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ORIGINAL PAPER

# Climate downscaling over South America for 1961–1970 using the Eta Model

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**Abstract** This study shows the results from a regional climate simulation of the present-day climate, corresponding to the period 1961–1970 over South America, using the regional Eta Model nested within the HadAM3P model from the UK Hadley Centre. The simulation analysis is focused on assessing the capability of the nested regional model in representing spatial patterns of seasonal mean climate and the annual cycle of precipitation and temperature. The goals of this 10-year run for South America are to verify if the Eta Model can be used in climate-change scenarios and to verify if this model has the ability to generate added value for the South American continent. The Eta Model was chosen because there are few investigations using the Eta Model for long integrations over South America and because the vertical coordinate system used in this model is recommended for use over South America due to the presence of the Andes range. In the present 10-year simulation, the regional model reproduced many of the South American mesoscale climate features and together added new value to the driver model. Value was also added to the driver model by reducing seasonal biases in austral winter relative to austral summer. The regional model also exhibits better performance in the representation of low-level circulation, such as the topographically induced north-westerly flux.

## 1 Introduction

Atmospheric general circulation models (AGCMs) are useful tools for representing the evolution of atmospheric processes at different time scales, ranging from weather to climate. Due to the large domain covered, the typical spatial resolutions of AGCMs are the order of a few hundred kilometers. Therefore, AGCMs are not able to handle the large number of feedback processes occurring on subgrid scales controlled by local features such as topography, shorelines, vegetation, and lakes. These small-scale processes, as well as subgrid turbulent heat and momentum fluxes, cannot be described in detail by AGCMs. The use of regional climate models makes it possible to deal with these scales. These models can be used for climate simulations on decadal time scales and are better able to take into account subgrid scale climate feedback mechanisms. Outside the domain of the regional model, surface conditions such as sea surface temperature (SST), ocean ice, and three-dimensional atmospheric fields are generally provided by the global model. During the last decade, the regional climate models with horizontal resolutions on the order of 10–20 km or higher have become available to represent atmospheric conditions.

Some of the first regional climate model simulations were the January climatology simulations over western North America carried out by Giorgi (1990) using the Pennsylvania State University (MM4) mesoscale model with 60 km resolution. The simulations were driven by two versions of the global Community Climate Model (CCM), one with a horizontal grid resolution of $4.5\times7.5°$ and the other with a resolution of $2.89\times2.89°$. The nested MM4 results were similar to the CCM simulations, but the precipitation and temperature fields showed better results than the CCM due to the higher resolution of the regional model. The frequency of intense daily precipitation showed good agreement with observations.

Lateral boundary conditions, from the driver model, are important in the nesting procedure because they are the

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source of biases being introduced into the regional model. To study the magnitude of this problem, Nobre et al. (2001) used the output of the ECHAM3 global model from January to April of 1999 to drive the Regional Spectral Model (RSM) on an 80-km grid. A second nesting was used to drive the RSM on a 20-km grid meshed with the 80-km grid output. The sea surface temperature used for lower boundary conditions was forecast over the tropical oceans. The results showed that the 80-km grid regional model had better precipitation fields than the global model, with reductions in the seasonal bias and root mean square error (RMSE). The 20-km model exhibited larger errors, with spatial precipitation patterns following the local topography. The 80-km regional model showed better representation of the Intertropical Convergence Zone (ITCZ) position over the Atlantic than the 20-km grid RSM and ECHAM3. Both regional climate models showed better spatial and temporal precipitation distribution and exhibited less spread than the other models studied. These errors can be associated with the nesting procedure, where the 20-km model was driven by contour values with errors transmitted from the two models. Chou et al. (2000) showed that lateral boundary conditions had a larger impact than lower boundary conditions in long-term Eta Model simulations of South American climate.

The Brazilian Center for Weather Forecasts and Climate Studies (CPTEC) has used the Eta Model operationally since 1996 to provide weather forecasts over South America. Due to its vertical coordinate system, the Eta Model is able to produce satisfactory results in regions with steep orography such as the Andes range. Chou and Tanajura (2002) conducted one of the first experiments of 1 month continuous integration with a seasonal regional model for South America. This work clearly displayed added value for the dry season and good results for the summer period, as compared with global model results (Chou et al. 2005). The Eta Model was used to investigate precipitation predictability at different time scales (seasonal, monthly, and weekly) over South America (Chou et al. 2005). The lateral boundary conditions used in this work were obtained from the CPTEC GCM forecast at T62L28. Twelve overlapping 4.5-month time integrations were performed from February, 2002 to February, 2003. The CPTEC GCM forecasts comparisons with Eta showed that the Eta Model provided considerable improvement over the driver model. The assessment of the Eta Model seasonal forecasts against climatology showed that, in general, the model produced additional useful information over climatology. Based on ten consecutive Januaries (1991–2000), Fernandes et al. (2006) investigated the ability of two regional models—the RegCM3 and the Eta Model—to simulate the mean climatological characteristics of the quasistationary circulation over South America. In general, the RegCM3 and Eta models showed, respectively, negative and positive biases for surface temperature in almost all regions over South America. The Eta Model exhibited better results in simulations of upper- and lower-level circulation and precipitation fields. In general, over the Amazon (AM), neither model was able to correctly simulate precipitation. Pisnichenko et al. (2008) described two time-slice integrations of the Eta Model driven by the HadAM3P Atmospheric Global Climate Model (Gordon et al. 2000). One time slice was for the period 1961 to 1990; the other was from 2071 to 2100. The results of Pisnichenko showed precipitation fields with a strong negative bias over a large part of South America during the summer for present-climate simulations and slightly less precipitation activity along the Atlantic ITCZ for the same period.

The RegCM3 regional climate model driven by HadAM3P outputs was also used to simulate 10 years of present climate over South America (Rocha et al. 2003). The model used 60-km horizontal resolution and 23 vertical levels. The results showed that the annual precipitation cycles simulated over the Amazon by the global and regional models are in good agreement. Both model runs had negative biases over the Amazon region from January to September. Relative to the HadAM3P, the RegCM3 provided only a poor indication of the beginning of the rainy season between October and November. The annual maximum temperature of the RegCM3 occurred in October, which does not agree with observations. More recently, Solman et al. (2008) presented a simulation of present-day climate, 1981–1990, over southern South America using the MM5 model (Grell et al. 1993). The simulation was evaluated in terms of seasonal means, interannual variability, and extreme events. In general, maximum temperatures were better represented than minimum temperatures. The warm bias was larger during austral summer for maximum temperatures and during austral winter for minimum temperatures, mainly over central Argentina. They concluded that the regional model is capable of reproducing the main regional seasonal features.

In this work, the results will be analyzed over South America to investigate the circulation patterns for summer and winter periods, looking at precipitation and near-surface temperature regimes. The goal of this work is to validate the modified Eta Model for use in Climate Simulations (Eta/CS) and to assess the progress due to the regionalization process. This work is an initial step in the preparation of the model for use in climate change studies as part of a project to conduct impact studies of different SRES over South America. The investigation focuses on near-surface air temperature and precipitation over land areas within the domain, because of the importance of these fields for climate impact studies. It also focuses on the availability of observed datasets for model validation and the possibility of comparison with previous work, such as Ambrizzi et al. (2007) and Solman et al. (2008). Moreover, some assessment of upper-air circulation patterns is also presented in order to better assess model behavior. The HadAM3P outputs were used as the available conditions during the development of this work. In the future, a Coupled General Circulation Model should be available as well. A brief description of the model and the experimental design are presented in Section 2, and simulation results are discussed in Section 3. Some final conclusions are drawn in Section 4.

## 2 Model descriptions

### 2.1 Eta

The regional climate will be simulated using the Eta Model (Mesinger et al. 1988) developed at Belgrade University and operationally implemented by the National Centers for Environmental Prediction (Black 1994). This model has been used in studies of seasonal forecasts over South America (Bustamante et al. 2006; Chou et al. 2005) where the forecasts were improved with respect to the driver global model, which had a resolution of T62.

The model is established with 38 vertical levels with the top of the model at 25 hPa and uses the *eta* vertical coordinate (Mesinger 1984). A detailed description of the dynamic component of the model is given by Mesinger (1984). The treatment of turbulence is based on the Mellor–Yamada level 2.5 procedure (Mellor and Yamada 1974); the radiation package was developed by the Geophysical Fluid Dynamics Laboratory, with long wave and solar radiation parameterized according to Fels and Schwarzkopf (1975) and Lacis and Hansen (1974), respectively. The Eta Model uses the Betts–Miller (Betts and Miller 1986) scheme modified by Janjic (Janjic 1994) to parameterize deep and

