZ, and the sign of the rainfall change. The internal variability of the driving GCM is quite small in terms of the projected uncertainty compared with the forcing global model selected and the RCM simulation. When looking at the annual cycle of the changes, September–October–November tend to show a larger increase of temperature, meanwhile precipitation annual structure of change is less clear. A patterns of increase over southern regions and decrease over northern ones seem to be obtained, but with remarkable discrepancies for some RCMs and over some subregions. Frequency distribution functions of temperature indicate no relevant change in the shape of the distribution at any region, but mainly a displacement towards higher values, with slight changes on the large tail over some regions, that could indicate an increase in the variability. Precipitation distribution shows smaller changes, although some indications of modifications of extreme precipitation events, such as over LPB, with a decrease in light precipitation and increase in the frequency of moderate to heavy values. Timeseries indicate that the degree of uncertainty increases for temperature and precipitation as it goes further in the future. A quasi-linear trend is obtained for temperature increases, being lager for tropical compared with subtropical regions. Larger discrepancies are seen for precipitation timeseries, together with strong interdecadal signal in many projections. However, some regions exhibit a more clear trend, both negative (S-Amazonia or SACZ) or positive (Low-Paraná or Uruguay).

Finally the combined figures of temperature and precipitation changes for both summer and winter seasons help us to identify regions where reliability of the change is high, when all the RCM projections agree on the sign and relative magnitude, for example for Low-Paraná and Uruguay in DJF or Ne-Brazil in JJA, among others. Globally, changes in temperature are in the range of 2–6 °C, being generally larger for JJA than for DJF in most of the regions. For precipitation the ranges are around 50 to 50 %.

The ensemble of RCM described there is therefore able to describe the main patterns of climate change projections for the twentyfirst century on regional scales over this region, despite the important uncertainties and biases also shown. The simulations database developed in the frame of CLARIS-LPB project shown here is expected to serve as a reference in the following years to further improve our understanding of the regional climate mechanisms, uncertainties and robust features of climate change projections for the current century, and serve as a key tool for impact studies over the region.

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References

Boulanger JP, Brasseur G, Carril AF, de Castro M, Degallier N, Ereño C, Treut HL, Marengo JA, Menéndez CG, Núñez MN, Penalba OC, Rolla AL, Rusticucci M, Terra R (2010) A Europe–South America network for climate change assessment and impact studies. Clim Change 98(3–4):307–329. doi:10.1007/s10584-009-9734-8

Cabré MF, Solman S, Nuñez M (2010) Creating regional climate change scenarios over southern South America for the 2020's and 2050's using the pattern scaling technique: validity and limitations. Clim Change 98(3–4):449–469

Carril A, Menéndez C, Remedio A, Robledo F, Sörensson A, Tencer B, Boulanger JP, De Castro M, Jacob D, Le Treut H, Li LZX, Penalba O, Pfeifer S, Rusticucci M, Salio P, Samuelsson P, Sanchez E, Zaninelli P (2012) Performance of a multi-RCM ensemble for South Eastern South America. Clim Dyn 39(12):2747–2768. doi:10.1007/s00382-012-1573-z

Castro M, Gallardo C, Jylhä K, Tuomenvirta H (2007) The use of a climate-type classification for assessing climate change effects in Europe from an ensemble of nine regional climate models. Clim Change 81(S1):329–341

Christensen J, Kumar KK, Aldrian E, An SI, Cavalcanti I, de Castro M, Dong W, Goswami P, Hall A, Kanyanga J, Kitoh A, Kossin J, Lau NC, Renwick J, Stephenson D, Xie SP, Zhou T (2013) Climate phenomena and their relevance for future regional climate change. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, New York

Christensen JH, Christensen OB (2007) A summary of the PRUDENCE model projection of changes in European climate by the end of this century. Clim Change 81:1–30

Christensen JH, Carter T, Rummukainen M, Amanatidis G (2007) Evaluating the performance and utility of regional climate models: the PRUDENCE project. Clim Change 81(S1):1–6

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon WT, Laprise R, Rueda VM, Mearns LO, Menéndez CG, Räisänen J, Rinke A, Sarr A, Whetton PH (2007) Regional climate projections. In: Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Technical report, IPCC, WMO

Déqué M, Rowell DP, Lüthi D, Giorgi F, Christensen JH, Rockel B, Jacob D, Kjellström E, Castro M, Van den Hurk B (2007) An intercomparison of regional climate simulations for Europe: assessing uncertainties in model projections. Clim Change 81(S1):53–70

