

Future change of climate in South America in the late twenty-first century: intercomparison of scenarios from three regional climate models

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Abstract Regional climate change projections for the last half of the twenty-first century have been produced for South America, as part of the CREAS (Cenários REGIONalizados de Clima Futuro da America do Sul) regional project. Three regional climate models RCMs (Eta CCS, RegCM3 and HadRM3P) were nested within the HadAM3P global model. The simulations cover a 30-year period representing present climate (1961–1990) and projections for the IPCC A2 high emission scenario for 2071–2100. The focus was on the changes in the mean circulation and surface variables, in particular, surface air temperature and precipitation. There is a consistent pattern of changes in circulation, rainfall and temperatures as depicted by the three models. The HadRM3P shows intensification and a more southward position of the subtropical Pacific high,

while a pattern of intensification/weakening during summer/winter is projected by the Eta CCS/RegCM3. There is a tendency for a weakening of the subtropical westerly jet from the Eta CCS and HadRM3P, consistent with other studies. There are indications that regions such of Northeast Brazil and central-eastern and southern Amazonia may experience rainfall deficiency in the future, while the Northwest coast of Peru-Ecuador and northern Argentina may experience rainfall excesses in a warmer future, and these changes may vary with the seasons. The three models show warming in the A2 scenario stronger in the tropical region, especially in the 5°N–15°S band, both in summer and especially in winter, reaching up to 6–8°C warmer than in the present. In southern South America, the warming in summer varies between 2 and 4°C and in winter between 3 and 5°C in the same region from the 3 models. These changes are consistent with changes in low level circulation from the models, and they are comparable with changes in rainfall and temperature extremes reported elsewhere. In summary, some aspects of projected future climate change are quite robust across this set of model runs for some regions, as the Northwest coast of Peru-Ecuador, northern Argentina, Eastern Amazonia and Northeast Brazil, whereas for other regions they are less robust as in Pantanal region of West Central and south-eastern Brazil.

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1 Introduction

The knowledge of changes in the meteorological fields (e.g. circulation, temperature, precipitation) in future

climate scenarios rely upon the use of numerical models. The continuous evolution of these models over recent decades has been driven by a considerable increase in computational capacity, with supercomputer speeds increasing by roughly a factor of a million in the three decades from the 1970s to the present day. This computational progress has permitted a corresponding increase in model complexity (by including more and more components and processes), in the length of the simulations and in spatial resolution.

A fundamental issue concerning the use of GCMs to provide regional climate change scenarios is that of horizontal resolution. Despite the recent increase in computing power, Atmosphere–Ocean General Circulation Models (AOGCMs) are still run at horizontal grid intervals of 100–300 km. While this resolution is sufficient to capture processes and climate statistics down to the sub-continental scale (approximately a few thousand kilometers), it is not suitable for finer regional and local scales. At the regional scale there remains an urgent need for relevant, targeted projections of the regional climate change.

The coarse grid spacing poses limitations to the explicit simulation of mesoscale processes and to the representation of topography, land use, and land–sea distribution. Regional climate models (RCMs) are promising tools, which, when nested into a GCM, permit the derivation of GCM-consistent climate change scenarios with more regional detail and a more trustworthy representation of processes active during heavy precipitation (see reviews in Christensen et al. 2007a).

Adaptation to climate change is inherently a local and regional scale issue, and limited by the measure of confidence in the projected changes at these scales. Without appropriate regional projections of climate change, it is arguable whether regional adaptation strategies can be developed or implemented. Developing climate change scenarios at regional scale is, thus, an important component of understanding climate impacts under global warming conditions, with critical implications for climate change adaptation and mitigation. In addition, climate change can show pronounced regional variability, which could suggest geographical distribution of climate impacts. Results from AOGCMs may be considered with some reservation as regards the sub-continental pattern and magnitude of the change.

In view of the pressing need for regional projections, much effort has been expended in recent years on developing regional projections through diverse methodologies (Wilby and Wigley 1997; Giorgi et al. 2004; Jones et al. 2004, 2008). Significant advances have been made to downscale the GCM skilful scale to the regional and local scales, either through high resolution dynamical modeling (Giorgi et al. 2001), or via empirical cross scale functions

or statistical downscaling techniques (Solman and Nuñez 1999; Hewitson and Crane 1996; Diaz-Nieto and Wilby 2005).

Previous experiments on dynamic downscaling of future climate change scenarios in South America have been performed in various regions of South America, for the Intergovernmental Panel on Climate Change (IPCC) Special Report Emission Scenarios (SRES) A2 and B2 (Marengo and Ambrizzi 2006; Nuñez et al. 2006, 2008; Alves and Marengo 2009; Solman and Nuñez 1999; Solman et al. 2008; Garreaud and Falvey 2008; Cabré et al. 2008; Soares and Marengo 2009; Marengo et al. 2009; Urrutia and Vuille 2009; Pesquero et al. 2009; Alves and Marengo 2009). An integrated picture of various regional models used suggest future warming, with rainfall increases in southeastern South America, and decreases in the central and eastern Amazon and Northeast Brazil regions, consistent with projections from IPCC AR4 AOGCMs (Vera et al. 2006; Boulanger et al. 2006, 2007; Cavalcanti et al. 2006; Grimm and Natori 2006; Li et al. 2006; Meehl et al. 2007).

High resolution scenarios developed from RCMs results have been obtained in various parts of the world: Bangladesh and India (Islam and Rehman 2009; Rupa Kumar et al. 2006), China (Zhang et al. 2006; Xu et al. 2006a, b), Europe (Christensen and Christensen 2003; Frei et al. 2006; Beniston et al. 2007; Graham et al. 2007; Lionello et al. 2007; Giorgi and Diffenbaugh 2008), and Southern Africa (Tadross et al. 2005; Marengo et al. 2003).

Various national and international projects have used RCMs to help quantify better regional climate change and provide regional climate scenarios for assessing climate change impacts and vulnerability: the UK Climate Impacts Programme (Hulme et al. 2002), the European Projects PRUDENCE (Christensen et al. 2007b; Gao et al. 2006) and STARDEX (Haylock et al. 2006). These have all followed a standard experimental design of using one or two GCMs to drive various regional models from meteorological services and research institutions in the regions to provide dynamically downscaled regional climate projections. Typically, a present day (e.g. 1961–1990) and a future climate (2071–2100) time slices are simulated to calculate changes in relevant climatic variables with interpolation techniques (e.g. Morales et al. 2007) used to derive information for nearer time periods. One important result from PRUDENCE (Déqué et al. 2005) was that individual RCMs present a larger spread than the difference between AOGCMs and RCMs.

Recognizing that multiple GCMs are required to provide comprehensive regional climate scenarios, current projects in Europe (ENSEMBLES, Hewitt and Griggs 2004) and North America (NARCCAP, Mearns 2004) are downscaling several GCMs to provide high resolution

climate change scenarios for each region, though still only sampling a limited uncertainty range. These are the most advanced regional programmes delivering detailed climate scenarios and whilst the output is not comprehensive it is still having a significant impact in raising awareness of the potential seriousness of climate change and providing plausible high resolution future climates being used in impacts models helping to lay the methodological basis for future impacts–vulnerability–adaptation (IVA) studies.

A similar initiative has been implemented in South America, CREAS (Marengo and Ambrizzi 2006; Marengo 2009). It aims to provide high resolution climate change scenarios in South America for raising awareness among government and policy makers in assessing climate change impact, vulnerability and in designing adaptation measures. CREAS follows PRUDENCE's strategy, and runs three regional models nested in the public version of the atmospheric global model of the UK Met Office Hadley Centre HadAM3P (a GCM used in PRUDENCE): Eta for Climate Change Simulations—Eta CCS—(Pisnichenko and Tarasova 2009a, b), RegCM3 (Seth and Rojas 2003; Pal et al. 2007) and the public version 3 of the regional climate model the UK Met Office Hadley Centre HadRM3P (Jones et al. 2004; Alves and Marengo 2009).

Regional projections are characterized by different sources of uncertainties and this study aims to evaluate only one of them. While intercomparison projects such as PRUDENCE, ENSEMBLES NAARCAP dealt with different sources of uncertainties, CREAS and the results presented in this study focus on the intercomparison among different regional models driven by the same boundary conditions. In consequence the results allow exploring the uncertainty due to the regional models. CREAS explores issues such as: the challenge of using regional climate projections to develop plausible scenarios for future changes at daily time scales for extreme events; an assessment of current methods of scenario development for regions where data is not available; assessments of IVA in regions and key sectors in South America.

Therefore, the objectives of this paper are to develop a broad intercomparison of downscaled circulation, rainfall and temperature scenarios for South America for future climate change scenarios. In this paper we assess the performance of the HadRM3P, Eta CCS and RegCM3 in projecting climate change scenarios for 2071–2100 under the IPCC SRES A2 high scenario (Nakicenovic et al. 2000). The projections are then compared with the 1961–1990 simulation to assess how those meteorological fields will change under this high emission climate change. The RCMs projections have been driven with initial and boundary conditions from HadAM3P and are run at 50 km horizontal resolution.

2 Methodology, models and experiments

2.1 HadRM3P regional model

The HadRM3P regional model was developed at the Hadley Centre and is part of the PRECIS (Providing Regional Climate for Impacts Studies) regional climate modeling system (see Jones et al. (2004), which also includes a detailed description of HadRM3P). HadRM3P has 19 vertical levels and a choice of two horizontal resolutions, 50 km as used in this study (and the standard resolution for larger areas) and 25 km for smaller areas and when higher resolution is particularly important. Lateral boundary conditions for HadRM3P are available from a range of model and observationally based sources and in this study are obtained from the HadAM3P GCM.

The model formulation is the same as HadAM3P, an experimental setup which promotes consistency of the high resolution climate change projections from the RCM with those from the global model. Matching the SST forcing the HadAM3P and HadRM3P simulations for the present climate incorporated observed greenhouse gas (GHG) concentrations and CO₂ emissions and for the future incorporated GHG concentrations and CO₂ emissions taken from two contrasting emission scenarios.

2.2 Eta CCS regional model

The INPE Eta CCS is a climate version of the NCEP Eta model (Mesinger et al. 1988; Janjic 1994; and Black 1994). The climate change version of the Eta model was prepared by Pisnichenko and Tarasova (2009a, b) for long-term climate integrations. Multiple modifications were made by Pisnichenko and Tarasova (2009a) in the model, such as: new programs to convert the HadAM3P output data to the Eta model data format; new restart programs; new SST update programs, new programs of the Sun's elevation angle, etc.

In the runs of the Eta CCS model considered here, the physics parameterization package of the NCEP Eta model was not modified. This package includes the planetary boundary layer model of Mellor and Yamada (1974), the convective precipitation scheme of Betts and Miller (1986) modified by Janjic (1994), the shortwave and longwave radiation codes of Lacis and Hansen (1974) and Fels and Schwartzkopf (1975), respectively, and the land-surface scheme of Chen et al. (1997).

The region for the Eta CCS model integration was centered at 58.5°W and 22.0°S and covers the territory of South American continent with adjacent oceans (55°S–16°N, 89°W–29°W). The model was integrated on 211 × 115 horizontal grid with grid spacing of 50 km and at the vertical grid of 38 eta coordinate levels. The

first results of these runs are analyzed by Pisnichenko et al. (2006); Pisnichenko and Tarasova (2009a, b); Tarasova and Pisnichenko (2009). The results of the analysis show that the Eta CCS model is consistent with the outputs of the HadAM3P driving model, that the model reproduces current climate reasonably well and that further improvement of the model performance can be achieved by the improvement in its physics parameterization package.

2.3 RegCM3 regional model

The Regional Climate Model (RegCM) Version 3 (Pal et al. 2007) is a limited area model built around the hydrostatic dynamical component of the National Center for Atmospheric Research (NCAR)/Pennsylvania State University Mesoscale Model version 5.0 (MM5) (Grell 1993). The model is a primitive equation, hydrostatic, compressible; limited-area model with sigma-p vertical coordinate and the simulations were carried out with a vertical resolution of 23 levels. The soil–vegetation–atmosphere interaction processes are parameterized through BATS scheme (Biosphere–Atmosphere Transfer Scheme; Dickinson et al. 1989). In the planetary boundary layer, the turbulent transport of heat, moment and moisture are computed as the product between the vertical gradient of these variables and the turbulent vertical diffusion coefficient, with corrections for non local turbulence proposed by Holtslag et al. (1990).

The radiative transfer in the RegCM3 follows the CCM3 (Community Climate Model 3; Kiehl et al. 1996) parameterization where the heating rate and surface fluxes for solar and infrared radiation for clear skies and cloudy conditions are computed separately. This parameterization also includes the effect of the GHG (CO₂, NO₂, CH₄, and CFCs), atmospheric aerosols and cloud water. The precipitation in the RegCM3 is represented in two forms: grid-scale (resolvable scale) and convective (sub-grid scale). The grid-scale precipitation scheme (Pal et al. 2000) only considers the water phase and includes formulations for auto-conversion of cloud water into rainwater, accretion of cloud droplets by falling raindrops and evaporation of falling raindrops. The convective precipitation utilized follows Grell (1993) with Fritsch and Chappell closure (Pal et al. 2007).