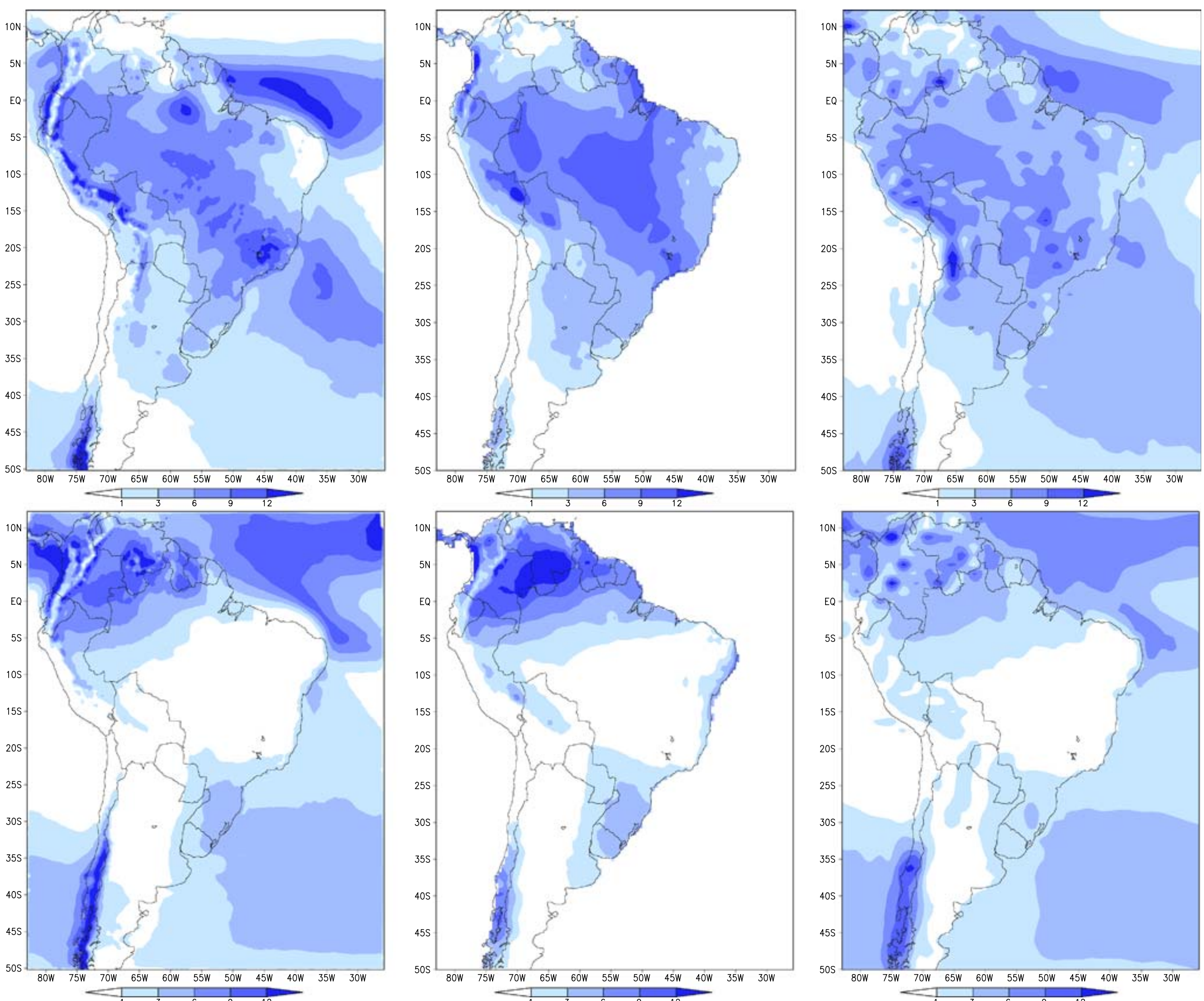



**Fig. 1** 1961–1970 DJF (*top*) and JJA (*bottom*) seasonal mean precipitation (mm/day) for Eta (*left*), CRU (*center*), and HadAM3P (*right*)

shallow cumulus convection. Cloud microphysics uses the Ferrier (2002) scheme. The land-surface transfer processes are parameterized by the NOAH scheme (Chen et al. 1997).

One of the modifications of the CS Eta version was in using SST derived from monthly mean observed data. The model updates daily SST by means of linear interpolation. The major modification is the 360-day calendar year, which is necessary in order to treat the HadAM3P as lateral boundary conditions.

### 2.2 HadAM3P

The HadAM3P model resolution is 1.25° latitude by 1.875° longitude. Details of the model characteristics can be found in Pope et al. (2000). The HadAM3P present-climate simulations from 1961 to 1970 were initialized with atmospheric and land surface conditions from the Coupled Ocean–Atmosphere Global Climate Model from the Hadley Centre (HadCM3) and forced with observed sea surface temperature and sea-ice distributions from the Hadley Centre. The distribution of different types of vegetation was held constant during the integration period. The HadAM3P output files provide the following prognostic variables: specific humidity, potential temperature, mean sea level pressure, and horizontal winds. These variables are available every 6 h. The model is hydrostatic and uses an Arakawa-B grid and a hybrid vertical coordinate with 19 levels.

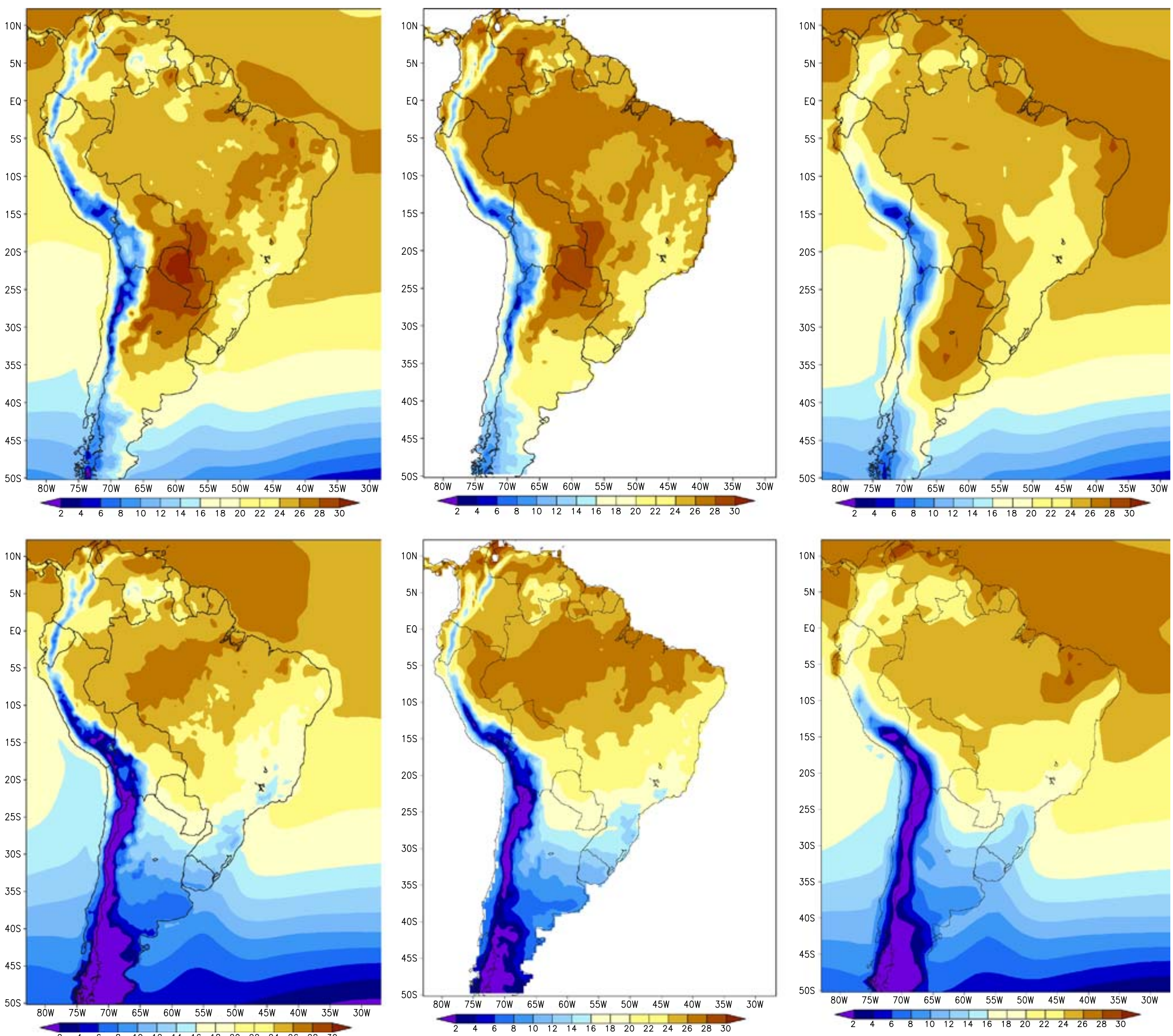



**Fig. 2** 1961–1970 DJF (*top*) and JJA (*bottom*) seasonal mean near-surface temperature (°C) for Eta (*left*), CRU (*center*), and HadAM3P (*right*)

## 2.3 Observed data

The ERA40 reanalysis (Upalla et al. 2005) is used for a climate simulation assessment for the years 1961–1970. The ERA40 reanalysis used here has monthly output files and a spatial resolution of 1.25×1.25° grid size. The Climate Research Unit (CRU; Mitchell et al. 2003) from East Anglia University is available over a 0.5×0.5° horizontal grid with monthly means of 1.5-m temperature and precipitation data from 1901–1999. The CRU precipitation and temperature will be compared against the Eta simulations of these variables.

## 2.4 Experimental design

The Eta Model was run continuously for the 10-year (1961–1970) simulation with HadAM3P as boundary conditions, which were updated every 6 h. The Eta Model has a horizontal resolution of 40 km and 38 vertical levels. Figure 6 shows the area used for the Eta model, from the latitude of 50.2° S to 12.2° N and from the longitude of 83° W to 25.8° W. The model was initialized at 00z January 1, 1960 and the simulation extended to the end of 1970. The period was chosen to compare this climate simulation with four other regional climate simulations over South America that also began in 1961. These other simulations are described by Ambrizzi et al. (2007). A 1-year period for atmospheric spin-up was allowed. The Eta Model results are compared with the HadAM3P model and ERA40 for wind and sea level pressure and with HadAM3P and CRU data for precipitation and near-surface temperature.