Déqué M, Somot S, Sanchez-Gomez E, Goodess C, Jacob D, Lenderink G, Christensen O (2012) The spread amongst ensembles regional scenarios: regional climate models, driving general circulation models and interannual variability. Clim Dyn 38(5–6):951–964. doi:10.1007/s00382-011-1053-x

der Linden PV, Mitchell JFB (2009) ENSEMBLES: climate change and its impacts: summary of research and results from the ENSEMBLES project. In: Technical report, Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK

Flato G, Marotzke J, Abiodun B, Braconnot P, Chou S, Collins W, Cox P, Driouech F, Emori S, Eyring V, Forest C, Gleckler P, Guilyardi E, Jakob C, Kattsov V, Reason C, Rummukainen M (2013) Evaluation of climate models. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, New York

Giorgi F (2014) Introduction to the special issue: the phase I CORDEX RegCM4 hyper-matrix (CREMA) experiment. Clim Change 125(1):1–5. doi:10.1007/s10584-014-1166-4

Giorgi F, Francisco R (2000) Evaluating uncertainties in the prediction of regional climate change. Geophys Res Lett 27(9):1295–1298

Giorgi F, Whetton PH, Jones R, Christensen JH, Mearns LO, Hewitson B, Von Storch H, Francisco R, Jack C (2001) Emerging patterns of simulated regional climatic changes for the 21st century due to anthropogenic forcings. Geophys Res Lett 28(L04703):3317–3320

Giorgi F, Jones C, Asrar GR (2009) Addressing climate information needs at the regional level: the CORDEX framework. World Meteorol Organ Bull 58(3):175

Gordon C, Cooper C, Senior CA, Banks H, Gregory JM, Johns TC, Mitchell JF, Wood RA (2000) The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. Clim Dyn 16(2–3):147–168

Grimm AM, Zilli MT (2009) Interannual variability and seasonal evolution of summer monsoon rainfall in South America. J Clim 22(9):2257–2275

Hawkins E, Sutton R (2009) The potential to narrow uncertainty in regional climate predictions. Bull Am Meteorol Soc 90(8):1095–1107

Hawkins E, Sutton R (2011) The potential to narrow uncertainty in projections of regional precipitation change. Clim Dyn 37(1–2):407–418

Hourdin F, Musat I, Bony S, Braconnot P, Codron F, Dufresne JL, Fairhead L, Filiberti MA, Friedlingstein P, Grandpeix JY et al (2006) The LMDZ4 general circulation model: climate performance and sensitivity to parametrized physics with emphasis on tropical convection. Clim Dyn 27(7–8):787–813

Jacob D, Barring L, Christensen OB, Christensen JH, de Castro M, Déqué M, Giorgi F, Hagemann S, Hirschi M, Jones R, Kjellström E, Lenderink G, Rockel B, Sánchez E, Schär C, Seneviratne SI, Somot S, Ulden AV, den Hurk BV (2007) An inter-comparison of regional climate models for Europe: model performance in present-day climate. Clim Change 81(S1):31–52

Jacob D, Elizalde A, Haensler A, Hagemann S, Kumar P, Podzun R, Rechid D, Remedio AR, Saeed F, Sieck K, Teichmann C, Wilhelm C (2012) Assessing the transferability of the regional climate model REMO to different coordinated regional climate downscaling experiment (CORDEX) regions. Atmosphere 3(1):181–199

Jones C, Giorgi F, Asrar G (2011) The coordinated regional downscaling experiment: CORDEX an international downscaling link to CMIP5. CLIVAR Exch 16(2):34–40

Kendon EJ, Jones RG, Kjellström E, Murphy JM (2010) Using and designing GCM–RCM ensemble regional climate projections. J Clim 23(24):6485–6503

Kjellström E, Boberg F, Castro M, Christensen JH, Nikulin G, Sánchez E (2010) On the use of daily and monthly temperature and precipitation statistics as a performance indicator for regional climate models. Clim Res 44:135–150. doi:10.3354/cr00932

Kjellström E, Nikulin G, Hansson U, Strandberg G, Ullerstig A (2011) 21st century changes in the European climate: uncertainties derived from an ensemble of regional climate model simulations. Tellus-A 63(1):24–40

Marengo J, Chou S, Torres R, Giarolla A, Alves L, Lyra A (2014) Climate change in central and South America: recent trends, future projections, and impacts on regional agriculture. In: CCAFS working paper 73 CGIAR research program on climate change, agriculture and food security (CCAFS) Copenhagen, Denmark

Marengo JA, Ambrizzi T, Da Rocha RP, Alves LM, Cuadra SV, Valverde MC, Torres RR, Santos DC, Ferraz SE (2010) Future change of climate in South America in the late twenty-first century: intercomparison of scenarios from three regional climate models. Clim Dyn 35(6):1073–1097