2.4 Experiment design

Three integrations were carried out with HadAM3P for both time slices 1961–1990 (present climate) and 2071–2100 (future) for the A2 and B2 emission scenarios, starting from different initial conditions. The output of these runs was made available by the UK Hadley centre to

be used as the boundary conditions for the downscaling performed here. The three RCMs ran for only one (but the same) pair of ensemble members and were integrated for the current and future climate periods. The first step in the evaluation of the dynamical downscaling results was the investigation of the consistency between the regional models outputs and GCM data used for driving the simulations (Giorgi et al. 1993). That is, the RCMs results should not diverge significantly from the GCM mean large scale patterns of circulation. We also expect that both models reproduce a low-frequency oscillation of the atmosphere in a similar manner.

The three RCMs were forced at its lateral and bottom boundaries by the output of HadAM3P, which was run using SST, SICE (sea ice) and GHG and aerosol concentration as external driving from the coupled model HadCM3. Data for lateral boundary conditions for the RCMs models were provided every 6 h and SST and SICE data every 15 days. Linear interpolation for values on lateral boundaries, SST, and SICE was used between these periods. For the initial conditions of soil moisture and soil temperature the climate mean values were used. Due to the spin up period of soil moisture and temperature, the first year of the integration was not used in analysis. We acknowledge that the underlying assumption adopted in this work, namely that a global model responding to monthly mean observed SSTs is physically constrained to produce a dynamical response over land, may induce a causal interpretation of any agreement between observed and modeled trends over land.

For the present climate, in the HadAM3P model the concentrations of GHG and sulphur are prescribed and their evolution and impact in the sulphur cycle are simulated by both HadAM3P and HadRM3P models. For the A2 and B2 future climate scenarios the evolution in the concentration of GHG and sulphur is the same as the HadCM3 (Wilson et al. 2005). In the RegCM3 the concentrations of GHG and CFC-11 and 12 were prescribed each 10 years, since 1960–2100 (as shown in Pope et al. 2000). For the Eta CCS model, the CO₂ used for both present and future is the same, 330 ppm (Pisnichenko et al. 2006; Fernandez et al. 2006).

The time-slice experiments using HadAM3P were designed to provide the best possible present-day global climate using an atmosphere stand-alone model. It is well known that a GCM is better constrained towards the observed climate when sea surface temperatures and sea-ice conditions are specified according to the observed climate, rather than using the SSTs that could be generated from an experiment where the model is coupled to an ocean model. For this reason, the SSTs used in the control experiment were taken from a gridded data set of monthly mean observations covering the period 1960–1990

(HadISST dataset, Rayner et al. 2003). Daily values were generated by interpolation between succeeding months.

All analyses of the simulations have been performed on the period present time 1961–1990, allowing for models to spin-up their surface variables during the first year of simulation. The climate change experiment used SSTs from an existing HadCM3 simulation. The changes in the future (represented as 2071–2100) are calculated with respect to the AOGCM control 30 year climatology for the present (1961–1990) from the respective RCM. The statistical significance of the changes is determined by conducting a Student's *t* test.

All results are displayed on maps over South America between 10°N–37°S and 35–85°W and emphasis will be given over Brazil. In order to present synthetic results, we aggregate the grid points in various boxes with relatively homogeneous climate, at least at the horizontal resolution of the RCMs. These sub-domains are shown in Fig. 1 and are approximate to the five political-geographical regions in which Brazil is divided: North including Amazonia), Northeast, Southeast, West Central (including Pantanal) and Southern Brazil. In order to reduce further the size of this study, we concentrate on the two extreme seasons: austral summer (DJF) and winter (JJA), as well as at annual time scale.



Fig. 1 Sub-regions used for a more detailed analysis of the annual cycle for precipitation and air temperature in Brazil: *N* Northern Brazil (including Amazonia), *NE* Northeast Brazil, *CW* West Central Brazil (including Pantanal), *S* Southern Brazil, *SE* Southeastern Brazil

3 Results

The main focus will be on the A2 high emissions scenario experiment, as all models clearly show that the B2 experiment gives a relatively scalable result with a similar but weaker climate change signal as compared to the A2 ones. The discussion is on the changes in near-surface climate, in particular the temperature, precipitation and lower and upper level wind conditions. For rainfall and temperature, an analysis of the annual cycle for the five regions of Brazil depicted in Fig. 1 is also shown for this A2 scenario. Previously, we include an analysis of the consistency between the HadAM3P GCM and the three RCMs for the present time.

3.1 Simulation of present climate derived from the three RCMs and consistency with the HadAM3P GCM

Various papers have assessed simulation of present time (1961–1990) climatology from the three RCMs with the global HadAM3P model, particularly for rainfall and temperature. Simulation from HadRM3P have been assessed in a companion paper (Alves and Marengo 2009). Precipitation and temperature patterns as well as the main general circulation features from the HadRM3P are consistent with those from the HadAM3P global model, and some details captured by the HadRM3P are at finer scales than those resolved by the HadAM3P. When compared to observations, the HadRM3P simulations exhibit systematic errors which might be related to the physics of the model (e.g. convective schemes, topography and land surface processes), the lateral boundary conditions and possible biases inherited from the global model. Some systematic biases in precipitation are detected during the warm rainy season in tropical South America (December–January–February, DJF) and March–April–May (MAM), and in northern Amazonia-southern Venezuela during the warm season (June–July–August, JJA).

Simulations from the RegCM3 and HadAM3P models climatology for the present climate were presented by da Rocha et al. (2009). These studies showed that both models simulated the main characteristics of the observed climatology of precipitation and air temperature. However, the RegCM3 results show some additional information in relation to the coarse HadAM3 field such as the better delimitation of the minimum precipitation over Northeast of Brazil and of the intense precipitation in the mouth of the Amazon River. In contrast, the RegCM3 and HadAM3P underestimated the intensity of the rainfall over the South Atlantic Convergence Zone (SACZ). Over Amazon, the rainfall annual cycles from HadAM3P and RegCM3 models are similar to the observation, but both

underestimated the rainfall intensity. For the air temperature, the RegCM3 generates a systematic negative bias during the rainy season while in the HadAM3P there is a positive bias all months. In the subtropics, HadAM3P and RegCM3 presented annual cycle of precipitation similar to the observed, with dry winter and wet summer. However, as RegCM3 rainfall intensity during the rainy season is smaller than observed this implies in maximum temperature occurring in October that is in disagreement with the observations.

The Eta CCS was integrated for South America for the present, forced with the lateral boundaries of HadAM3P (Pisnichenko and Tarasova 2009b). This regional model tends to underestimate precipitation along the SACZ, Amazonia and Northeast Brazil during summer, together with higher temperatures as compared to observations and to the other two RCMs, possibly due to problems on the simulation of convective cloudiness on these regions present in the Eta CCS model (Tarasova et al. 2006).

In this paper we make a comparison of sea level pressure (SLP) and lower level circulation patterns from the three RCMs and the HadAM3P that was not discussed before. The SLP fields for the annual mean, summer and winter over the present climate, from the global and regional models exhibit the main patterns of the observed fields, are shown in Fig. 2. As compared to the NCEP reanalyses (not shown here), all the models show negative SLP anomalies along the Andes. The HadAM3P, the Eta CCS and the HadRM3P show some of the summer time circulation patterns such as the Chaco thermal low and the low pressure over tropical South America between 1 and 3 hPa underestimated. The RegCM3 shows positive SLP anomalies on the order of 1–2 hPa east of the Andes and along the Amazon region. In winter the negative SLP anomalies detected in summer along the Andes still persist, while SLP on the South Atlantic is between 2 and 3 hPa higher in the HadAM3P and Eta CCS as compared to the reanalyses. For PRECIS and RegCM3 the overestimation of SLP over the subtropical Atlantic high is lower (~ 1 hPa).

The time series of annual SLP shown on Fig. 3a–d suggests that for the present, the global and the three RCMs simulate the subtropical Pacific high somewhat underestimated as compared to the NCEP reanalyses, and with an inter-model difference reaching up to 4 hPa. For the Atlantic high the HadRM3P shows values closer to observations, while the Eta CCS shows overestimation of the order of 4–5 hPa with respect to the NCEP reanalyses. In the continental regions, while the RegCM3 and HadRM3P exhibit values closer to the NCEP reanalyses, the HadRMP and the Eta CCS show underestimations of the order of 4–6 hPa. In the Amazon region, the simulations is similar to that in the Chaco thermal low, but the scatter

among simulations and NCEP reanalyses is lower than 4 hPa.

Consistent with the SLP distribution, the near surface circulation (Fig. 4) simulated by all models depict the Pacific and Atlantic trades, the anticyclonic circulation over the subtropical Pacific and Atlantic highs, the intense northwesterly flow from the tropics into the subtropics along the Andes during summer, and the cyclonic gyre of the Chaco thermal low. Both the HadAM3P and the HadRM3P show a narrow cyclonic anomaly off the coast of Chile between 20 and 35°S. As compared to the NCEP reanalyses (not shown), the models show an intensified anticyclonic circulation over the subtropical Pacific all year long, while the Eta CCS shows the Chaco low and the Atlantic trades intensified and the RegCM3 shows weakening during summer. In winter, all models shows an intensification of the subtropical Atlantic high, and as in summer the Eta CCS/RegCM3 show an intensification/weakening of the North Atlantic trades along Equatorial South America.

The simulations from the RCMs are able to add small scale features that are absent in the GCM driving fields, and agree better with the rainfall and temperature observations, as shown by Alves and Marengo 2009, Pisnichenko and Tarasova (2009a) and da Rocha et al. (2009), and with the SLP and nears surface winds, even though with some systematic biases. This brings us to suggest that there are no significant differences in behavior and spatial arrangement of large-scale patterns of the three RCMs as compared to the HadAM3P.

3.2 Climatological fields for the A2 scenario as projected by the three RCMs

All fields shown on this section are presented as the projected changes in the future (2071–2100) relative to the present 1961–1990 as produced by the 3 RCMs.

3.2.1 Upper and lower level circulation and sea level pressure

The upper-level circulation (Fig. 5a–i) exhibits the main features that are detected during the present climate, especially the upper tropospheric Bolivian high and the Northeast trough during summer. These features are shown in the future by the RegCM3 and HadRM3, while the Eta CCS does not depict the Bolivian high, and simulates a weak Northeast trough. In winter the upper level wind shows a zonally subtropical jet in all RCMs where the RegCM3 is the only one to simulate a closed upper level anticyclone circulation in the northern South America. The difference fields (future minus present, Fig. 3j–r) exhibit a weak Bolivian high and an intensification of Northeast