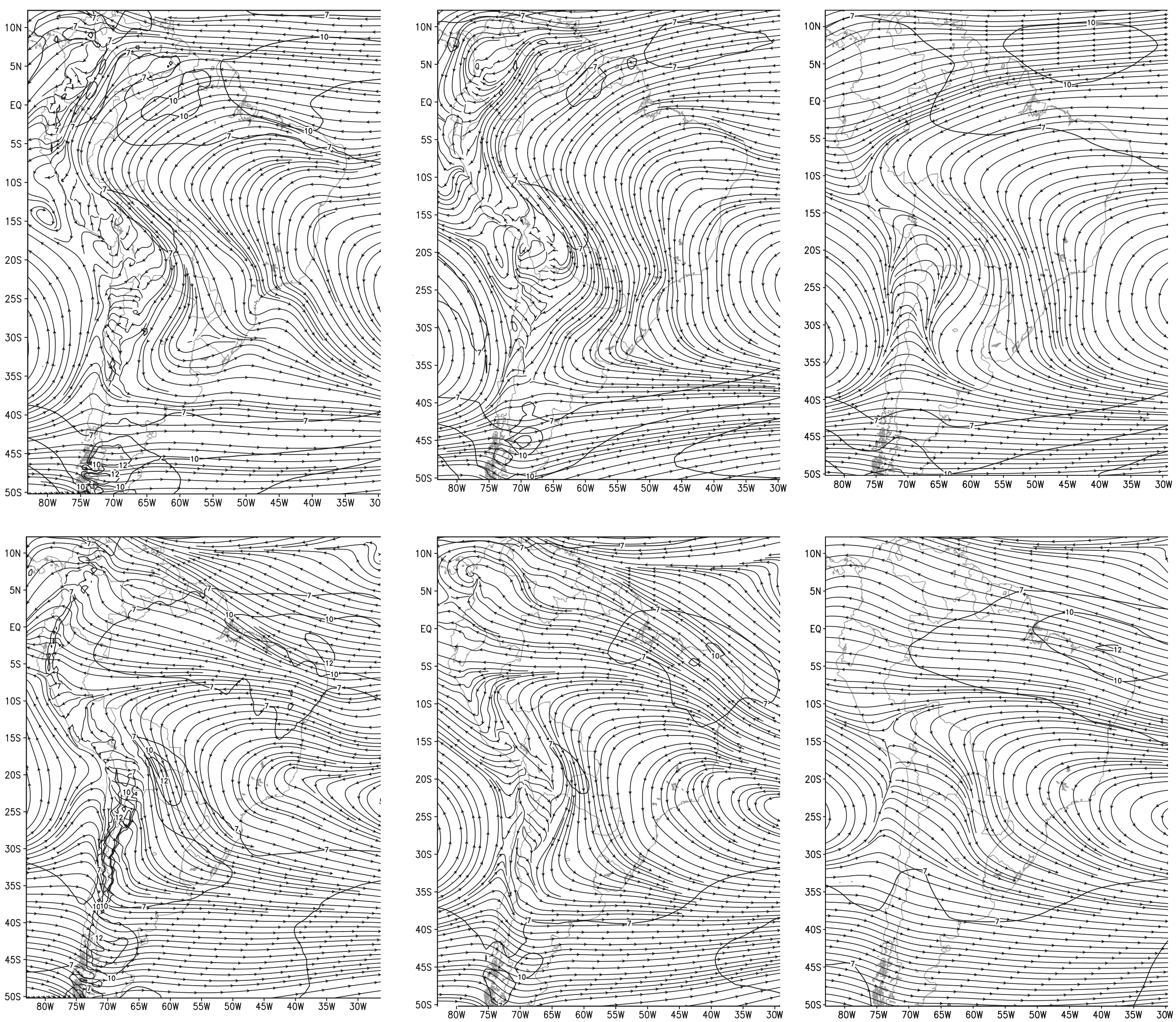



**Fig. 3** 1961–1970 DJF (*top*) and JJA (*bottom*) seasonal mean wind at 850 hPa (m s$^{-1}$) for Eta (*left*), ERA40 (*center*), and HadAM3P (*right*)

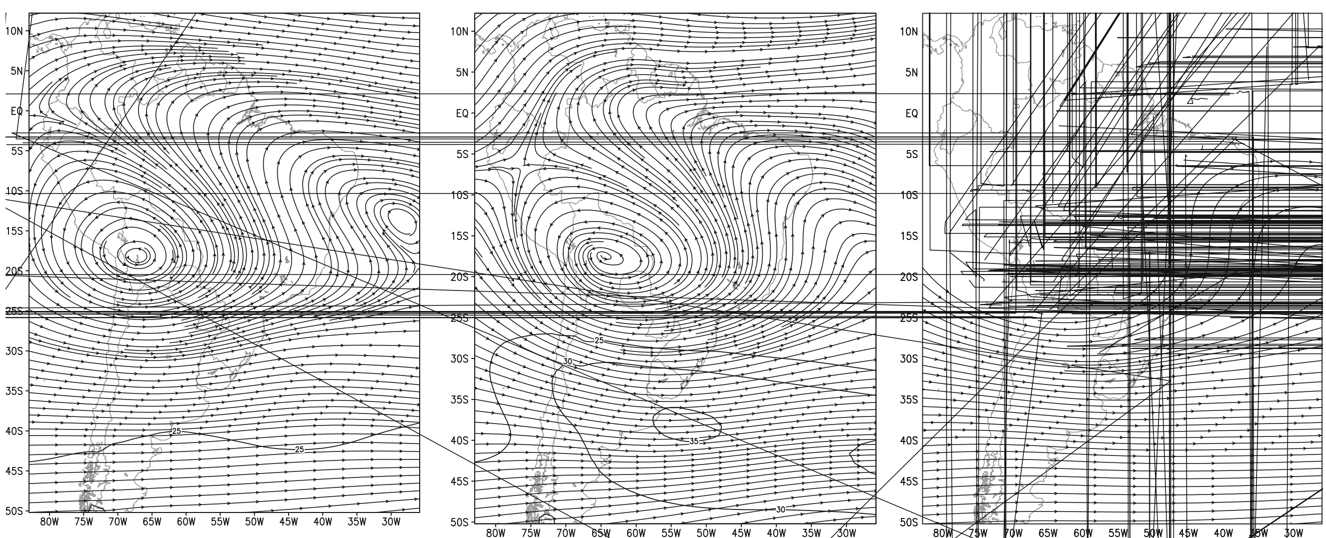
## 3 Results

### 3.1 DJF and JJA seasonal means

Due to differences in parameterization, resolution, and topography, it is important to analyze how well the Eta Model is able to describe seasonal spatial distribution and intensity of certain selected meteorological variables. The analyzed variables are wind fields at 850 and 200 hPa, precipitation, near-surface temperature, and sea level pressure. The contrasting seasons of December–January–February (DJF; the austral summer) and June–July–August (JJA; the austral winter) are used for evaluation of model performance over the period 1961–1970.

#### *3.1.1 Precipitation*

Figure 1 shows the 1961–1970 DJF and JJA seasonal mean precipitation for the Eta and HadAM3P models together with the CRU precipitation data. During DJF, the Eta Model shows the major summer circulation features over South America, such as the South Atlantic Convergence Zone (SACZ) and the ITCZ. The maximum precipitation associated with the SACZ is underestimated by the Eta Model over central and northern Brazil and overestimated over southeastern Brazil. The HadAM3P model exhibits weaker ITCZ and SACZ summer configurations, but underestimates the summer precipitation more than the Eta Model does over central and northern Brazil. The ITCZ precipitation intensity over the northern cost of South



America (from HadAM3P) is weaker and has an insufficient seasonal volume when compared with Eta and CRU data. During the austral summer, the high precipitation values over southeastern Brazil in the Eta Model are due to the extra air mass ascent produced by the local topography. Significant differences between the Eta Model and the CRU data are noticeable over northeastern (NE) Brazil; however, the HadAM3P generated results closer to observed precipitation while the Eta underestimated the values. For the JJA season, precipitation does not occur in the interior of the continent, but is present over southern Brazil and Uruguay, northern South America, and the eastern coast of northeastern Brazil. The Eta Model captures this precipitation pattern. The HadAM3P underestimates the precipitation values but captures the spatial distribution.

In general, the broad-scale precipitation and the seasonal contrast is well captured by Eta Model. For the whole of South America, the simulated present climate is better represented in JJA than in DJF. The improvement of the Eta precipitation simulations over HadAM3P is more significant in DJF than in JJA, when both models show very similar precipitation patterns and precipitation is reduced in the central part of the continent. The Eta Model has more detailed topography than HadAM3P and therefore can produce larger amounts of precipitation near the higher elevation areas. This is a common feature for regional simulations over mountainous terrain (Leung et al. 2003).

### 3.1.2 Near-surface temperature

Figure 2 shows the 1961–1970 DJF and JJA seasonal mean near-surface temperature from the Eta and HadAM3P models and CRU observed temperature data. The effects of the Eta Model higher-resolution topography are appar-

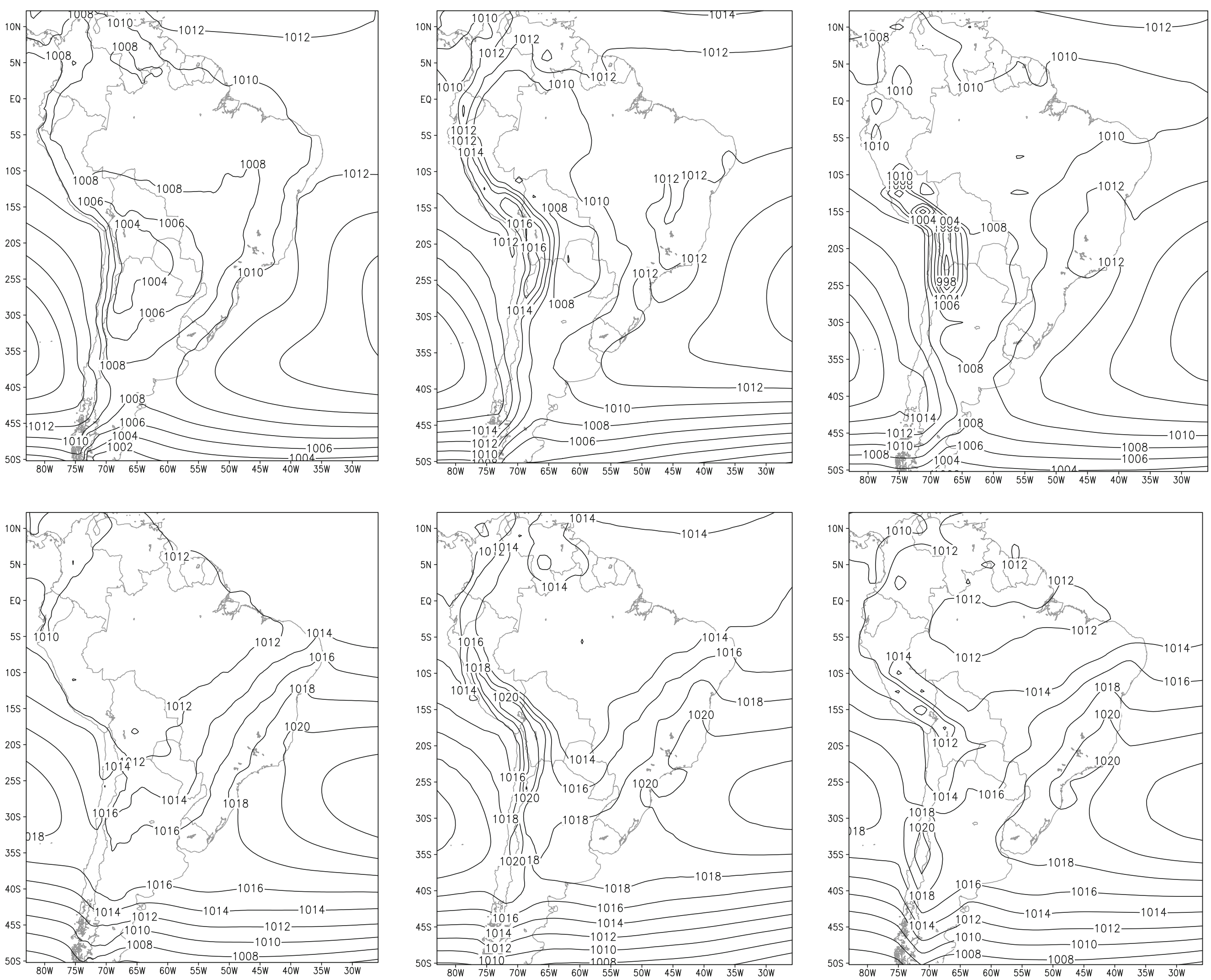



**Fig. 5** 1961–1970 DJF (*top row*) and JJA (*bottom row*) seasonal mean sea level pressure (hPa) for Eta (*left*), ERA40 (*center*), and HadAM3P (*right*)

ent. During DJF, the Eta Model exhibits a positive temperature bias over Paraguay and a cold bias over the Amazon region, similar to the pattern of the HadAM3P bias. During DJF and JJA, over the south (S) and southeastern (SE) regions of Brazil, the Eta model shows a near-surface temperature configuration that is very similar to the CRU data. During JJA, the Eta Model exhibits a weak negative bias over northeastern Brazil, and the HadAM3P again shows a weaker negative bias over the Amazon region (similar to that of DJF).