Mearns L, Sain S, Leung L, Bukovsky M, McGinnis S, Biner S, Caya D, Arritt R, Gutowski W, Takle E, Jones R, Leung R, M-Okia W, McDaniel L, Nunes A, Qian Y, Roads J, Sloan L, Snyder M (2013) Climate change projections of the north american regional climate change assessment program (NARCCAP). Clim Change 120(4):965–975

Mearns LO, Arritt R, Biner S, Bukovsky MS, McGinnis S, Sain S, Caya D, Correia J Jr, Flory D, Gutowski W, Takle ES, Jones R, Leung R, Moufouma-Okia W, McDaniel L, Nunes AMB, Qian Y, Roads J, Sloan L, Snyder M (2012) The North American regional climate change assessment program: overview of phase I results. Bull Am Meteorol Soc 93(9):1337–1362

Menéndez C, de Castro M, Boulanger JP, Donofrio A, Sanchez E, Sörensson A, Blazquez J, Elizalde A, Jacob D, Le Treut H, Li ZX, Núñez MN, Pessacg N, Pfeiffer S, Rojas M, Rolla A, Samuelsson P, Solman SA, Teichmann C (2010) Downscaling extreme month-long anomalies in southern South America. Clim Change 98(3–4):379–403

Mitchell TD, Jones PD (2005) An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int J Climatol 25(6):693–712

Nakicenovic N, Swart R (eds) (2000) Emissions scenarios: a special report of working group III of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Paegle JN, Byerle LA, Mo KC (2000) Intraseasonal modulation of South American summer precipitation. Mon Weather Rev 128(3):837–850

Reboita M, da Rocha R, Dias C, Ynoue R (2014) Climate projections for South America: RegCM3 driven by HadCM3 and ECHAM5. Adv Meteorol. doi:10.1155/2014/376738

Roeckner E, Brokopf R, Esch M, Giorgetta M, Hagemann S, Kornblueh L, Manzini E, Schlese U, Schulzweida U (2006) Sensitivity of simulated climate to horizontal and vertical resolution in the ECHAM5 atmosphere model. J Clim 19(16):3771–3791

Ruti PM, Williams JE, Hourdin F, Guichard F, Boone A, Van Velthoven P, Favot F, Musat I, Rummukainen M, Domnguez M, Gaertner M, Lafore JP, Losada T, Rodriguez de Fonseca MB, Polcher J, Giorgi F, Xue Y, Bouarar I, Law K, Josse B, Barret B, Yang X, Mari C, Traore AK (2011) The West African climate system: a review of the AMMA model inter-comparison initiatives. Atmos Sci Lett 12(1):116–122. doi:10.1002/asl.305

Solman SA (2013) Regional climate modeling over South America: a review. Adv Meteorol. doi:10.1155/2013/504357

Solman SA, Pessacg NL (2012) Evaluating uncertainties in regional climate simulations over south america at the seasonal scale. Clim Dyn 39(1–2):59–76

Solman SA, Sanchez E, Samuelsson P, da Rocha R, Li L, Marengo J, Pessacg N, Remedio A, Chou SC, Berbery H, Treut HL, de Castro M, Jacob D (2013) Evaluation of an ensemble of regional climate model simulations over South America driven by the ERA-Interim reanalysis: models' performance and uncertainties. Clim Dyn 41:1139–1157. doi:10.1007/s00382-013-1667-2

Tapiador FJ, Sánchez E, Gaertner MA (2007) Regional changes in precipitation in Europe under an increased greenhouse emissions scenario. Geophys Res Lett 34:l06701. doi:10.1029/2006GL029035

Teichmann C, Eggert B, Elizalde A, Haensler A, Jacob D, Kumar P, Moseley C, Pfeifer S, Rechid D, Remedio AR, Ries H, Petersen J, Preuschmann S, Raub T, Saeed F, Sieck K, Weber T (2013) How does a regional climate model modify the projected climate change signal of the driving GCM: a study over different CORDEX regions using REMO. Atmosphere 4(2):214–236

Torres RR, Marengo JA (2013) Uncertainty assessments of climate change projections over South America. Theor Appl Climatol 112(1–2):253–272

Vera C, Silvestri G (2009) Precipitation interannual variability in South America from the WCRP-CMIP3 multi-model dataset. Clim Dyn 32(7–8):1003–1014

Vera C, Silvestri G, Liebmann B, Gonzlez P (2006) Climate change scenarios for seasonal precipitation in South America from IPCC-AR4 models. Geophys Res Lett. doi:10.1029/2006GL025759