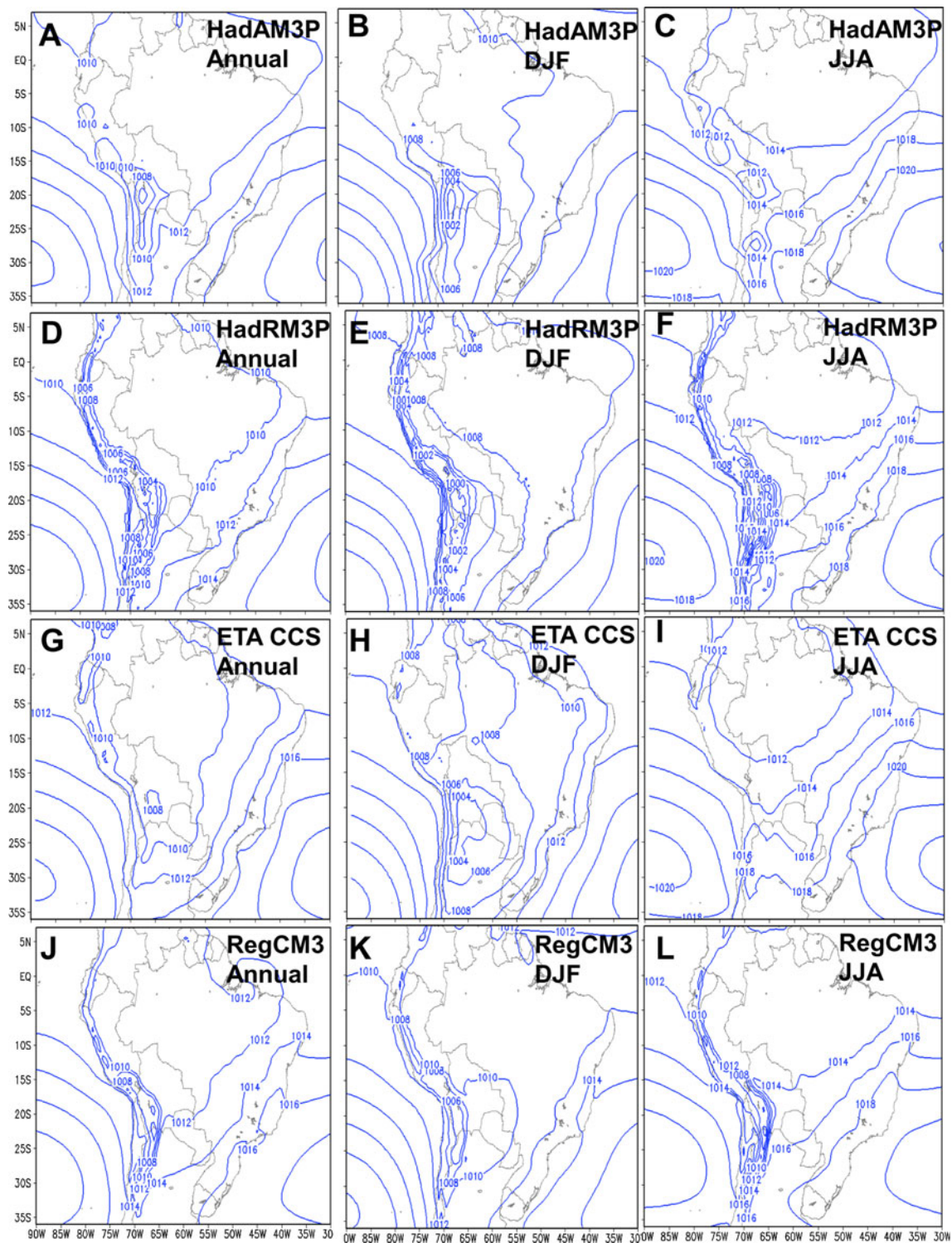
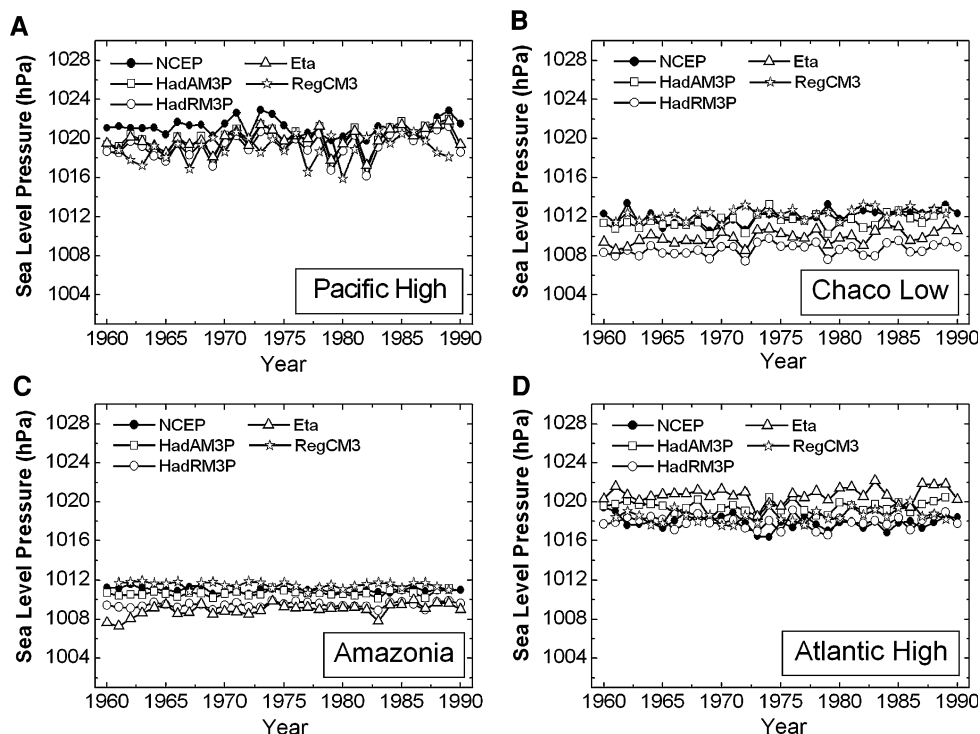


Fig. 2 Simulated present time (1961–1990) patterns of sea level pressure (SLP) from the HadAM3P (a, b, c), HadRM3P (d, e, f), Eta CCS (g, h, i) and RegCM3 (j, k, l). Maps are for the annual, summer and wintertime scales, in hPa

trough during summer and the intensification of the subtropical westerly jet during winter in the RegCM3, while the HadRM3 shows both, the Bolivian high and the Northeast trough, less intense.

The difference fields projected by the three RCMs suggest a weakening of the main upper-air circulation features of South American warm season climate, consistent with Nuñez et al. (2006) who used the MM5 forced

Fig. 3 Time series of SLP simulated for the HadAM3P, Eta CCS, RegCM3 and HadRM3P and compared with the NCEP reanalyses for 1961–1990. Figures are for these regions: **a** subtropical Pacific high, **b** Chaco thermal low, **c** Amazon region, **d** subtropical Atlantic high. Units are in hPa



with the same HadAM3P GCM. These changes have their consequences in the summer time convection and rainfall fields in summer and winter. The projected changes in upper level circulation are large, particularly during summer. Even though the three (as well as the MM5 run by Nuñez et al. 2006) models were run with the same boundary conditions, the differences could be due to the representation of the Andes and the differences in the parameterization of physical processes in the RCMs.

The projected low-level circulation and SLP fields (Figs. 6a–i, 4a–i) represent accordingly the subtropical Pacific and Atlantic highs, and the thermal low over the Chaco region during summer, as well as the trade winds seasonality in the equatorial region, northeast winds during summer and southeast winds in the winter. All models also presented the south Pacific and Atlantic subtropical highs, and the south Atlantic high seasonal zonal migration eastward/westward during summer/winter.

From the wind and SLP difference fields (Fig. 4j–r) one can see that the Eta CCS and the RegCM3 show for the future an increase in the trade winds intensity over tropical South America and a weaker flow to the east of the Andes. Both RCMs project for the future a deeper low pressure region over the Amazon region, particularly during summer. This suggests an intensification of the trade flow over the region, due to the large SLP gradient between the tropical North Atlantic and Amazonia. The RegCM3 presents a subtropical Atlantic high intensified and located to the east of its current position during winter, while the

Pacific high is weakened all year long, as shown by the cyclonic anomalies over the region.

Projections from the HadRM3P for the future indicate a deepening of the SLP over Amazonia (with less intensity than in the other 2 RCMs), suggesting that at annual time scale and in summer a reduced SLP gradient and North Atlantic, with the trades weaker than in the present and with an intensified flow east of the Andes at 50°W as compared to the Eta CCS and RegCM3 (Fig. 6m, n). A recent paper by Soares and Marengo (2009) using the HadRM3P projections for the A2 scenario suggest increased moisture transport to the east of the Andes from the tropics east, associated with an intensified and closer to the continent subtropical Atlantic high, especially in summer in the future. This would result in more intense/frequent LLJ episodes in the future. An enhanced cyclonic circulation (especially in the RegCM3) is detected in austral summer over Paraguay. This circulation pattern may lead to more frequent/intense rainfall in southern Brazil (see Sect. 3.2, and Marengo et al. 2009) associated with an intensification of the Chaco thermal low, as shown in Fig. 7 h.

The HadRM3P shows the intensification of the subtropical Pacific high in winter, and this produces enhanced southerly flow off the coast of Chile, which is detected until 30°S from our maps. Garreaud and Falvey (2008) analyzed projections from the HadRM3P A2 scenario performed for Chile, and show that the largest southerly wind increase occurs also at 37–41°S during spring and summer,

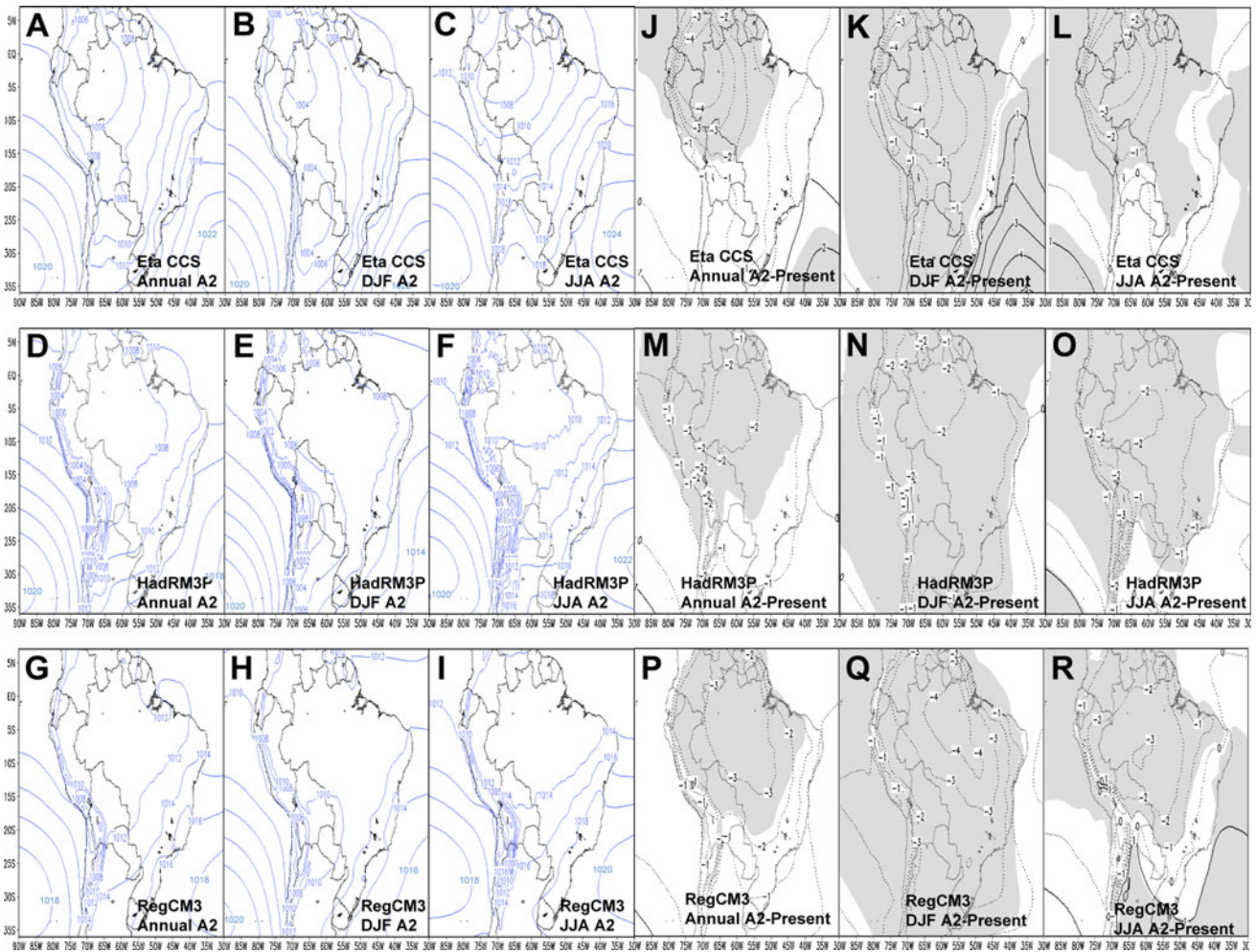


Fig. 4 Projected patterns of sea level pressure (SLP, hPa) and changes relative to the present over South America for the A2 scenario, at annual, summer (DJF) and winter (JJA) time scales. **a–i** the projections for 2071–2100 from the Eta CCS, HadRM3P and the RegCM3, and *gray-scale* represents the wind speed as shown in the

scale bar on the lower side of the panel. **j–r** the differences between the 2071–2100 projections and the 1961–1990 model climatology, and *shaded areas* represent regions where the change in wind speed reaches statistical significance at the 95% level using the Student *t* test

expanding the upwelling-favorable regime in that region. Their results are confirmed by an analysis of 15 GCMs from IPCC AR4 in the coast of Chile, suggesting the strengthening of the southerlies along the subtropical coast as a result of a marked increase in surface pressure further south, as reported by Falvey and Garreaud (2008). The subtropical Atlantic high is closer to the continent in summer.

The Eta CCS and the RegCM3 models show an intensification of the subtropical Atlantic high during summer. The projections for the A2 scenario in the second half of 2100 produced by Nuñez et al. (2008) using a different RCM (MM5) reflects changes in the atmospheric circulation during winter and spring. Changes in mean sea level pressure show a cell of increasing pressure centered

somewhere in the southern Atlantic Ocean and southern Pacific Ocean, mainly during summer and fall in the Atlantic and in spring in the Pacific. In relation to the pressure distribution in the control run, this indicates a southward extension of the summer mean Atlantic and Pacific subtropical highs.

All the aforementioned RCM experiments using the MM5 and HadRM3P from Nuñez et al. (2008) and Garreaud and Falvey (2008), as well as the three RCMs discussed on this paper show consistencies and agreements. All the simulations were conducted by the same global model. This would suggest that to some extent, the agreement among different RCMs may also be interpreted in terms of the low uncertainty in climate change signals due to the RCMs themselves.