In general, the near-surface temperature configuration from the Eta and HadAMP3 models shows weak differences during the two seasons. Most of the differences are from 1°C to 2°C and are related to the different topographical resolutions. The added value by the Eta Model near-surface temperature simulations was clearer during DJF and JJA for southeastern and southern Brazil. In general, for the whole South America region, the Eta simulation of present climate showed clearer improvements over the HadAM3P simulation in JJA than in DJF, except for northeastern Brazil, when verified against CRU.

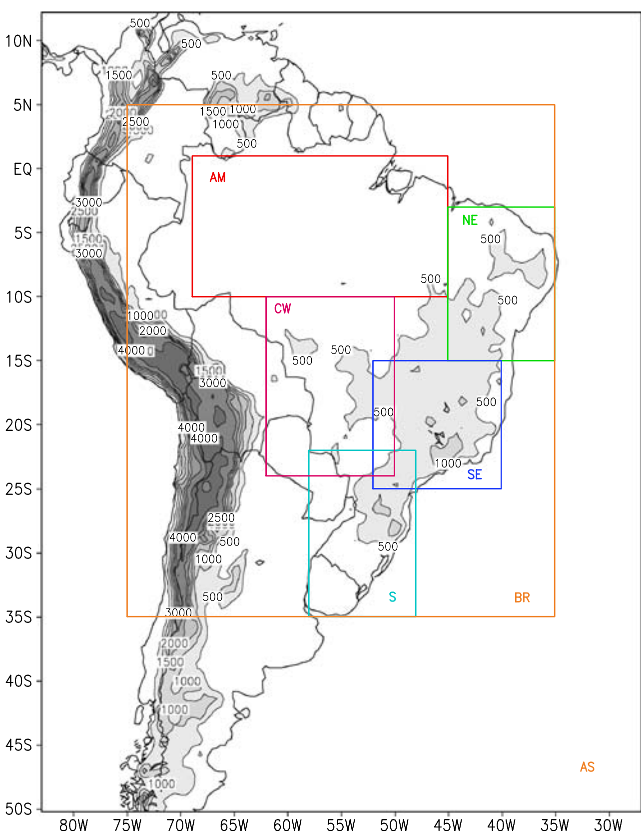



**Fig. 6** Domain and topography of evaluated areas. The *colored squares* refer to regions for which an annual cycle verification was carried out: *AM* Amazon, *NE* northeast, *SE* southeast, *S* south, *CW* center-west, *BR* Brazil, *AS* whole South America continent. Topography height contours are drawn every 500 m from 0 to 2,000 m and every 1,000 m thereafter. Heights greater than 500 m are *shaded*

### *3.1.3 850 and 200-hPa circulation*

The low-level jet (LLJ) is an important feature of the moisture source at subtropical latitudes, flowing from northern to southern South America. Saulo et al. (2000) used the Eta model in short-term integrations to show the LLJ core to be located at around 850 hPa and 17° S. They showed that the Eta Model has good skill in representing the LLJ structure over South America. Figure 3 shows the 1961–1970 850-hPa DJF and JJA seasonal mean circulation from the Eta and HadAM3P models together with the ERA-40 reanalysis data. The northwesterly along the eastern slope of the Andes is shown in both high- and low-resolution simulations, but the intensity is better captured at higher resolutions of the Eta Model and ERA-40. To the north of 5° S, near the equatorial Atlantic, trade wind strength is overestimated during DJF and JJA by the Eta and HadAM3P models; this bias may have partly originated from the HadAM3P model. For JJA and DJF, only the Eta Model and ERA-40 show the effect of the Andes on the downwind flow. During DJF over Southern Brazil, mainly over the Atlantic coast, there is a northwesterly flow in the Eta model and a northerly flow in the HadAM3P model and ERA-40. In general, the Eta Model showed the main characteristics of the seasonal low-level circulation over South America and, in particular, the northwesterly flow along the east flank of the Andes.

Figure 4 shows the 1961–1970 DJF and JJA seasonal mean circulation at 200 hPa from the Eta and HadAM3P models together with ERA40 reanalysis data. For the DJF period, the models showed good agreement in the upper-air circulation patterns over South America, such as the anticyclonic circulation or Bolivian High and the trough over northeastern Brazil. In the vicinity of the subtropical jet stream, the wind velocity of the models is weaker than in the reanalysis. The upper-level Bolivian High is more intense in the Eta Model, which is probably caused by the stronger convective activity indicated by higher amounts of precipitation over the continent. For the JJA period, the model mean circulation pattern also shows good agreement with the reanalysis. In JJA, the Eta Model shows stronger convective activity occurring in the northern part of South America, which generated the upper-level anticyclonic circulation over this region. Both models show weak winds over most areas, mainly in the vicinity of the jet stream. The core of the jet stream in the reanalysis is at around 25° S with speeds of about 38 m/s. The Eta Model shows a weaker jet stream core displaced poleward.

At upper levels, the regional model does not provide clear added value to the wind description; however, most of the circulation patterns for DJF and JJA present in the reanalysis data are also shown in the Eta Model. The differences related to the weaker and poleward-displaced jet stream of the Eta Model during DJF and

JJA are biases coming partially from the HadAM3P model. However, for DJF, the Eta Model simulated a weaker upper-level jet stream than the HadAM3P model.

### 3.1.4 Mean sea level pressure

Figure 5 shows the 1961–1970 DJF and JJA mean sea level pressure for the Eta and HadAM3P models together with

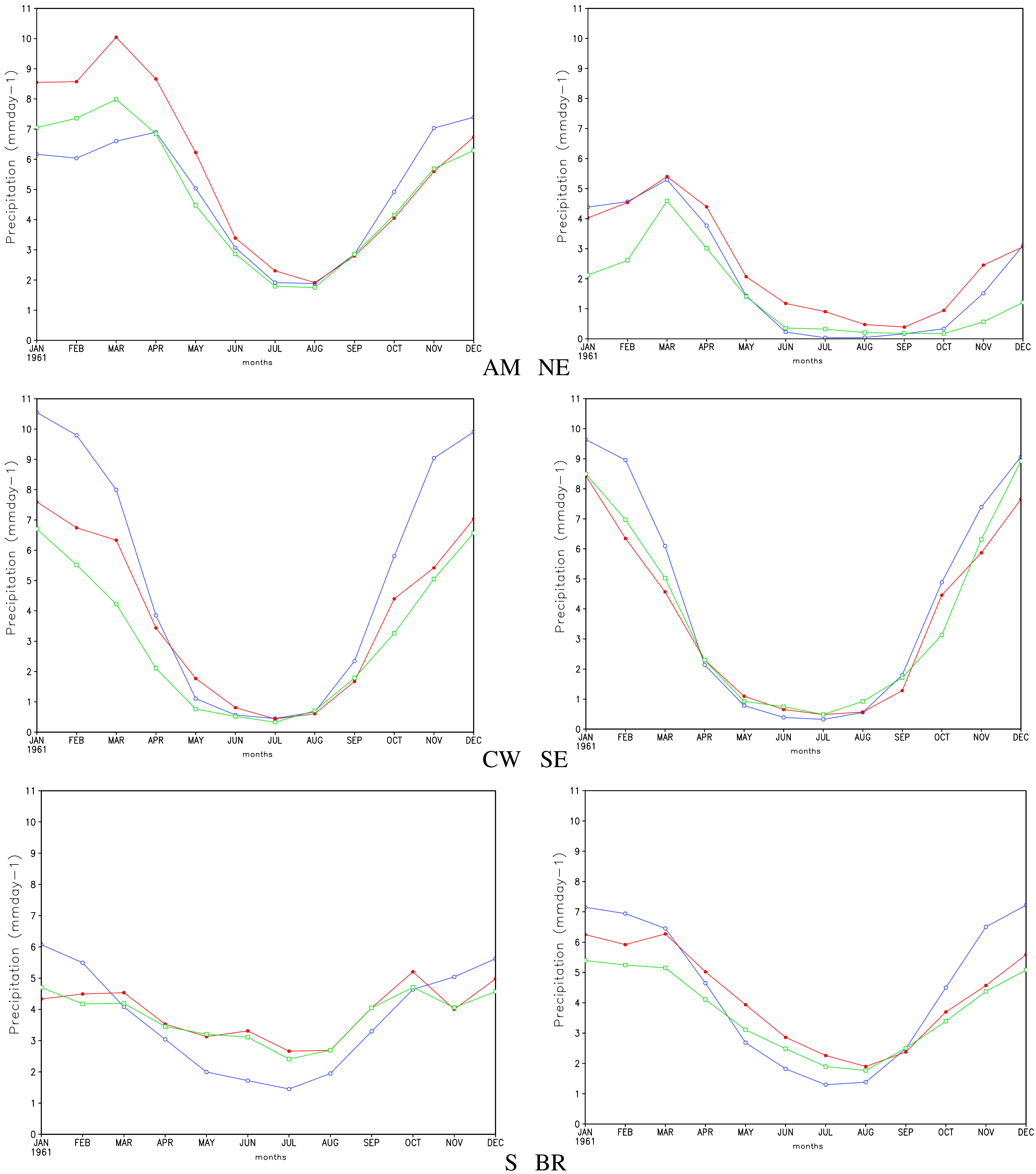



**Fig. 7** Annual precipitation cycle (mm/day) for CRU (*red*), Eta (*green*), and HadAM3P (*blue*) over six of the regions referred to in Fig. 6. *AM* Amazon, *NE* northeastern, *CW* center-west, *SE* southeastern, *S* southern, *BR* Brazil

ERA40 reanalysis data. During DJF, the Eta Model shows the major summer pressure patterns, such as the thermal low over northern Argentina, although its strength is overestimated by about 3 hPa. This difference can be related to the effect of the higher resolution of the Eta Model, which has a higher and narrower Andes topography than the HadAM3P model. In the Eta Model, the subtropical Atlantic high is weaker than in the reanalysis. The pressure differences shown between the model

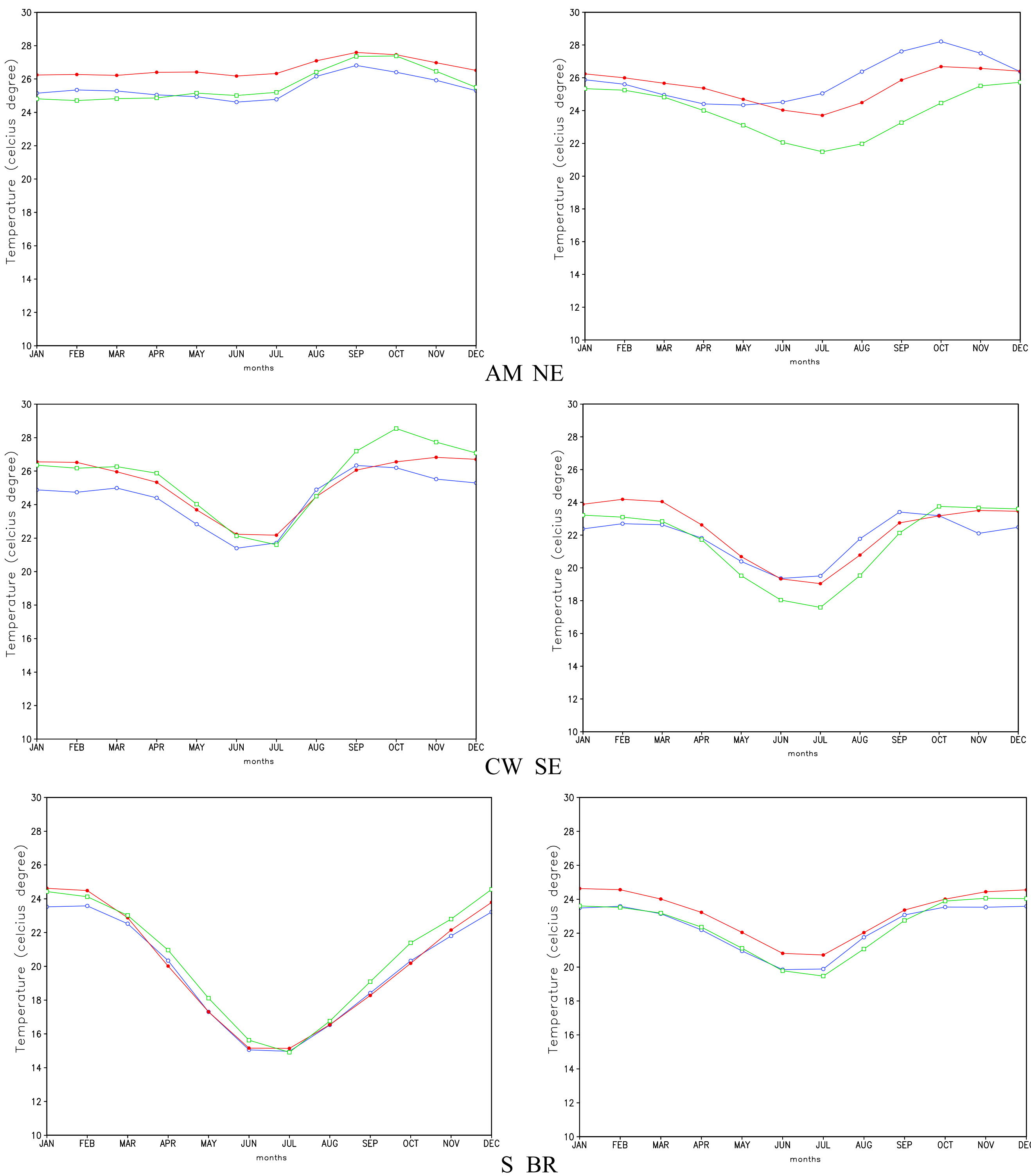



**Fig. 8** Annual temperature cycle (°C) for CRU (*red*), Eta (*green*), and HadAM3P (*blue*) over six regions shown in Fig. 6. *AM* Amazon, *NE* northeastern, *CW* center-west, *SE* southeastern, *S* southern, *BR* Brazil

**Table 1** Eta and HadAM3P MAE, CC, RMSE, and bias for precipitation during DJF and JJA periods

| | MAE | | CC | | RMSE | | Bias | | |
|---|---|---|---|---|---|---|---|---|---|
| | Eta | HadAM | Eta | HadAM | Eta | HadAM3P | Eta | HadAM | |
| AM | **2.99** | 3.18 | **0.18** | 0.18 | 0.18 | 4.01 | **−1.2** | −2.6 | DJF |
| | 1.34 | **1.29** | **0.78** | 0.77 | **0.78** | **1.52** | −0.6 | **−0.5** | JJA |
| NE | 2.67 | **2.19** | **0.45** | 0.39 | **0.45** | **2.85** | −2.2 | **−0.4** | DJF |
| | **0.69** | 0.91 | **0.72** | 0.52 | **0.72** | 1.12 | **−0.4** | −0.8 | JJA |
| SE | 3.69 | **3.64** | 0.21 | 0.21 | 0.21 | 4.45 | **0.5** | −1.5 | DJF |
| | 0.63 | **0.49** | **0.58** | 0.56 | **0.58** | **0.66** | **0.08** | −0.3 | JJA |
| S | **2.24** | 2.50 | **0.26** | 0.23 | **0.26** | 3.07 | −0.2 | **0.13** | DJF |
| | 1.99 | **1.93** | **0.36** | 0.21 | **0.36** | 2.45 | **−0.2** | −1.0 | JJA |
| CW | **2.81** | 3.06 | **0.55** | 0.26 | **0.55** | 3.71 | −1.1 | **−1.0** | DJF |
| | **0.57** | 0.62 | **0.47** | 0.39 | **0.47** | **0.83** | **−0.1** | **−0.1** | JJA |
| BR | **2.66** | 2.93 | **0.53** | 0.38 | **0.53** | 3.56 | **−0.8** | −1.0 | DJF |
| | **1.27** | 1.48 | **0.81** | 0.75 | **0.81** | 1.74 | −0.4 | **−0.8** | JJA |
| AS | **2.57** | 2.70 | **0.55** | 0.38 | **0.55** | 3.33 | −0.8 | −1.0 | DJF |
| | **1.27** | 1.83 | **0.89** | 0.75 | **0.89** | 2.19 | −0.4 | **−0.8** | JJA |

Bold values are the better scores between Eta and HadAM3P

and the reanalysis for DJF are comparable in magnitude to those found over South America in other studies, such as Solman et al. (2008) and Rocha et al. (2003).

During JJA, the Eta Model shows the low pressure over northern Argentina in DJF that is weaker and shifted northward. Comparing Eta with HadAM3P, the pressure simulation for JJA shows more added value than for the DJF simulation. The differences for JJA compared against the reanalysis are minimal. The differences in the subtropical Atlantic high during DJF are related to a weaker bias from the driver model. There is added value in the Eta Model sea level pressure in JJA.

### 3.2 Precipitation and annual cycle of near-surface temperature

Due to the long-term model integration and the changes introduced into the Eta calendar, it is important to verify the

**Table 2** Eta and HadAM3P MAE, CC, RMSE, and bias for near-surface temperature during DJF and JJA periods

| | MAE | | CC | | RMSE | | Bias | | |
|---|---|---|---|---|---|---|---|---|---|
| | Eta | HadAM | Eta | HadAM | Eta | HadAM | Eta | HadAM | |
| AM | 1.52 | **1.31** | **0.83** | 0.34 | 1.69 | **1.39** | −1.3 | **−1.1** | DJF |
| | **1.25** | 1.66 | **0.50** | 0.23 | **1.41** | 1.77 | **0.6** | −1.4 | JJA |
| NE | **1.35** | 1.48 | **0.56** | 0.28 | **1.51** | 1.71 | −2.2 | **−0.3** | DJF |
| | 2.29 | **1.59** | **0.90** | 0.87 | *2.39* | **1.74** | **−0.6** | 1.3 | JJA |
| SE | **1.26** | 1.43 | **0.77** | 0.62 | **1.48** | 1.71 | **0.5** | −1.2 | DJF |
| | 1.78 | **1.47** | 0.80 | **0.81** | 1.98 | **1.72** | **0.1** | 0.7 | JJA |
| S | 1.61 | **1.32** | **0.87** | 0.75 | 1.91 | **1.62** | **−0.2** | −0.7 | DJF |
| | 1.56 | 1.56 | **0.91** | 0.90 | **1.90** | 1.95 | −0.2 | **−0.1** | JJA |
| CW | **1.26** | 1.64 | **0.77** | 0.76 | **1.48** | 1.86 | **−1.1** | −1.6 | DJF |
| | **1.43** | 1.66 | **0.81** | 0.75 | **1.67** | 1.95 | −0.1 | −0.1 | JJA |
| BR | **1.69** | 1.72 | **0.91** | 0.90 | **1.91** | 1.93 | **−0.8** | −1.0 | DJF |
| | **1.71** | 1.77 | **0.96** | 0.95 | **1.92** | 2.01 | **−0.4** | −0.6 | JJA |
| AS | 1.74 | **1.72** | **0.90** | 0.88 | **2.00** | 2.03 | **−0.9** | −1.1 | DJF |
| | 1.81 | **1.80** | **0.93** | 0.91 | 2.07 | **2.06** | **−0.7** | −0.8 | JJA |

Bold values are the better scores between Eta and HadAM3P annual cycle in different regions of the domain. These domains are described in Fig. 6, and this evaluation is considered only at land grid points where CRU data is available.

Figure 7 shows the annual precipitation cycle for the six selected areas indicated in Fig. 6. For the first 6 months of the year, the Eta Model showed better results than HadAM3P, except for in the central-west (CW) region. Some of the differences between CRU and Eta are from 0.5 mm/day in SE to 2.0 mm/day over the Amazon region. During the last 6 months of the year, the Eta and CRU showed similar results in five regions, but not in NE. For the first 6 months of the year, the Eta Model shows a negative bias relative to CRU data over all analyzed regions, reaching about −2.0 mm/day in region AM. During the last 6 months, the Eta Model tries to correct this and diminishes the biases over five regions, but not in NE. In general, the Eta Model showed good results for most of the year, the performance varying with seasonal cycle. In some cases, the Eta Model attempts to reduce the HadAM3P errors coming through the lateral boundary condition mainly during the dry months. The Eta Model generally keeps precipitation magnitude between the CRU and HadAM3P values. During the rainy months in the Amazon region, the HadAM3P model greatly underestimates precipitation with a mean bias of −3mm/day; however, this error decreases toward dry months. The models are biased in the rainy season and much less so in the dry season; the percentage error is small in the dry season. For northeast Brazil, both the HadAM3P and Eta models underestimate the precipitation throughout the year. The best simulations of the annual cycle of precipitation by the Eta Model were found to be over the AM, S, and SE regions. The annual