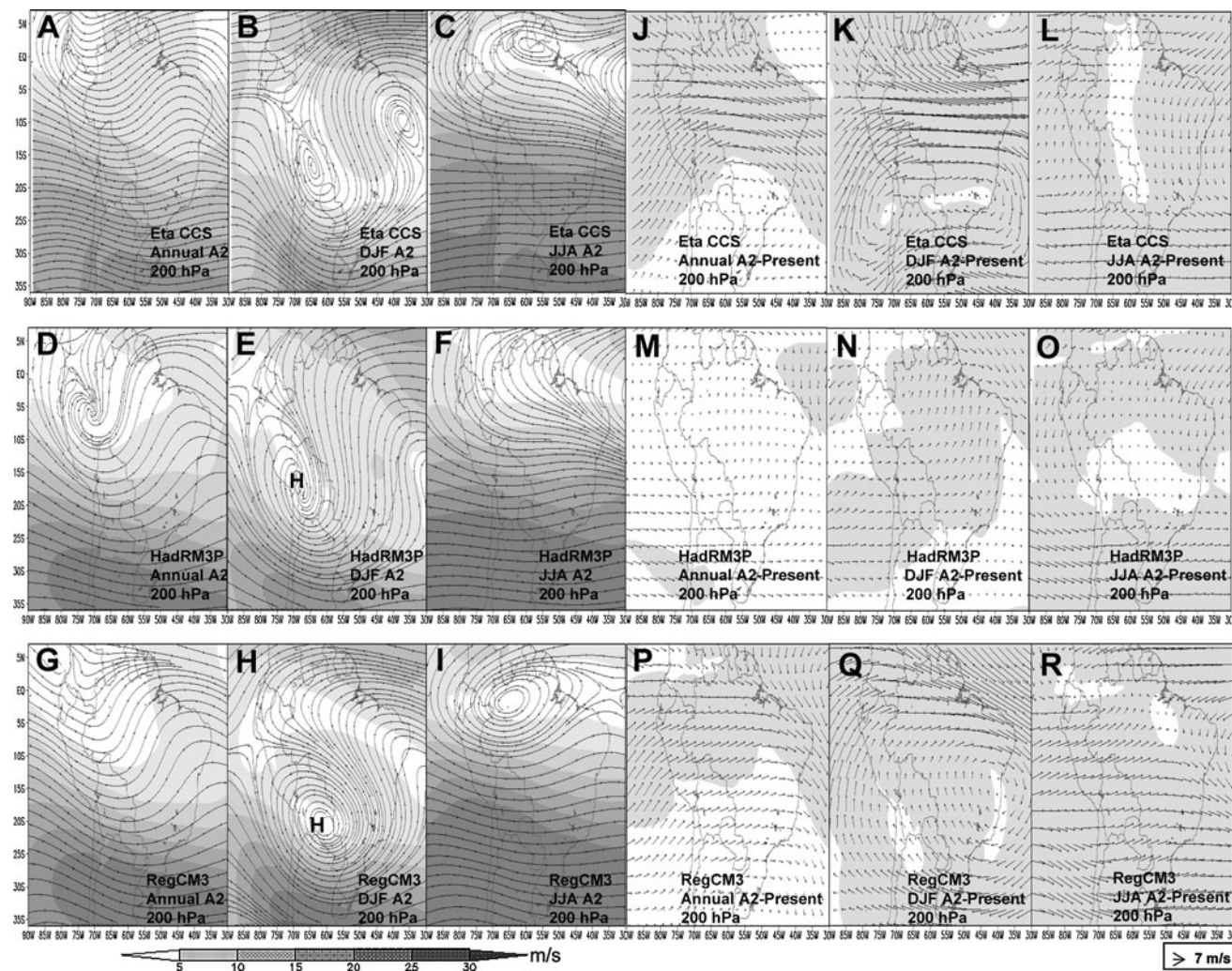


Fig. 5 Projected patterns of upper-level circulation (200 hPa) and changes relative to the present over South America for the A2 scenario, at annual, summer (DJF) and winter (JJA) time scales. **a–i** the projections for 2071–2100 from the Eta CCS, HadRM3P and the RegCM3, and *gray-scale* represents the wind speed as shown in the

scale bar on the lower side of the panel. **j–r** the differences between the 2071–2100 projections and the 1961–1990 model climatology, and *shaded areas* represent regions where the change in wind speed reaches statistical significance at the 95% level using the Student *t* test

3.2.2 Rainfall

3.2.2.1 Geographical distribution of rainfall The geographical distribution of rainfall (Fig. 8a–i) shows at the annual level that the RCMs exhibit for the future the major features of rainfall in South America; the Intertropical Convergence Zone (ITCZ) on the tropical North Atlantic and Eastern Pacific Oceans, the South Atlantic Convergence Zone and the maximum of rainfall in western Amazonia, even though with different intensity among models. During austral summer DJF, the three RCMs exhibit a similar behavior in the depiction of the South Atlantic Convergence Zone, the relative abundant rainfall in the southern Brazil, western Amazonia, and in the west Coast of Peru-Ecuador. In winter, the RCMs simulated the northward position of the ITCZ, and rainfall over Colombia

and Southern Brazil. The HadRM3P and the RegCM3 simulate the rainfall field associated with the ITCZ over tropical equatorial South America, a feature that is absent in the Eta CCS summer simulation.

For the A2 scenario, on the annual and summer change fields (Fig. 8k, n, q), the three RCMs show positive rainfall changes over the northwest coast of Peru-Ecuador and Argentina south of 25°S and negative rainfall changes over eastern Amazon and Northeast Brazil. The Eta CCS and the RegCM3 models show rainfall reductions in the future for most of tropical South America east of the Andes, and extending into southern Brazil during winter, with the largest negative departures (less than 40%) in the Amazonia and Northeast Brazil. In contrast, the HadRM3P shows a regional pattern with increased rainfall in the future (above 20%) over the western Amazon, which extends all the way

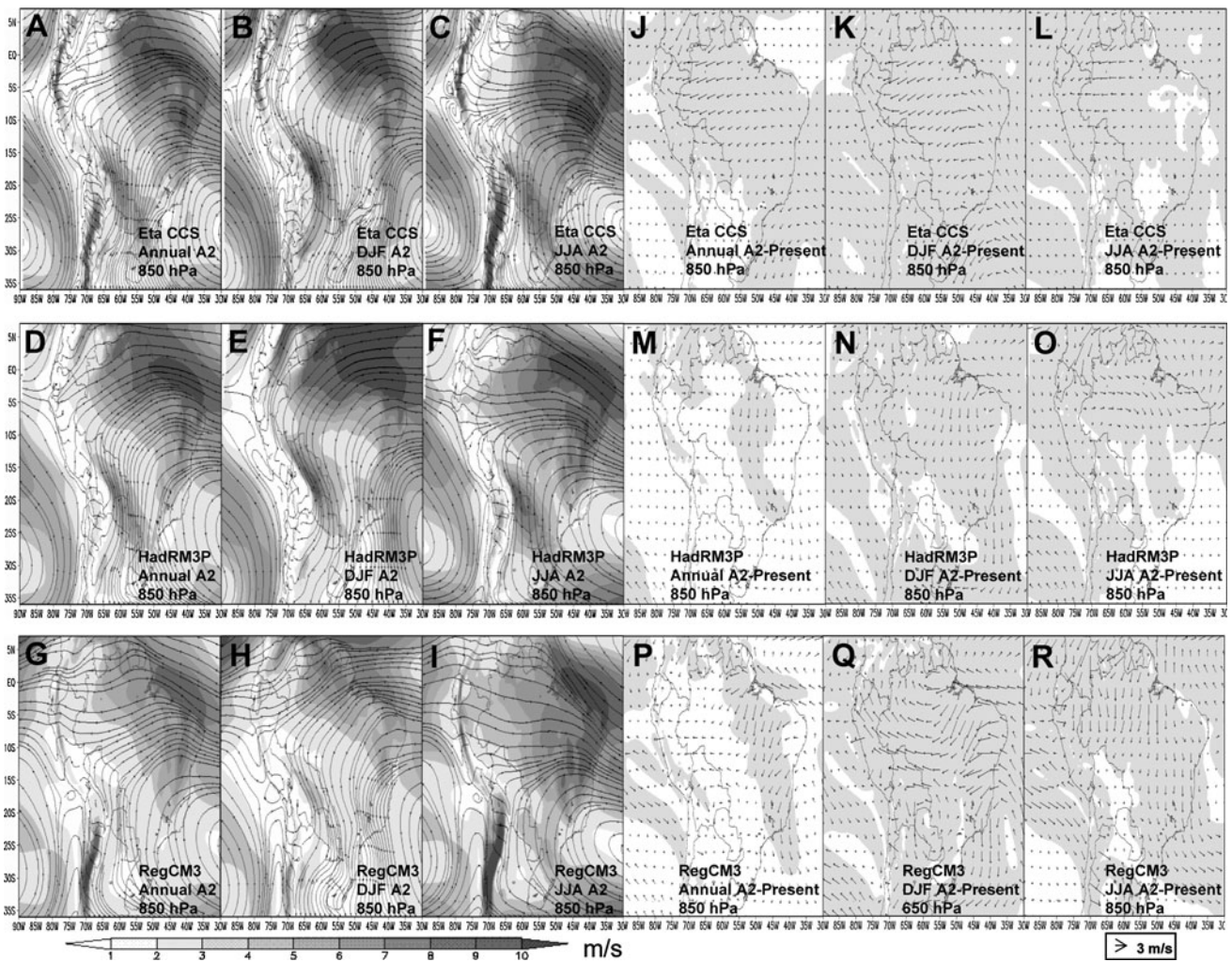


Fig. 6 Projected patterns of lower-level circulation (850 hPa) and changes relative to the present over South America for the A2 scenario, at annual, summer (DJF) and winter (JJA) time scales. **a–i** the projections for 2071–2100 from the Eta CCS, HadRM3P and the RegCM3, and *gray-scale* represents the wind speed as shown in the

scale bar on the lower side of the panel. **j–r** the differences between the 2071–2100 projections and the 1961–1990 model climatology, and *shaded areas* represent regions where the change in wind speed reaches statistical significance at the 95% level using the Student *t* test

to southern Brazil and into the South Atlantic. The projected changes in precipitation in the three regional models (such as the drying over east-central Amazonia and northeast Brazil and the wetter conditions over south-eastern South America and the Northwest coast of Peru and Ecuador) could be a partial consequence of an El-Niño like response in the three models. This is also projected by the IPCC AR4 models regarding rainfall increases in the Northwest coast of Peru and Ecuador and the wetter conditions over south-eastern South America (Christensen et al. 2007a). Projections of increase of intense rainfall in that region by Tebaldi et al. (2007) derived from the IPCC AR4 models, and by Marengo et al. (2009) from the HadRM3P simulation suggest that this increase in rainfall in the future would be in the form of more intense and/or frequent rainfall extremes.

The projected changes of rainfall from the IPCC AR4 (Christensen et al. 2007a) show increase of rainfall in Ecuador and northern Peru as well as in southeastern South America, while rainfall reductions are projected for eastern Brazil and the southern coast of Chile and on the northern tip of the continent. From the rainfall projections derived from the three RCMS, there is qualitative consistency among the simulations with the IPCC AR4 regional means, particularly and decreasing rainfall increases in southeastern South America and on the northwest coast of Peru and Ecuador. In winter (Fig. 8l, o, r), the RCMS exhibit rainfall reductions in the future in large parts of Amazonia, central South America, and Northeast Brazil, reaching up to 60–80% reduction in the Eta CCS and 20–40% in the other two models.

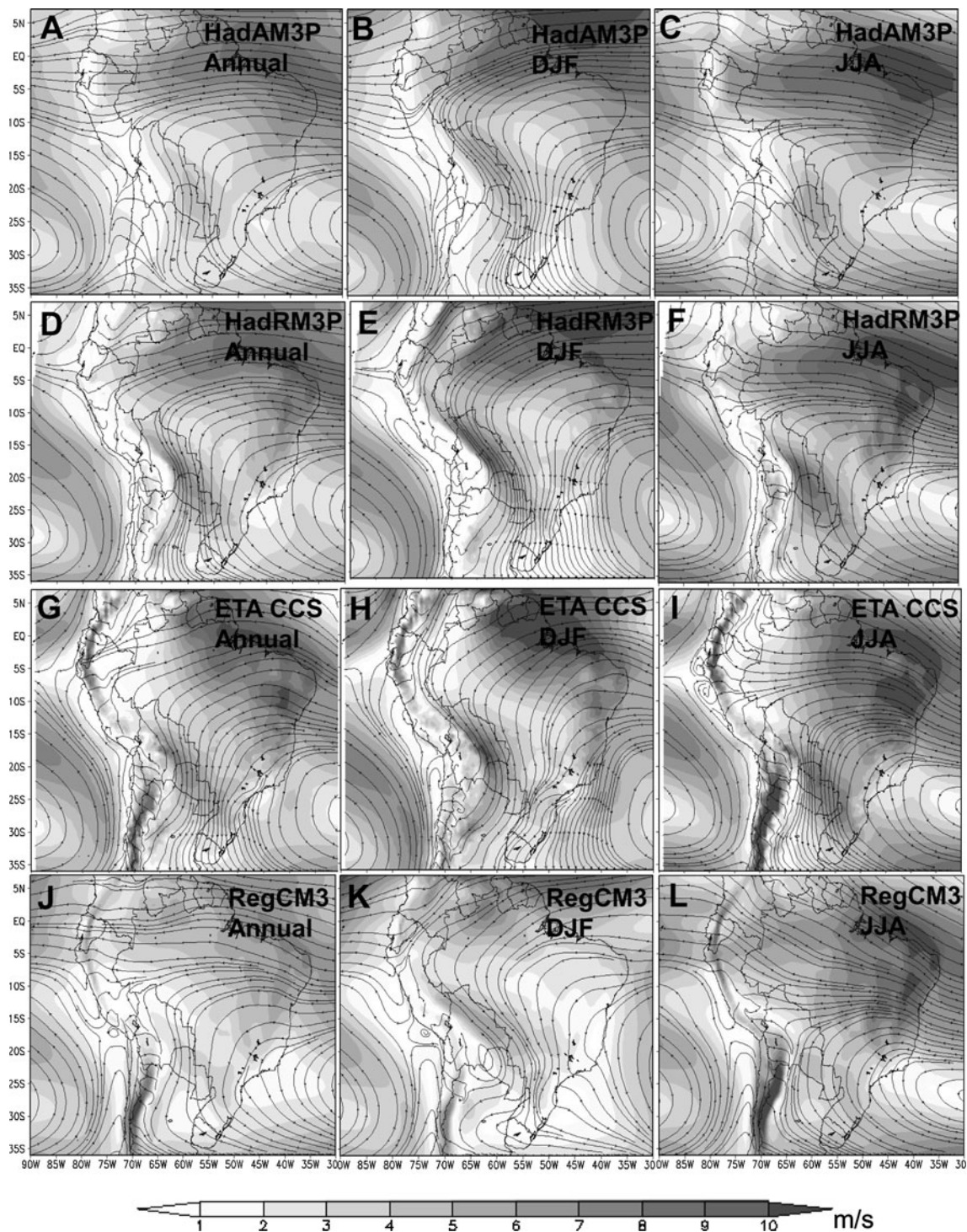


Fig. 7 Simulated present time (1961–1990) patterns of sea level pressure (SLP) from the HadAM3P (a, b, c), HadRM3P (d, e, f), Eta CCS (g, h, i) and RegCM3 (j, k, l). Maps are for the annual, summer