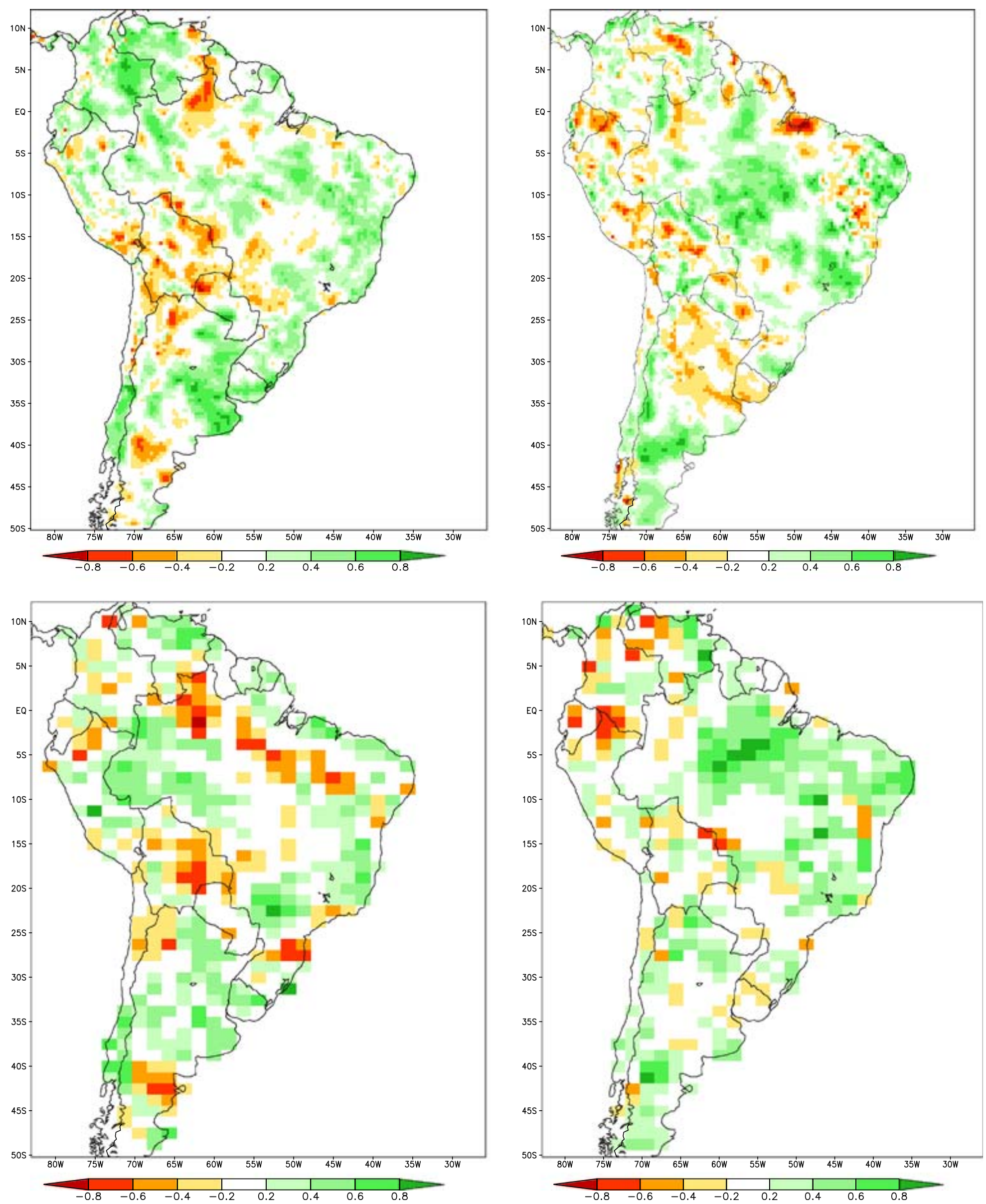



**Fig. 9** 1961–1970 DJF (*left*) and JJA (*right*) seasonal anomaly precipitation correlation for Eta (*top row*) and HadAM3P (*bottom row*)

cycle of the Brazil region shows the Eta Model in better agreement with CRU than HadAM3P, mainly between the months of February and August.

Figure 8 shows the annual near-surface temperature cycle for the six selected areas indicated in Fig. 6. In general, the Eta annual cycle of temperature is similar to that of the CRU. The differences between CRU and Eta are on the order of 2.0°C over the NE region up to 0.5°C for the S region. Comparing the Eta Model against reanalysis data over the BR region, one can see a negative bias throughout the year. Over the BR region, the differences are smaller than 1°C during the first 6 months and smaller than 0.5°C in the last 6 months. The seasonal cycle is not well represented over the NE region by the HadAM3P model, where the coldest temperature occurs in May instead of July. For the NE region, the Eta Model showed a good annual cycle but a larger negative bias, with −2.5°C in July; however, the October maximum occurs later than in observed data. As in the precipitation assessment, the best agreement among the models was in the Southern Brazil region. The smallest temperature bias was found in the S and CW regions.

### 3.2.1 *Mean absolute error, correlation coefficient, RMSE, and bias for precipitation*

In order to evaluate the magnitude of the simulation errors, Table 1 shows the mean absolute error (MAE), correlation coefficient (CC), RMSE, and bias for both models during DJF and JJA. In DJF and JJA, the Eta MAE is generally smaller than for HadAM3P. Considering the overall Brazilian (BR) and South American (SA) areas, the Eta simulations produced better MAE in both seasons. In this sense, for these larger domains, BR and SA, the Eta model added value to the precipitation simulations. During DJF, the HadAM3P model displayed an equal value of the correlation coefficient (shown in bold), over the SE and

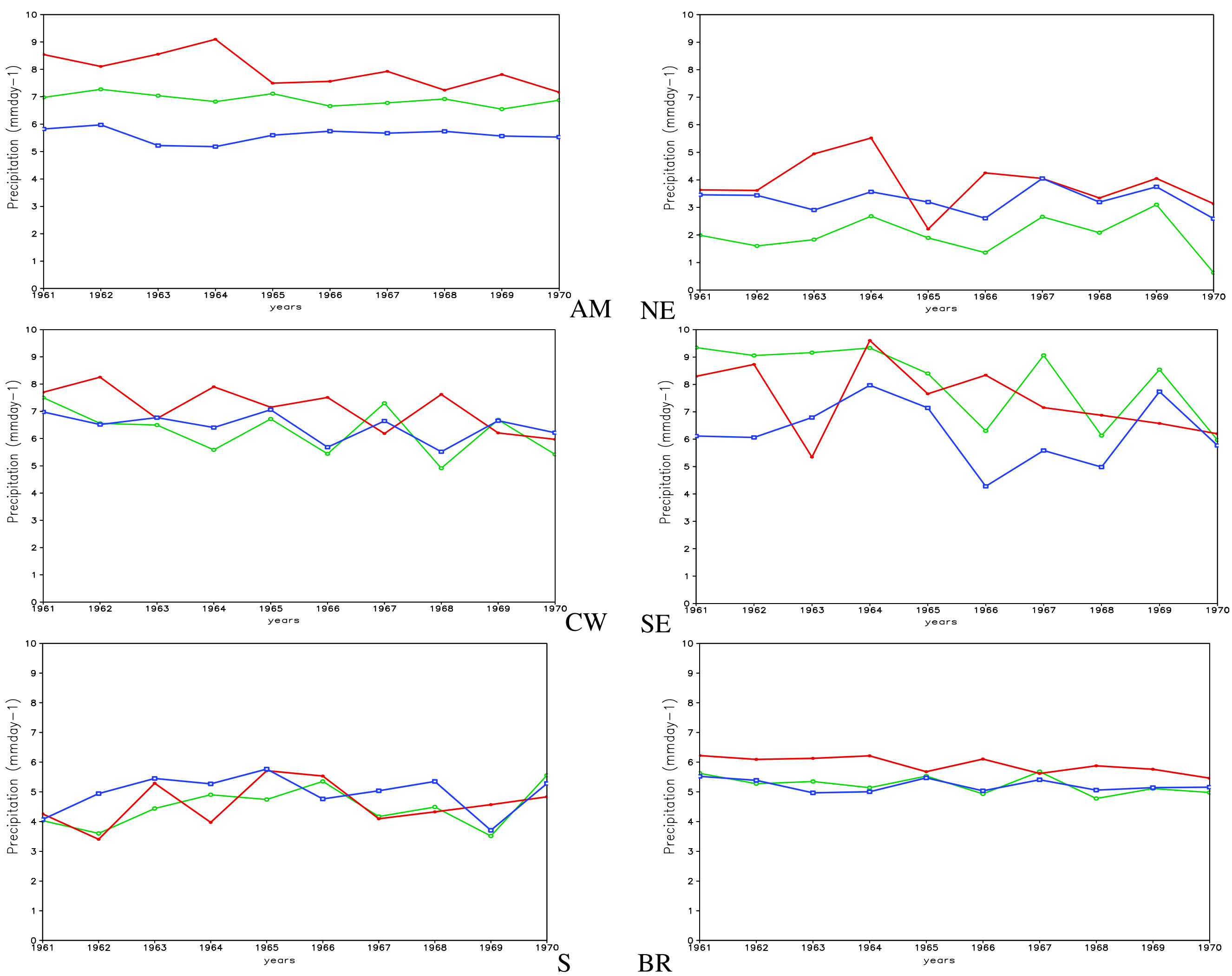



**Fig. 10** DJF interannual precipitation variability (mm/day) for CRU (*red*), Eta (*green*), and HadAM3P (*blue*) over six regions shown in Fig. 6. *AM* Amazon, *NE* northeastern, *CW* center-west, *SE* southeastern, *S* southern, *BR* Brazil

AM regions. This shows that the Eta Model simulated precipitation better. The mean RMSE of the Eta Model is smaller than that of the HadAM3P for precipitation fields during DJF and JJA over the BR and SA regions. Regarding bias, the Eta model seems to simulate better the precipitation during the winter than during the summer. The BR and SA values summarize the negative precipitation generally found in the Eta and HadAM3P models during most seasons, although the Eta biases have the smaller magnitude.

*3.2.2 Mean absolute error, correlation coefficient, RMSE, and bias for near-surface temperature*

Table 2 shows the mean absolute error (MAE), CC, RMSE, and bias for both models during DJF and JJA. In DJF, a smaller temperature MAE was most frequently found in the Eta simulations (NE, SE, and CW), whereas in JJA ,the Eta Model did not show a clear advantage. However, considering the larger domains of BR and SA, the Eta simulations have marginally smaller temperature MAE compared to the HadAM3P simulations. The Eta Model showed higher CC during both DJF and JJA, but in some regions, this difference between the models was very small. The mean RMSE of the Eta Model is smaller than that of the HadAM3P for temperature fields during DJF and JJA over the CW, BR and AS regions. The Eta Model shows better RMSE results than HadAM3P over a great part of the South America region, mainly during DJF. The Eta model had a smaller bias during DJF and JJA, while the HadAM3P model had a smaller bias in JJA over AM, NE and S regions. These results show the reduction of temperature biases produced by the Eta Model, mainly during DJF.

3.3 Precipitation anomaly correlation

Figure 9 shows the spatial correlation of the seasonal precipitation anomaly for the Eta and HadAM3P models. The regions in red show low spatial correlation and green

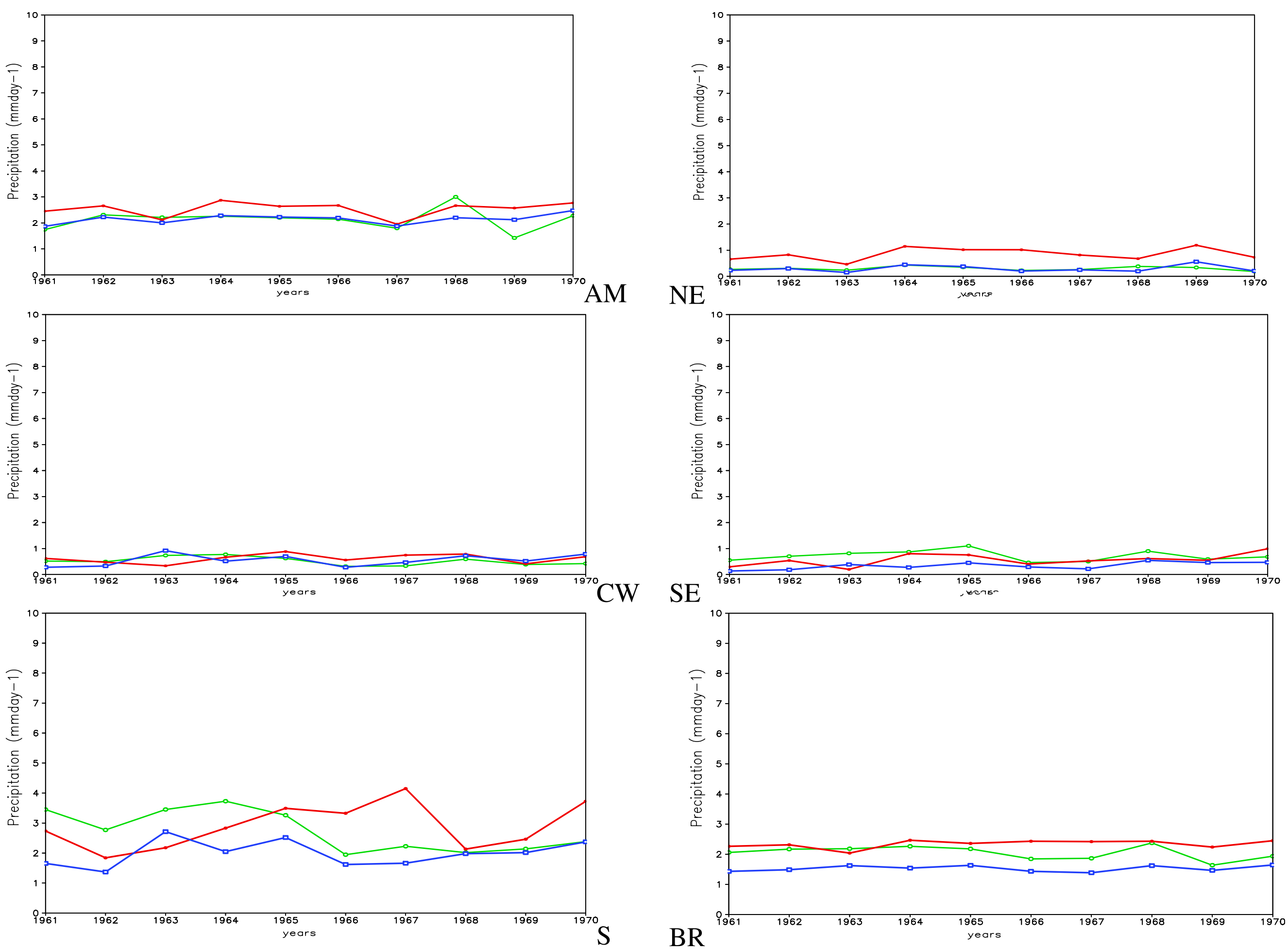



**Fig. 11** JJA interannual precipitation variability (mm/day) for CRU (*red*), Eta (*green*), and HadAM3P (*blue*) over six regions shown in Fig. 6. *AM* Amazon, *NE* northeastern, *CW* center-west, *SE* southeastern, *S* southern, BR = Brazil

regions show high spatial correlation. The Eta Model shows higher correlations during JJA than DJF and the same occurs with HadAM3P. The higher values occur during JJA, probably because it is the dry season of the year. HadAM3P shows higher values for anomaly correlation over the northern part of northeast Brazil during JJA.

### 3.4 Interannual variability

Results show that both models simulate precipitation and temperature patterns averaged over the 10-year period reasonably well. However, interannual variability is important for correct climate description. In this section, the interannual variability is evaluated in comparison with CRU data.

The interannual variability of precipitation for 1961–1970 is shown in Fig. 10 for the Eta and HadAM3P models as well as CRU data during DJF. It was found that the Eta interannual variability closely follows the HadAM3P during most of the analyzed period in all regions. In 1965 and 1966, moderate El Niño events caused a reduction of precipitation in the Amazon and Northeast regions, which is also shown in the CRU data. Both models show the reduction but not as clearly as in the observations. When the models are compared against the CRU interannual variability, it can be seen that region S represented the interannual variability best, but on the other hand, interannual variability in the CW region was poorly simulated: The observed and simulated curves are out of phase.

Figure 11 shows the interannual variability of precipitation for 1961–1970 for the HadAM3P and Eta models as well as CRU data during JJA. In this period, precipitation is reduced in most of the regions (CW, SE, and NE), and therefore, interannual variability is small and the simulated and observations curves are close. Only the S and AM regions exhibit more precipitation and therefore some interannual variability. However, none of the simulated curves correctly follow the observations.

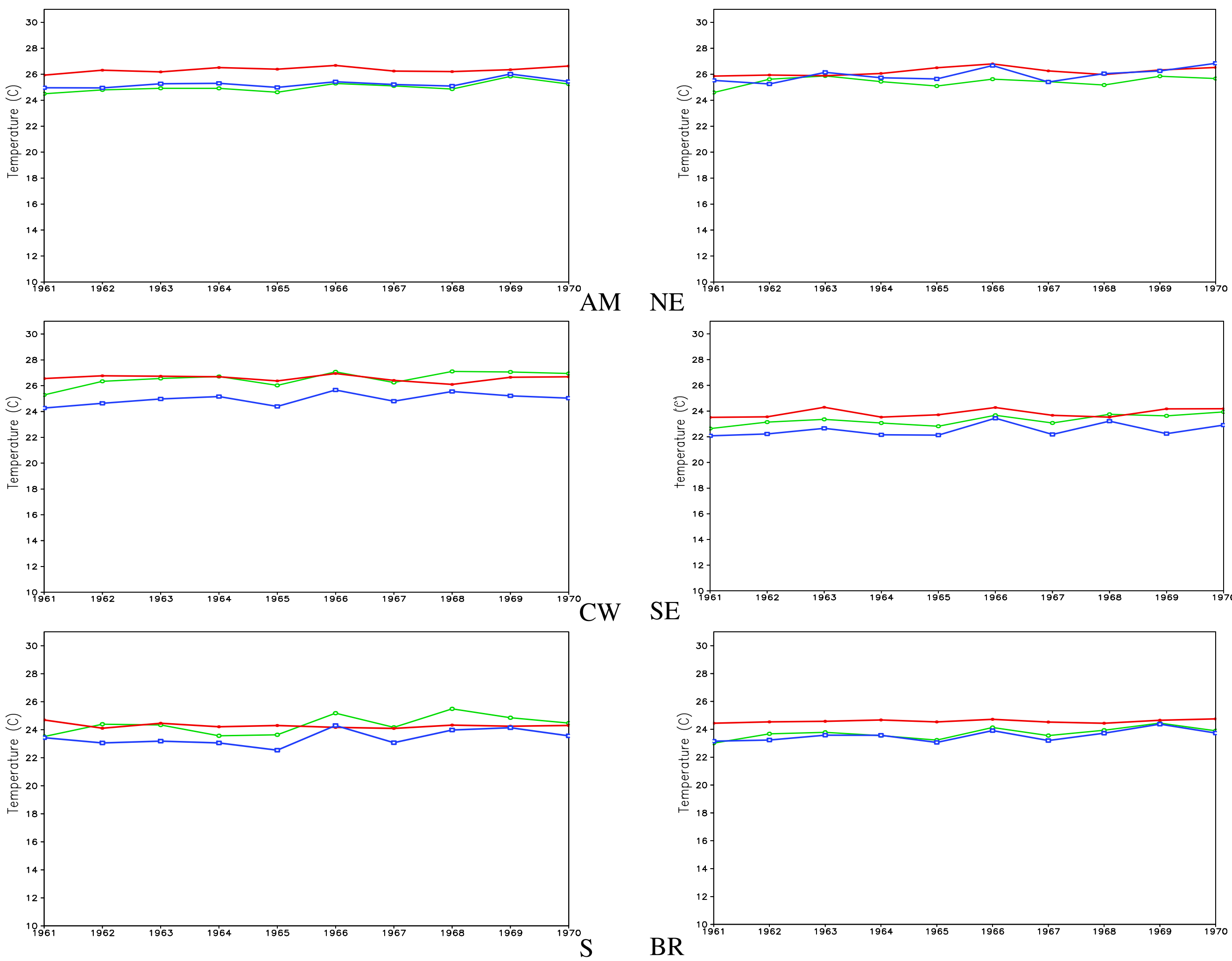



**Fig. 12** DJF interannual temperature precipitation variability (°C) for CRU (*red*), Eta (*green*), and HadAM3P (*blue*) over six regions shown in Fig. 6. *AM* Amazon, *NE* northeastern, *CW* center-west, *SE* southeastern, *S* southern, *BR* Brazil

Figure 12 shows the 1961–1970 interannual variability of temperature for the HadAM3P and Eta models with CRU data during DJF. Similar to precipitation, the interannual variability of temperature simulated by the Eta Model closely follows the HadAM3P simulations in all regions. In general, CRU data show little variability in temperature and the simulations show more variability. The Eta Model simulations more closely follow the observations in the CW, SE, and S regions.

Figure 13 shows the 1961–1970 interannual variability of temperature for the HadAM3P and Eta models with CRU data during JJA. The JJA interannual variability of the Eta temperature simulations closely follows the HadAM3P simulations. In the NE region, results show that HadAM3P more closely follows the observations than the Eta simulations. In general, it can be seen that the Eta Model was advantageous over the S and Amazon regions.