and wintertime scales, in 850 hPa winds. Gray-scale represents the wind speed as shown in the scale bar on the lower side of the panel. Units are in m/s

The projections by Nuñez et al. (2008) show an increase of rainfall in northern Argentina especially in summer and fall and a general decrease in precipitation in winter and spring. In fall, their simulations agree on a general decrease in precipitation in southern Brazil. The MM5 projections and those

from the three regional models show rainfall increases in the future in Argentina south of 25°S and in all projections the changes in rainfall on that region are consistent with changes in SLP and low level circulation in the future, and with the rainfall increases from the IPCC AR4 models.

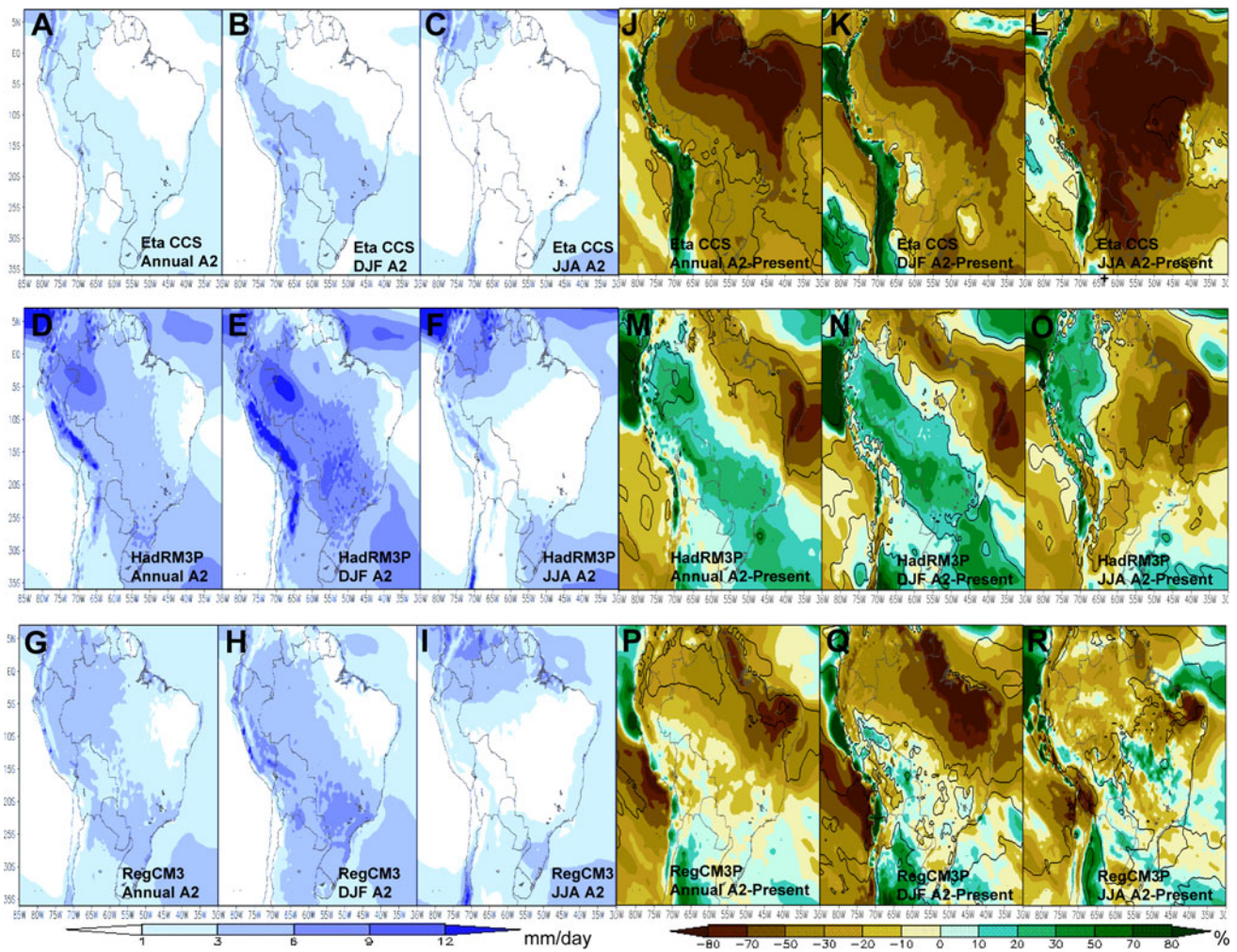


Fig. 8 Projected patterns of rainfall (mm/day) and rainfall change (%) over South America for the A2 scenario, at annual, summer (DJF) and winter (JJA) time scales. **a–i** the projections for 2071–2100 from the Eta CCS, HadRM3P and the RegCM3. **j–r** the differences

between the 2071–2100 projections and the 1961–1990 model climatology (in %). Shaded areas represent regions where statistical significance at the 95% level is reached

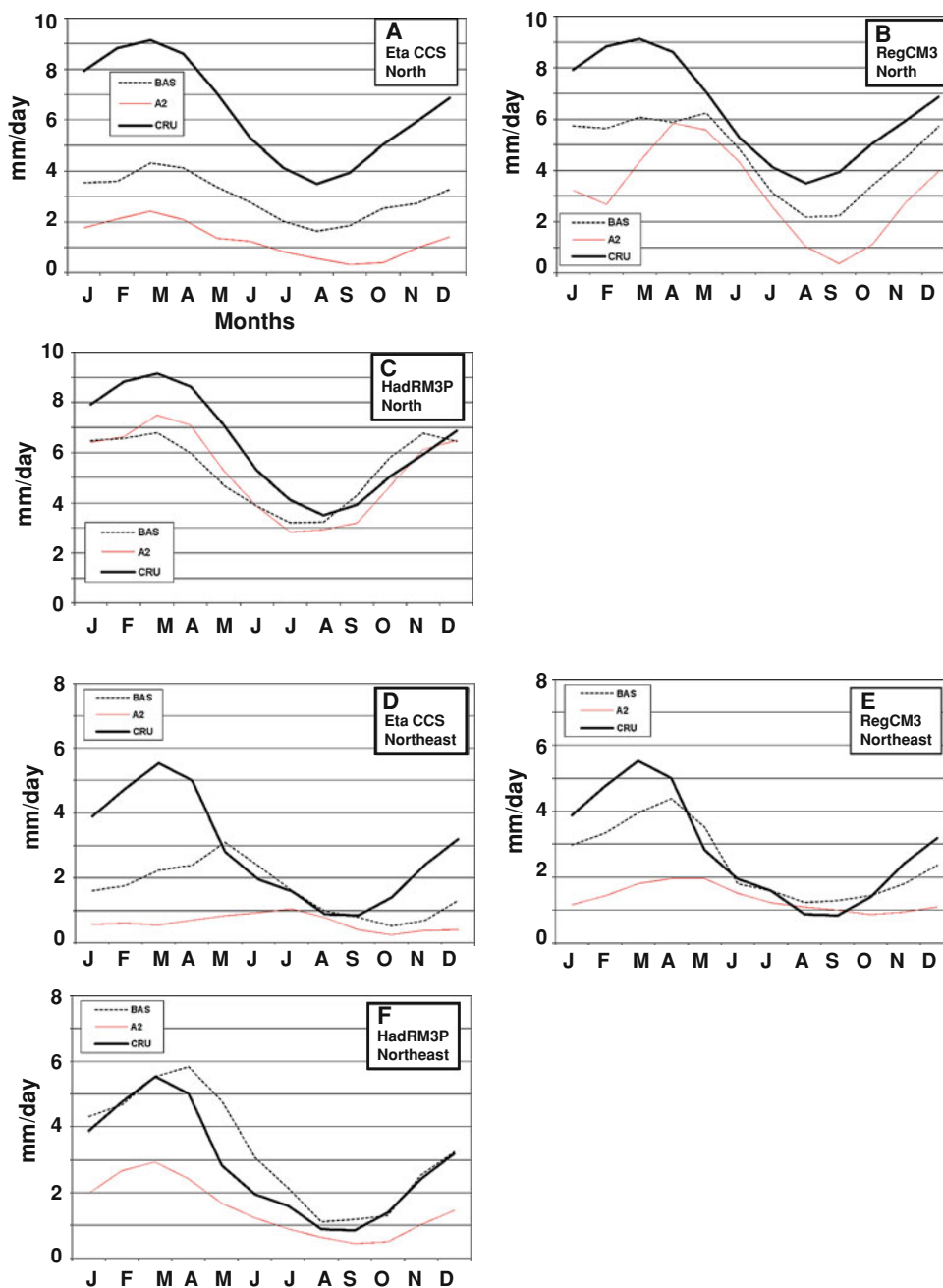
In sum, all regional models show reductions and increases in precipitation in the future for the A2 scenario depending on the region and the reductions are lower in the HadRM3P in some regions. Rainfall decrease is detected by all models over the eastern Amazon and Northeast Brazil, while for West Central and Southern Brazil the HAdRM3P model shows rainfall increases in the future, while the other models show reductions. Perhaps the largest uncertainties are in the West Central region; with the largest inter model differences.

The reductions of rainfall in the future from the HadRM3P in North and Northeast Brazil may be explained in terms of changes in the frequency of dry days, as shown in the analyses of future trends in extremes using the HadRM3P by Marengo et al. (2009). In those regions, the risk of drought is likely to increase. In southern Brazil, the increase in mean precipitation is also associated with the

increase in the wet day frequency and reductions in consecutive dry days

3.2.2.2 Annual cycle of rainfall The annual cycle of rainfall in some regions of Brazil is depicted in Fig. 9. As for CRU, all modeled precipitation values were calculated taking into account only land grid points. Precipitation from each one of the regional models was interpolated to the CRU grid and then averaged for each of the regions. The timing of the rainy and dry seasons from the three models for the present time (baseline in Fig. 9) in all regions, agrees reasonably well with observations, though the intensity is in general, underestimated. In Northern Brazil (Fig. 9a–c), although the simulated present time climatology shows a good depiction of the observed annual cycle (from CRU), all models underestimated the total precipitation, especially during the peak of the rain season.

Fig. 9 Seasonal cycles of precipitation (mm/day): observed (*black line*), simulated for the present (control run-*black thin broken line*), and projections for the future [A2 (*red thin line*) for 2071–2100] for each one of the regions shown in Fig. 1. *Panel* represent the seasonal cycle from the Eta CCS, HadRM3P and RegCM3. With the exception of Northern Brazil (Amazon region) from the HadRM3P, the changes in the amplitude of the annual cycle reach statistical significance at the 95% using the Student *t* test



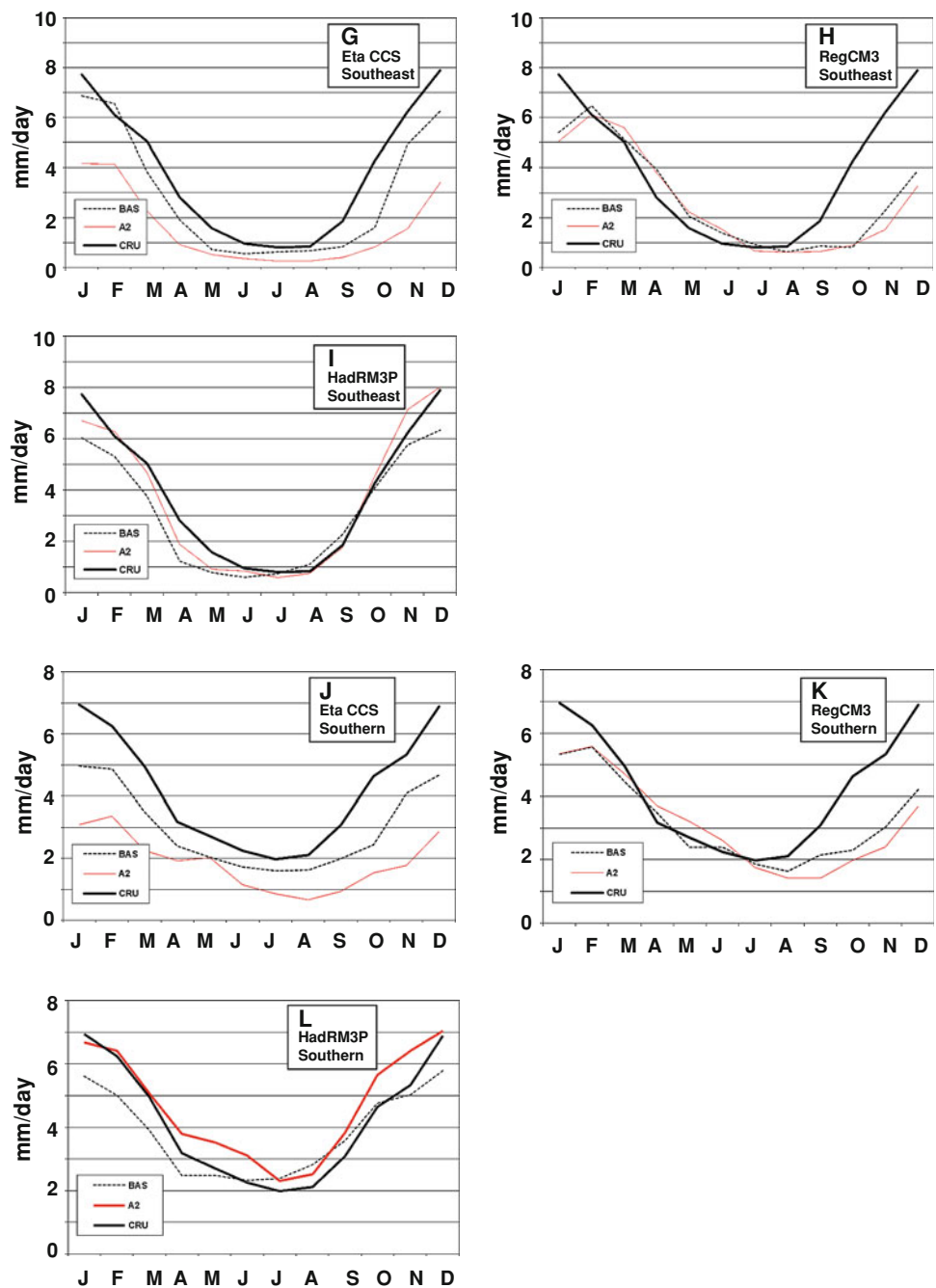
For instance, for Northern Brazil the Eta CCS shows between 4 and 5 mm/day less rainfall than the observed values during the peak season (January–April), while the other models underestimation varies between 2 and 3 mm/day. In the Eta CCS the underestimation is shown from January to November. On the HadRM3P this occurs during the first half of the year.

For the future, and using the baseline as reference, it is detected that projections for Northern Brazil show large reductions of rainfall in 2071–2100, as compared to the present. In the case of the HadRM3P the model tends to show slightly less rainfall than in the present during

February to June by less than 1 mm/day. In the RegCM3 the largest reduction is on the transition from the dry to wet seasons, suggesting a late onset of the rainy season. The RegCM3 projection extends also this reduction throughout the wet season in the A2 scenario for the late of the century.

Over Northeast Brazil (Fig. 9d–f), in present climate the three RCMs depict the annual cycle of rainfall in the region, even though the Eta CCS seems to miss the annual cycle of rainfall. Negative biases during the austral summer are found in the RegCM3. In the HadRM3P the annual cycle is well depicted, with some overestimation between

Fig. 9 continued

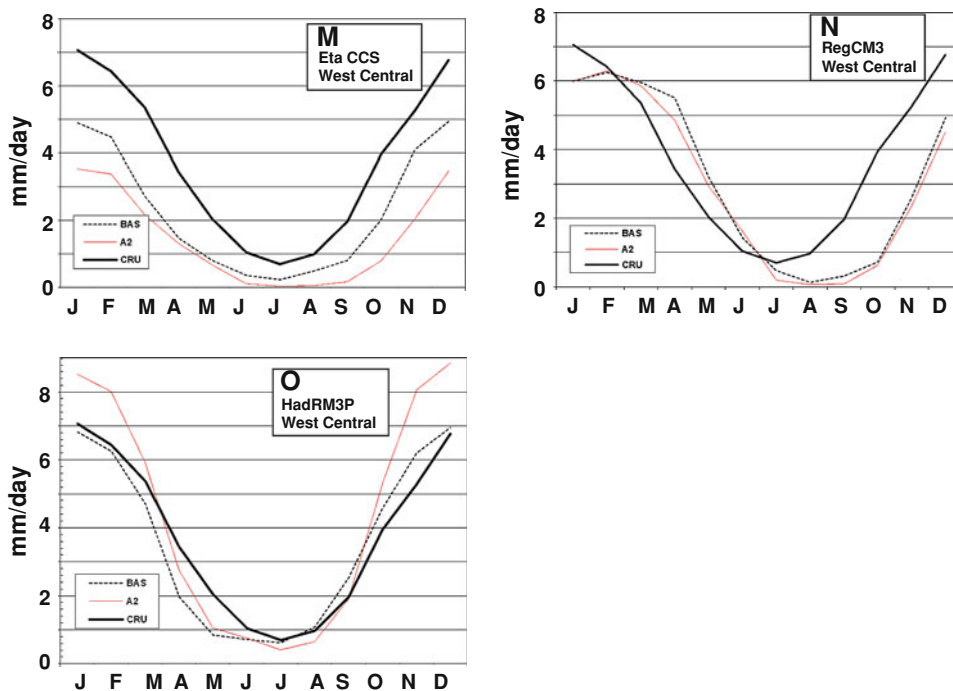


April and September. For the future, the three models show underestimation. The three RCMs show a pronounced reduction along the year for the A2 scenario, with rainfall reductions of the order of 2–3 mm/day in summer. Similar patterns of change have been detected in the mean rainfall for the end of the twenty-first century in Northeast Brazil, from the mean of several IPCC AR4 models (Meehl et al. 2007).

Over Southeast Brazil the simulated climatology captures the observed annual cycle, but with systematic underestimation of the Eta CCS and underestimation all

over the year in the RegCM3 (Fig. 9g–i). For the future, the projections are not revealing, since the Eta CCS shows less rainfall in the future all year long, while the RegCM3 shows reductions in the spring and summer as compared to the present. In the HadRM3P some seasons show more rainfall in the future while the rest of the year shows reductions. The simulations for the Southern Brazil (Fig. 9j–l) indicated a good representation of the annual precipitation cycle for all three models. The Eta CCS results still underestimate the precipitation and projects less rain in the future. On the other hand, the HadRM3P suggests more rain for the A2

Fig. 9 continued



scenario while the RegCM3 this pattern only occurs between March and June, indicating a decrease for the other months. In general the simulated annual cycle for Southern Brazil is similar to West Central Brazil. This result suggests that both regions can have the same climatic features for the greenhouse gases scenarios analyzed. Southern Brazil is one of the regions where almost all global IPCC AR4 models show rainfall increase in a future warm climate by the end of the twenty-first century.

In West Central Brazil (Fig. 9m–o), the simulated annual cycle by the HadRM3P is quite similar to the CRU in amplitude and phase. Although the Eta CCS shows a similar annual cycle, there is a systematic underestimation. On the other hand, RegCM3 simulates better than Eta CCS the amplitude of the rainfall but shows a shifting of the annual cycle of about 2 months. By the end of the twenty-first century, while the Eta CCS model shows less rainfall in the future, the HadRM3 shows more rainfall, especially in summer and spring. It is detected that in some of the above indicated regions, rainfall reduction for the future is smaller than the actual model bias.

3.2.3 Temperature

3.2.3.1 Geographical distribution On the geographical distribution, all of South America is very likely to warm during this century (Fig. 10a–r). The analyses by Christensen et al. (2007a) for tropical South America from the IPCC AR4 GCMs shows that the annual mean warming under the A1B scenario for the end of the century varies in

the tropical region between 1.8 and 5.1°C, with half of the models within 2.6–3.7°C, and in the subtropical South America varies from 1.7 to 3.9°C, with half of the models between 2.3 and 3.1°C.

The projected warming from the three RCMs is generally largest in the most continental regions, such as inner Amazonia. The temperature field for the A2 scenario from the HadRM3P and RegCM3 is quite similar. The Eta CCS model shows the largest temperature in the tropical region above 30°C. In the HadRM3 and the RegCM3 the values are lower those from the Eta CCS model (reaching between 28 and 30°C), but these two models show the largest temperatures in eastern Amazonia between 5°N and 15°S. In winter, the temperature fields in Argentina south of 30°S is colder in the Eta CCS model, as compared to the other models, and the projected warm temperatures in eastern Amazonia by the HadRM3P and RegCM3 are still large. Particularly, the HadRM3P projects warmest temperatures in winter than in summer for this region. Christensen et al. (2007a) suggests that the warming in central Amazonia tends to be larger in JJA than in DJF in the global IPCC AR4 models, while the reverse is true over the Altiplano where, the amplitude of the seasonal cycle of temperature is projected to increase. Similar results were found by Boulanger et al. (2006), who studied the regional thermal response over South America by applying a statistical method based on neural networks and Bayesian statistics.

The three models show temperature increases larger than 3°C in the entire tropical and subtropical South America. The Eta CCS model shows temperature increases

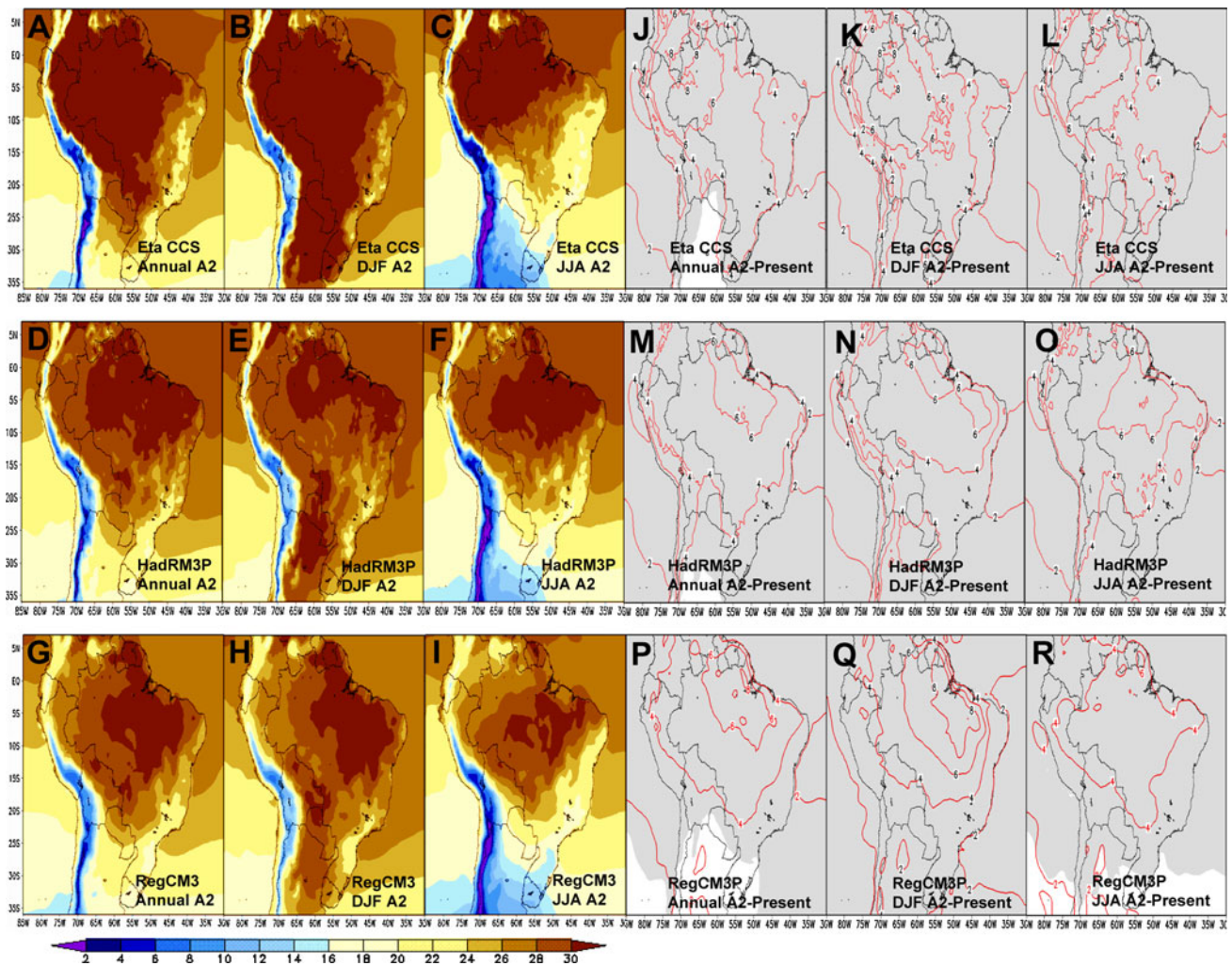


Fig. 10 Projected patterns of air temperature and temperature changes (°C) over South America for the A2 scenario, at annual, summer (DJF) and winter (JJA) time scales. a–i the projections for 2071–2100 from the Eta CCS, HadRM3P and the RegCM3. j–r the