Another way to verify whether the model is able to reproduce the interannual variability is by analyzing the precipitation coefficient of variation (CV) and near-surface temperature standard deviation (Giorgi et al. 2004; Solman et al. 2008), as shown in Table 3. For the precipitation coefficient of variation, in general, the Eta Model has an interannual variability closer to CRU than HadAM3P. The CRU shows higher values of the precipitation coefficient of variation during JJA, because the coefficient is divided by mean precipitation, which is smaller in JJA. Both the Eta and HadAM3P models show similar results, but in general, the Eta variability is closer to CRU and HadAM3P is larger.

The standard deviation of temperature for CRU shows a similar configuration, with DJF values smaller than JJA. According to the CRU data, the differences between DJF and JJA grow from lower to higher latitudes. The Eta and HadAM3P models do not show this growth in the AM and NE latitudes. The Eta and HadAM3P models seem to show

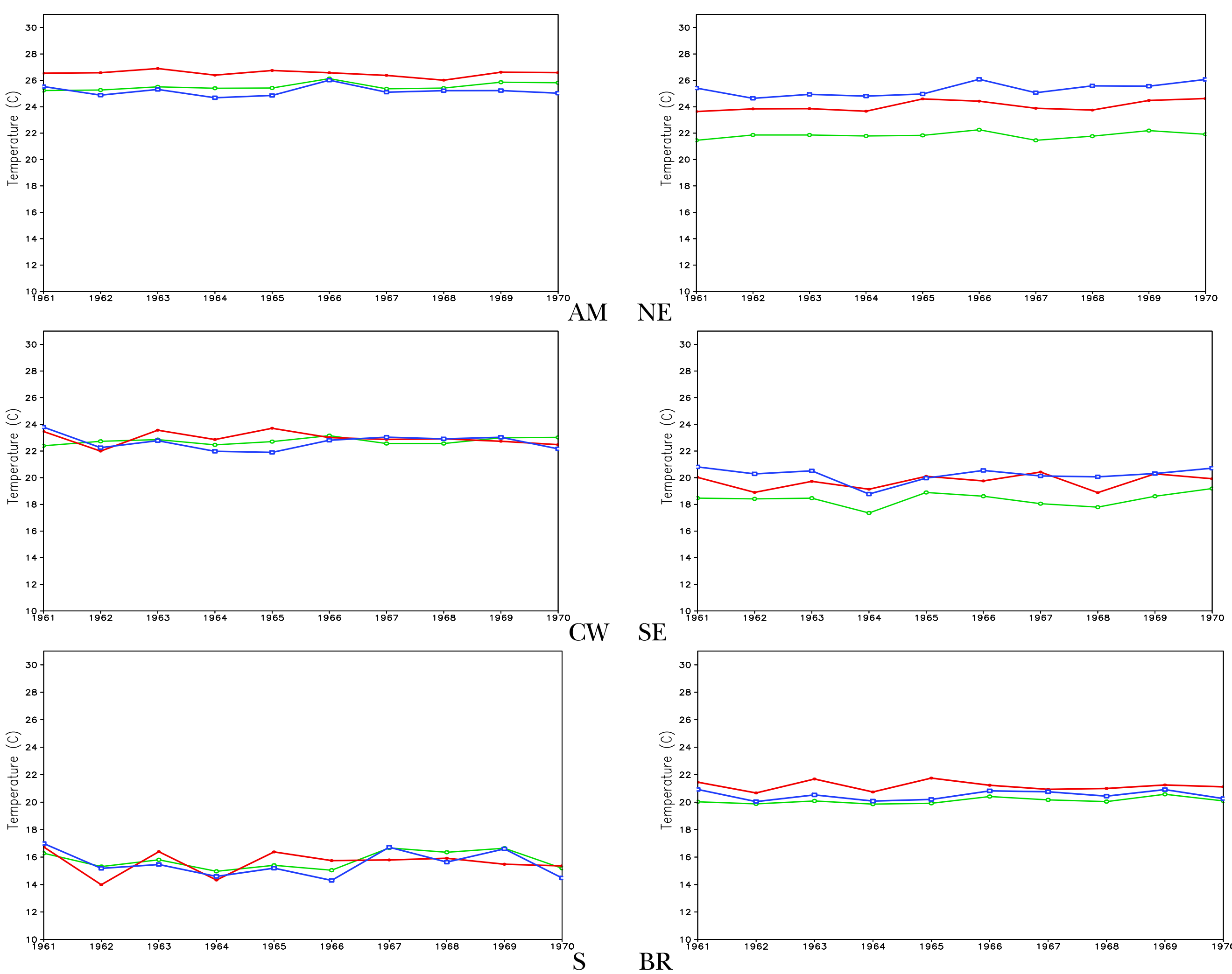



**Fig. 13** JJA interannual temperature variability (°C) for CRU (*red*), Eta (*green*), and HadAM3P (*blue*) over six regions shown in Fig. 6. *AM* Amazon, *NE* northeastern, *CW* center-west, *SE* southeastern, *S* southern, *BR* Brazil

**Table 3** Coefficient of variation for precipitation and standard deviation for near-surface temperature (°C) for both models during DJF and JJA

| | CV (precipitation) | | | Standard deviation (temperature) | | | |
|---|---|---|---|---|---|---|---|
| | Eta | HadAM3P | CRU | Eta | HadAM3P | CRU | |
| AM | **0.27** | 0.60 | 0.30 | 0.61 | **0.42** | 0.46 | DJF |
| | 0.91 | **0.75** | 0.73 | 0.57 | **0.49** | 0.52 | JJA |
| NE | 0.95 | **0.22** | 0.66 | **0.70** | 0.94 | 0.58 | DJF |
| | 1.27 | **1.10** | 0.88 | **0.45** | **0.70** | 0.58 | JJA |
| SE | **0.35** | 0.31 | 0.39 | **0.76** | 0.77 | 0.68 | DJF |
| | **1.01** | 2.22 | 1.05 | **0.80** | 0.98 | 0.81 | JJA |
| S | **0.37** | 1.12 | 0.47 | 1.13 | **1.02** | 0.75 | DJF |
| | **0.61** | 1.85 | 0.59 | 1.26 | **1.35** | 1.37 | JJA |
| CW | **0.33** | 0.43 | 0.32 | 0.89 | **0.75** | 0.52 | DJF |
| | **1.25** | 1.50 | 0.97 | **0.97** | **1.14** | 1.06 | JJA |
| BR | **0.45** | 0.52 | 0.40 | 0.81 | **0.80** | 0.58 | DJF |
| | **0.91** | 1.25 | 0.78 | 0.76 | **0.86** | 0.84 | JJA |
| AS | **0.49** | 0.60 | 0.44 | **0.82** | 0.85 | 0.60 | DJF |
| | **0.82** | 1.17 | 0.72 | 0.74 | **0.82** | 0.81 | JJA |

Bold values are the best scores closer to CRU

higher interannual variability than CRU, but in a few cases, the interannual variability of the HadAM3P is closer to CRU.

## 4 Summary and conclusion

This work shows the results of the regional Eta Model nesting simulation, driven by the HadAM3P model from the Hadley Centre for the period 1961–1970. This 10-year continuous regional simulation is focused on evaluating the capability of the nested modeling system to represent spatial patterns of seasonal mean climate and its annual cycle of precipitation and temperature. One of the goals of this study is to verify if the Eta Model can be used for climate change scenarios and whether the model has the ability to generate added value for South America over HadAM3P simulations. The Eta Model was chosen because there have been few investigations using the Eta Model in long integrations over South America. In addition, the *eta* vertical coordinate is highly recommended for South America due to the steep slopes of the Andes Range.

In this simulation, the regional model reproduced many of the South American mesoscale climate features and introduced a seasonality added value over some areas of South America, mainly over Brazil. For precipitation, the added value was clearly noted during DJF, the austral summer. For near-surface temperature, there was added value for JJA and DJF over most of the regions.

The regional model exhibited better representation of low-level circulation induced by the topography, such as the northwesterly flux whose major features were represented in DJF and JJA. The HadAM3P did not produce a good representation of this system due its low horizontal resolution. At upper levels, the HadAM3P underestimated the magnitude of the jet stream during DJF and JJA over South America, and since these fields were used to drive the Eta Model, it too produced a weaker jet. The Bolivian High in the Eta Model was overestimated due to the high near-surface temperatures simulated during DJF and due to the positive bias in the thermal low pressure over northern Argentina.

The results of the Eta Model were influenced by HadAM3P biases coming from the lateral boundaries, but in some cases, it was possible to verify that the Eta partly showed smaller biases. The annual precipitation cycle of the Eta Model produces better results than the HadAM3P for the first 6 months of the year over the Amazon region; however, both models exhibit lower negative bias for near-surface temperature over this region.

The Eta and HadAM3P models exhibit different systematic errors in their surface climatology due, at least partially, to their different treatments of boundary layer and convective processes. Solman et al. (2008) simulated the MM5 with the HadAM3P for the southern South America climate for the period 1981–1990. They found that the MM5 overestimated the precipitation in the summer and underestimated the precipitation during the winter over southern Brazil. Here, the Eta and HadAM3P models showed smaller bias throughout the year over the same region.

In the work of Solman et al. (2008) over Southern America with the MM5 regional model, it was verified that the regional model performance is generally better during the cold season, while larger biases are found during the warm season. A survey of the literature reveals that the size of errors found here is comparable to that of other regional climate simulations (Solman et al. 2008; Misra et al. 2003; Giorgi et al. 2004). Here, smaller negative temperature biases were found in the wet season (DJF). In general, the Eta errors were smaller than the HadAM3P errors, indicating improvement in the simulations.

Ambrizzi et al. (2007) compared the Eta/CCS model (1961–1974), RegCM3 (1961–1990), and HadRM3P (1961–1990) precipitation results. None of the models showed climatological summer configurations for South America like the ITCZ and SACZ. The current Eta simulations showed better representations of these austral summer configurations. Compared against RegCM3, the current Eta Model also showed better climatological values for summer precipitation. For JJA, all models showed a similar precipitation configuration.

In simulations carried out by Giorgi et al. (2004), it was shown that interannual variability was strongly regulated by boundary conditions during winter months but only weakly in summer months. In summer, mesoscale processes play an important role in regulating the simulated interannual variability. Analyzing the coefficient of variation, the Eta interannual variability is clearly strongly influenced by HadAM3P forcing.

The analysis undertaken in this study does not systematically diagnose the physical explanation for model errors, but it may suggest possible pathways for model improvement (Solman et al. 2008). The nested simulations clearly showed added value over the driven global model. It was found that the present simulations verify reasonably well against observations of temperature and precipitation, and they represent an improvement over the Ambrizzi et al. (2007) results with regional models. The current model setup is therefore considered adequate for application in future climate studies.

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