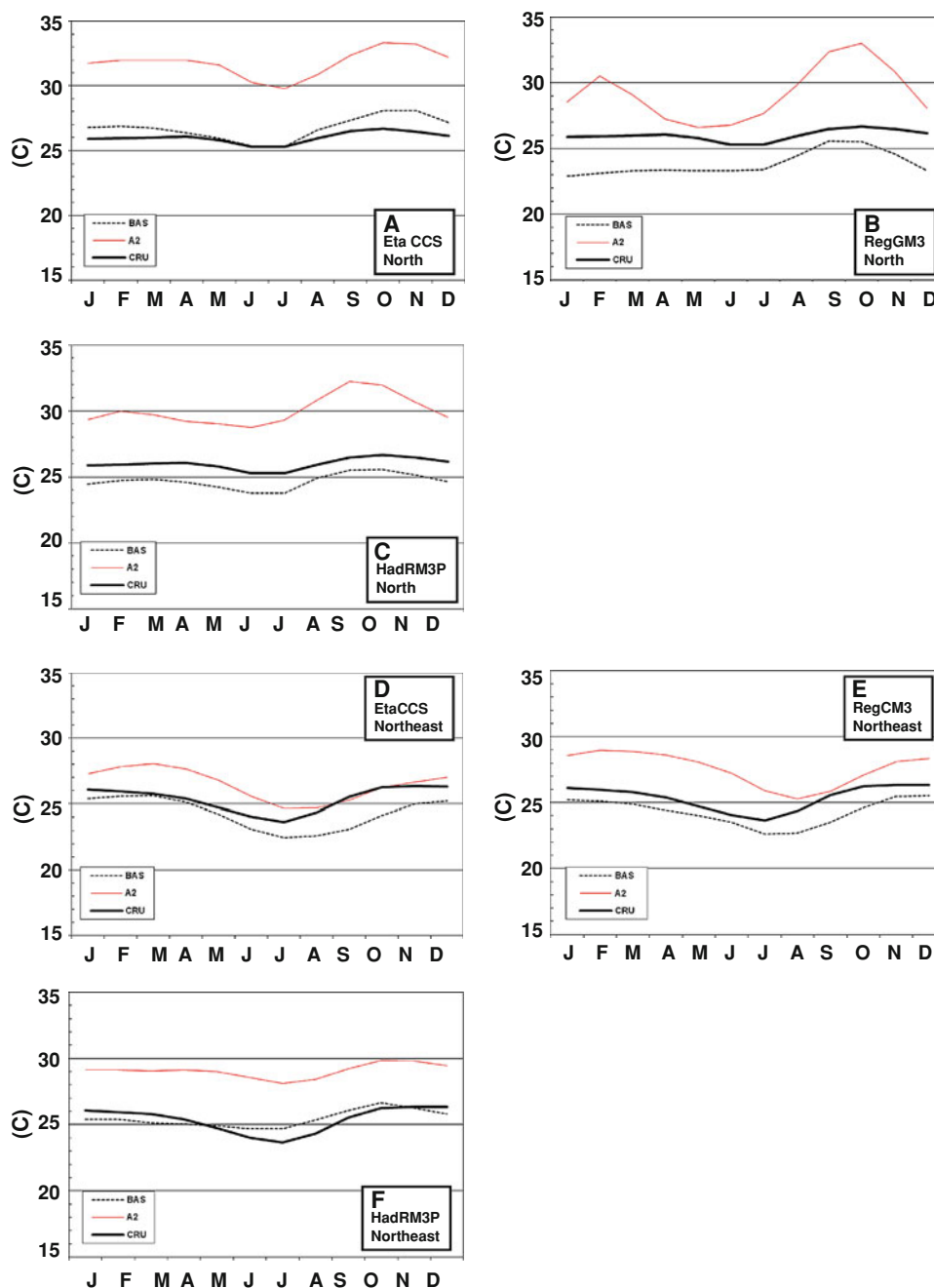
differences between the 2071–2100 projections and the 1961–1990 model climatology. Shaded areas represent regions where statistical significance at the 95% level is reached

of the order of 6°C in western Amazonia at annual level, reaching 8°C in summer, and above 4°C warmer in southeastern South America in summer, and 2–5°C warmer in winter. In the HadRM3P and the RegCM3 projections the warming in the tropical region is larger than 6°C, reaching 9°C in eastern Amazonia (RegCM3 in summer), while for the rest of Brazil the warming ranges between 3 and 6°C in summer and winter. The difference with the Eta CCS simulation is that in this model the warming is more on the western side of Amazonia, while in the HadRM3P and RegCM3 the intense warming concentrated in eastern Amazonia during summer. In wintertime the pattern is similar to those during summer, but during summer the larger changes extend for a large area in the continent, especially to the north of the Argentina. For the A2 scenario, the warming in southern Brazil, Paraguay, Bolivia and northeastern Argentina is particularly large in summer.

In general the three models project warming in the A2 scenario stronger in the tropical region, especially in the 5°N–15°S band, both in summer and winter, being larger in summer for the Eta CCS and the RegCM3 of the order of 6–8°C, and in winter for the HadRM3P (warming reaching 6°C) over eastern Amazonia during winter. For subtropical South America South of 20°S, projected warming from the 3 RCMs is consistent with Nuñez et al. (2008) who found the warming larger in winter (3–5°C) than in summer (3–4°C) in the MM5 A2 future climate scenarios. In our paper, the warming in summer varies between 2 and 4°C and in winter between 3 and 5°C in the same region from the three RCMs.

3.2.3.2 Annual cycle of temperature The temperature annual cycle for the present (models and CRU for 1961–1990) and for the A2 scenario is shown in Fig. 11 for the

Fig. 11 Seasonal cycles of air temperature (°C): observed (black thick line), simulated for the present (control run-black thin broken line), and projections for the future [A2 (red thin line) for 2071–2100] for each one of the regions shown in Fig. 1. Panels represent the seasonal cycle from the Eta CCS, HadRM3P and RegCM3. All changes in the amplitude of the annual cycle reach statistical significance at the 95% using the Student *t* test

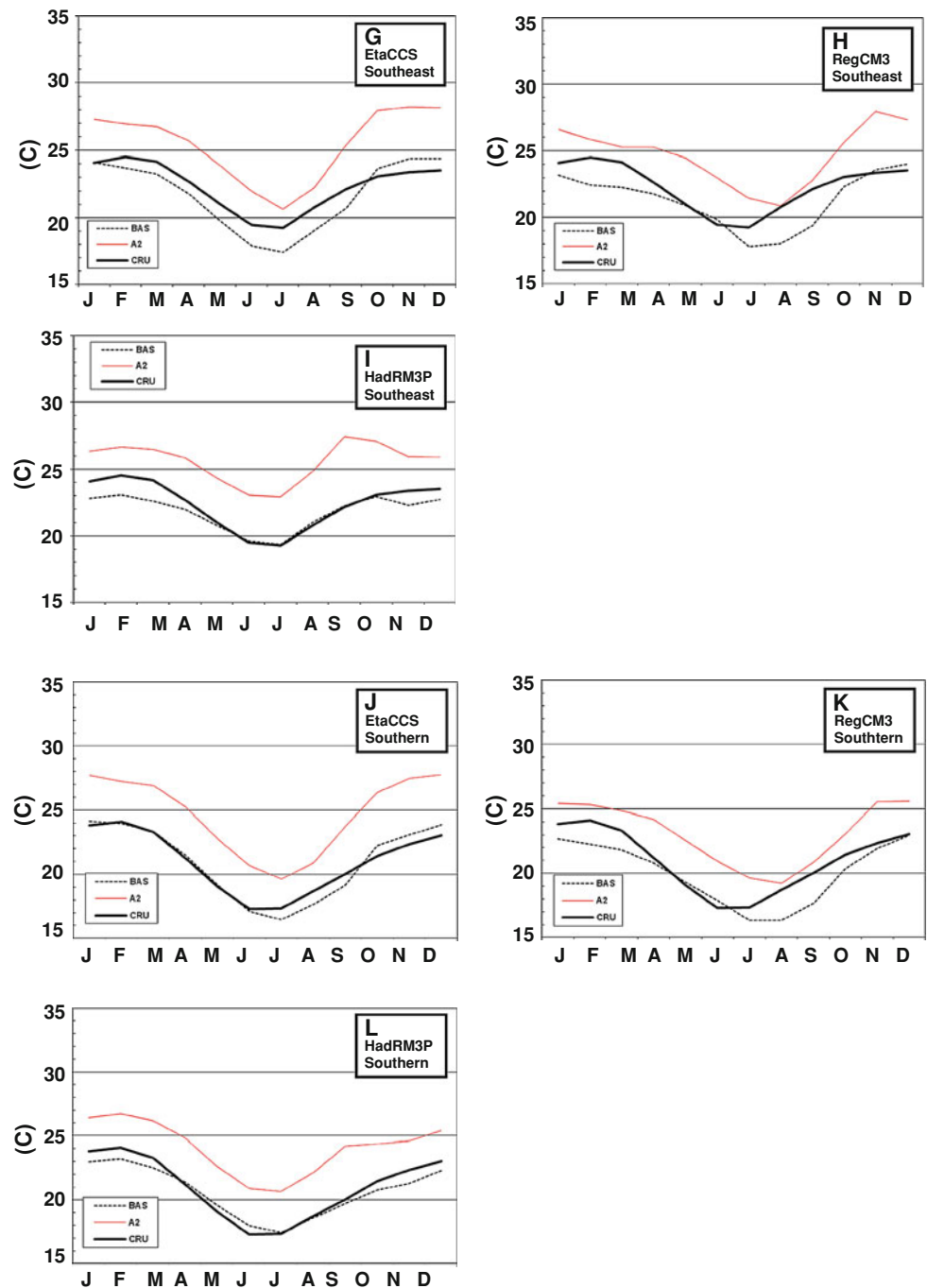


five regions depicted in Fig. 1. For northern Brazil (Fig. 7a, b, c), the three regional models simulate the annual cycle, with the maximum and minimum at the correct season, even though the Eta CCS shows overestimation, and the RegCM3 and HadRM3P exhibit underestimation, reaching 1°C and 1–2°C, respectively. Perhaps the exception is on Fig. 11b, where there is a disagreement between observations and simulations from the RegCM3. In the future, in all models, warming is detected all year long for the A2 high emission scenario, with a warming that can reach about 5°C, with largest changes (almost 8°C in some

months), as compared to the simulated baseline. Over Northeast Brazil (Fig. 11d, e, f) the simulated present time annual cycle is underestimated by the Eta CCS and the RegCM3, while the HadRM3P presents less deviation. For the future, the A2 scenario shows warming larger in autumn in the Eta CCS (by about 2–3°C) and the RegCM3 (by about 4°C), while the HadRM3P shows intense warming in early summer, by about 4°C.

In subtropical regions, as in Southeast and West Central Brazil (Fig. 11g, h, i, m, n, o) the models simulated in some degree the observed annual cycle of temperature. The three

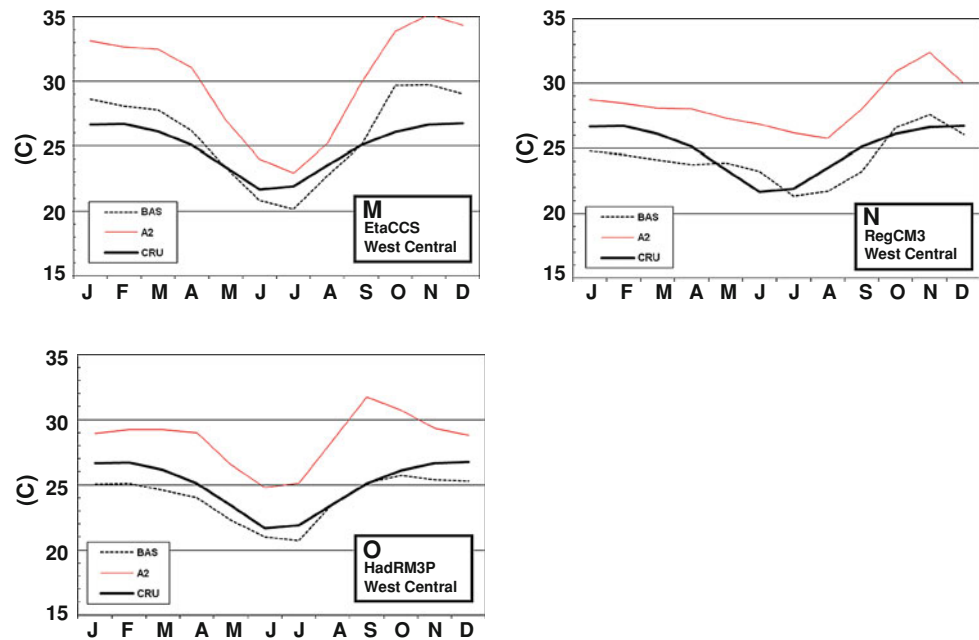
Fig. 11 continued



models show some degree of underestimation in Southeast Brazil, with the Eta CCS and RegCM3 slightly warmer during early austral summer. In West Central Brazil the three RCMs show different behavior, and in the case of the RegCM3 and Eta CCS they show a maximum between September and October that is not depicted in the observations. All models show warming all year long in the future, particularly during autumn and spring in the RCMs. In winter, while the Eta CCS shows temperatures of 21°C, the other RCMs are warmer (about 23°C). In southern

Brazil (Fig. 11j–l), the simulated annual cycle for the present are similar to the observed, and the warming is projected all year long by all models, by about 3–4°C. As for the southeast region, the largest projected warming is from the Eta CCs and the HadRM3P. Projections from the three RCMs for the West Central region (Fig. 11m–o) show consistency simulations and observations regarding the annual cycle, even though the model shows cold or warm biases that varies among the seasons of the year. The projections show largest warming during spring and

Fig. 11 continued



summer, by about 5°C in the Eta CCS, and about 4°C in the RegCM3 and HadRM3P. This is in agreement with the projections by Nuñez et al. (2008), which show a warming in Southeastern South America, mainly in spring in the A2 scenario, reaching 6°C.

Therefore, all regional models show increase in mean temperatures in the future for the A2 scenario, and in the Amazon region the location of the warmest region varies among models, being either eastern or western Amazonia. In any case, the degree of warming for 2071–2100 as compared to 1961–1990 is consistent with that projected by the IPCC AR4 AOGCMs as shown by Meehl et al. (2007) and for the warming projected by the MM5 in South America South of 20°S (Nuñez et al. 2008).

These increases in air temperature for the future are concomitant with changes in extreme short-term temperature extremes, mainly increases in the frequency of warm nights and warm days, and also reductions in the frequency of cold nights and cold days. As shown in analyses of future trends in extremes using the HadRM3P by Marengo et al. (2009), the positive trend in the mean is also accompanied by increases in the frequency and intensity of warm nights and days, and negative trends in cold night, consistent with a warming scenario.

The lowest uncertainties are in the region South of 20°S, where simulations and observations show similar tendencies for the present climate, and the future for the above mentioned seems to show a continuation of the observed warming trends, as shown on the projections of mean and extreme temperature. In tropical regions, as in Amazonia and mainly in West Central Brazil, the lack of observations

does not allow for a careful validation of temperature trends.

4 Summary of future climate change projections for South America by the end of the twenty-first century

In general, the RCMs show interesting patterns of change in circulation, rainfall and temperature in a warm future for the A2 scenario by the end of the twenty-first century. The three models project reductions of rainfall in regions such as eastern Amazonia and Northeast Brazil, and increased rainfall in the Northwest Coast of Peru-Ecuador and Argentina south of 25°S. In some regions the annual cycle has not changed but the intensity of rainfall peak and the length of the dry season may change in the A2 scenario, together with a consistent warming all year long, and in some regions winter warms more than summer.

The evaluation of precipitation from the HadRM3P shows increase of rainfall in the future, perhaps in the form of more extreme rainfall events, suggesting that this model shows ability in projecting high-frequency precipitation statistics, in terms of precipitation frequency and extreme events. For the HadRM3P, projections of changes in extremes (Marengo et al. 2009) together with the regional changes in mean rainfall projected by the HadRM3P, may suggest that the projected increase in precipitation over southern Brazil-Northern Argentina may be due to an increase on frequency of extremes. This is also detected in the future projections using the

Consensus-Rainfall reduction in 2071-2100 as compared to 1961-90

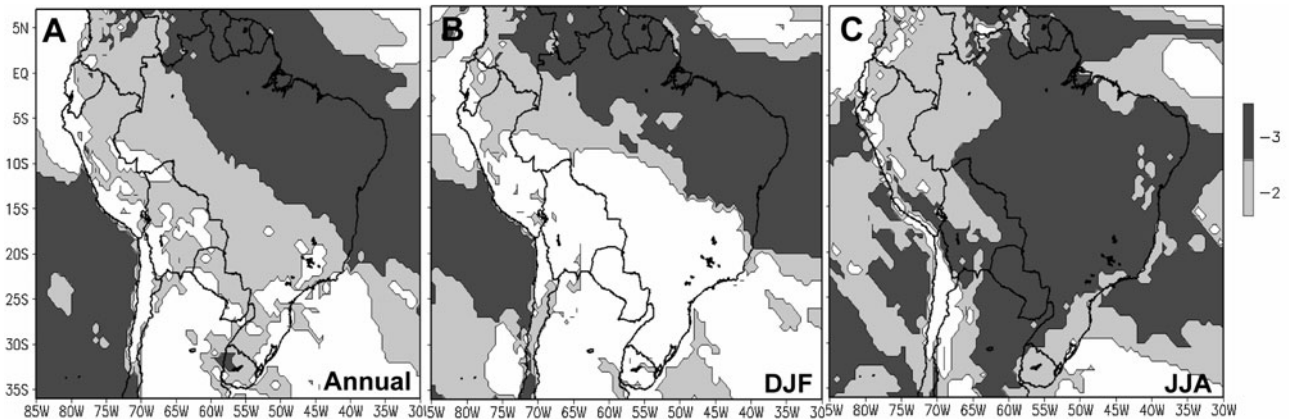


Fig. 12 Consensus maps of rainfall changes for the future relative to the present for the A2 emission scenario. Models considered are the Eta CCS, RegCM3 and HadRM3P, for annual, summer and winter

timescales: **a** for rainfall increase and **b** for rainfall decrease. Shaded scale indicating the number of models where the change is of the same sign is shown on the right side

MM5 RCM by Nuñez et al. (2008) and the RCM projections for the regions as shown in Tebaldi et al. (2007). This type of information provides much added value to the use of regional models on climate change projections.

As a summary for projected rainfall changes, Fig. 12a, b provides a synthesis of the RCMs rainfall projections, displaying at annual, summer and winter time seasons the number of models that project changes of a given sign. At annual and summer time scales the three models shows a reduction of precipitation a vast section of tropical Northeastern South America, from Venezuela all the way including central and eastern Amazonia until Northeast Brazil. In winter, the three models project rainfall reduction in most of South America east of the Andes. Increased future precipitation is detected in the Northern coast of Peru and Ecuador and in the southern Andes over Argentina. Moderate levels of agreement (2 out of 3 RCMs) are associated with the overall positive changes in Southeastern South America along the ZACS and the northwestern

coast of South America, while rainfall reductions are projected over Northwest Amazonia.

In an attempt to analyze uncertainties of these climate change projections shown in Fig. 12a, b; Table 1 was prepared in order to analyze the consistency of the signal of change in temperature and precipitation from the three RCMs in the five regions of Brazil under analyses. We assign a scale (from 0 to 3) based on the match between changes among the models (regardless the magnitude of the change), and scales between 2 and 3 show less uncertainties as compared to 0–1.

The table suggests that at continental scale, the regions of Brazil that show more confidence in the projected rainfall changes are North (including Amazonia) and Northeast Brazil, with significant reductions of rainfall at annual, summer and wintertime, as well as temperature increases for the A2 scenario, in the time slice 2071–2100 relative to the present. On the other regions, the sign of rainfall changes are with less confidence in Southern Brazil, as well as in Southeast and West Central Brazil, where

Table 1 Qualitative indicators of changes in rainfall and temperature in the five regions of Brazil (Fig. 1), for the future (2071–2100) relative to the present (1961–1990), derived from the three RCMs for the A2 emission scenario

Region	Annual		Summer		Winter	
	P	T	P	T	P	T
North (including Amazonia)	–2	+3	–2	+3	–2	+3
Northeast	–3	+3	–2	+3	–2	+3
Southeast	–1	+3	–1	+3	–1	+3
West Central (including Pantanal)	–1	+3	–1	+3	–1	+3
Southern	–1	+3	–1	+3	–1	+3

Numbers indicate degree of agreement along the RCMs: 3 = the three RCMs agree in the direction of the changes that are statistically significant (high confidence), 2 = two RCMs show similar direction of the change that are statistically significant, and the third one does not agree in the sign of the change, or show a small change (moderate); 1 = One model shows change that is statistically significant, and the other RCMs show small changes or no changes, or in opposite directions (lower confidence). Signs + or – indicate increase or decrease

P precipitation, *T* temperature

the signals are conflicting among models. In relation to temperatures, all models show high confidence in temperature increases. These projections, even though may experience some bias related to the behavior of the HadAM3P GCM, show consistency with the drier and warmer climates for North and Northeast Brazil produced by the GCM and the three RCMs.

Temperature projections show warming more concentrated in the tropical region, being more concentrated in central and eastern Amazonia in the HadRM3P and RegCM3 models, while it is widely extended along the tropical region and stronger in western Amazonia in the Eta CCS. Warming is observed all year long, with some tendencies for warmer winters than summers in the future. It is possible that the warming detected over the South American Monsoon region, more intense during summer, may be due to drier soils and less rain over subtropical latitudes, which in turn induces higher surface air temperatures. Warming over the central plains of subtropical South America (of about 3°C) is a common feature obtained in the three regional models.

5 Conclusions

In this paper we show the results from regional simulations of climate change under the A2 IPCC high emission scenario for the period 2071–2100 over South America, part of the CREAS regional program. We analyzed the projected climatic changes with respect to the reference period 1961–1990. The simulations were performed using three Regional climate models (Eta CCS, RegCM3 and HadRM3P) nested

within the Hadley Centre Global Atmospheric Model (HadAM3P). The focus was on the changes in the mean circulation and surface variables, in particular, surface air temperature and precipitation. In summary, some aspects of projected future climate change are quite robust across this set of model runs for some regions, whereas for other regions are less robust.

There is a consistent pattern of changes in circulation, rainfall and temperatures as depicted by the three RCMs and the HadAM3P GCM. The HadRM3P shows a strengthening and a more southward position of the subtropical Pacific high, while for the subtropical Atlantic high there is a northward or southward displacement and a pattern of increasing or weakening during summer and winter as derived from the Eta CCS or RegCM3 models, respectively. As for the upper level, there is a tendency for a weakening of the subtropical westerly jet, consistent with our simulations from the Eta CCS and HadRM3P. All regional models show reductions and increases in precipitation in the future for the A2 scenario depending on the region and the reductions are lower in the HadRM3P in some regions. There are indications that regions such as Northeast Brazil and central-eastern Amazonia may experience rainfall deficiency in the future, while the Northwest coast of Peru-Ecuador may experience rainfall excesses in a warmer future. The projections exhibit an increase of rainfall in northern Argentina especially in summer and fall and a general decrease in precipitation in winter and spring, and in southern Brazil during fall. These are consistent with changes in low level circulation from the models.

In general the three models show warming in the A2 scenario stronger in the tropical region, especially in the 5°N–15°S band, both in summer and especially in winter, reaching up to 6–8°C warmer than in the present. In southern South America, the warming in summer varies between 2 and 4°C and in winter between 3 and 5°C in the same region for the three RCMs. The changes in rainfall and temperature discussed here seem to be consistent with changes in rainfall and temperature extremes published elsewhere.

Changes in the large-scale atmospheric circulation are identified as a major source of uncertainty, in particular for the changes in precipitation and windiness, as well as rainfall in Andean regions. This study only covered the uncertainties associated with the choice of the RCM, not those associated with the driving GCM and the emissions scenario.

This uncertainty can only be reduced by painstaking improvement of our knowledge of the climate system and of global climate models. Other aspects of the simulated changes might be more sensitive to the formulation of the regional model itself and the nesting of the regional models. A prime example is the large summer warming in parts the Amazon that for one regional model is concentrated in

the eastern part, while other show the warming in the western side.

The results reported here are based on one realization forced by a single driving model. This study only covered the uncertainties associated with the choice of the RCM, not those associated with the driving GCM and the emission scenarios. With the slow appearance of new studies on regional climate change simulations in South America, it is now possible to start an assessment of the robustness of the projected changes. Our regional climate change projections agree with the global multi-model ensemble mean results reported in Meehl et al. (2007) suggesting the added value of the regional simulation. It is hoped that with other regional climate change simulations being currently implemented we can gain a better understanding on the uncertainties of the regional projections discussed. It is hoped that the suite of regional climate simulations being conducted within the CREAS project for the Second National Communication of Brazil to the UNFCCC and the EU CLARIS-LPB project, using various global and regional models will give further insight to this issue.

For stakeholders in each of the regions, these changes and uncertainties pose different challenges for the management of water resources. For the scientific community, the challenge raised is how to incorporate this uncertainty in climate change projections in a way that allows those groups to make informed decisions based on model projections.

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