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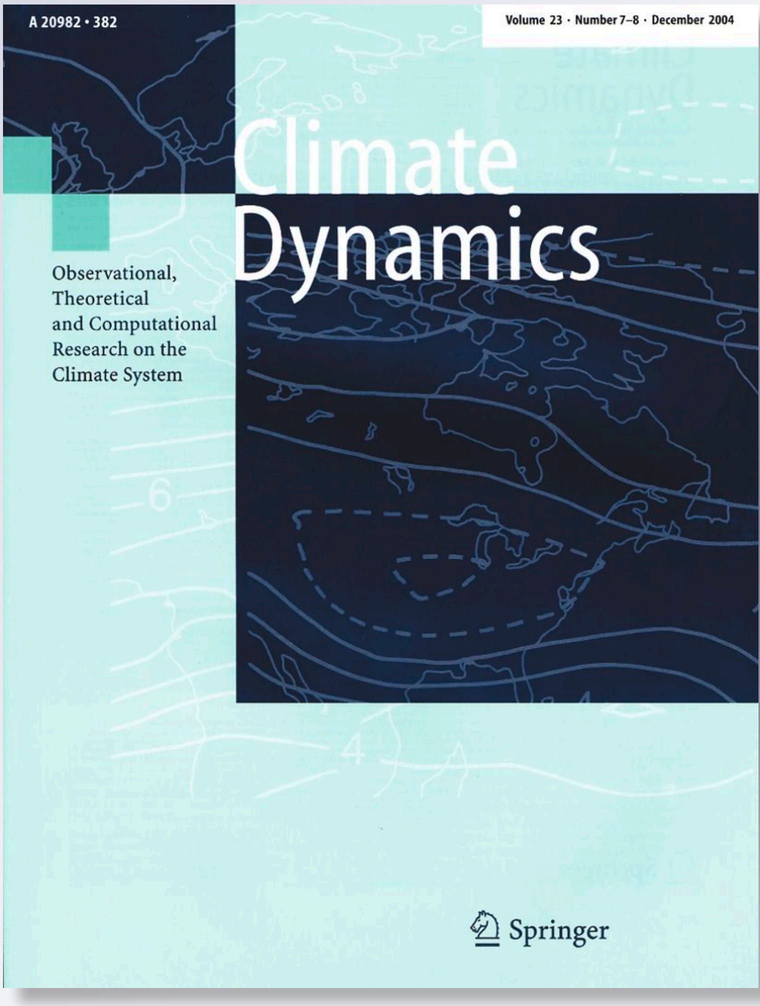

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Regional climate simulations over South America: sensitivity to model physics and to the treatment of lateral boundary conditions using the MM5 model

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Abstract In this study the capability of the MM5 model in simulating the main mode of intraseasonal variability during the warm season over South America is evaluated through a series of sensitivity experiments. Several 3-month simulations nested into ERA40 reanalysis were carried out using different cumulus schemes and planetary boundary layer schemes in an attempt to define the optimal combination of physical parameterizations for simulating alternating wet and dry conditions over La Plata Basin (LPB) and the South Atlantic Convergence Zone regions, respectively. The results were compared with different observational datasets and model evaluation was performed taking into account the spatial distribution of monthly precipitation and daily statistics of precipitation over the target regions. Though every experiment was able to capture the contrasting behavior of the precipitation during the simulated period, precipitation was largely underestimated particularly over the LPB region, mainly due to a misrepresentation in the moisture flux convergence. Experiments using grid nudging of the winds above the planetary boundary layer showed a better performance compared with those in which no constrains were imposed to the regional circulation within the model domain. Overall, no single experiment was found to perform the best over the entire domain and during the two contrasting months. The experiment that outperforms depends on the area of interest, being the simulation using the Grell (Kain–Fritsch) cumulus scheme in combination with the MRF planetary boundary layer scheme more adequate for subtropical (tropical) latitudes. The ensemble of the sensitivity experiments showed a better performance compared with any individual experiment.

Keywords Regional climate modeling · South America · Sensitivity experiments · MM5 model

Abbreviations

MM5	Fifth-generation Pennsylvania-State University-NCAR non-hydrostatic Mesoscale Model
ERA40	European reanalyses
SA	South America
LLJ	Low level jet
LPB	La Plata Basin
SACZ	South Atlantic Convergence Zone
RCM	Regional climate model
AGCM	Atmospheric general circulation model
GCM	General circulation model
LBC	Lateral boundary conditions
PBL	Planetary boundary layer
CRU	Climate research unit from the University of East Anglia
CPC-SA	Dataset for South America on a 1° resolution
CPC-NIJSSEN	Dataset for South America on a 2° resolution
CPC	Climate Prediction Center

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1 Introduction

It has been demonstrated in the literature that regional climate models (RCMs) provide a clear added value with respect to simulations with coarse resolution general circulation models (GCMs), particularly for variables such as precipitation and near surface temperature (Denis et al. 2002; Misra et al. 2003; Giorgi et al. 2004; Solman et al. 2007). Consequently, there is a general consensus that regional climate studies are better achieved using RCMs than using global models. However, when a RCM is used to simulate the climate over a given region, driving data imperfections, regional model configuration and model imperfections may limit the quality of the results. Some of these factors may be associated with systematic biases of the RCM, in consequence, it is important to quantitatively test the sensitivity of the model to different configurations and different combinations of physical parameterizations in order to assess the systematic biases in the simulated climate.

Several studies have dealt with the sensitivity of regional model configuration, particularly to model domain size and location, and to the methodology for ingesting the lateral boundary conditions (LBCs). Model sensitivity to the nesting configuration has been evaluated by de Elía et al. (2007), Alexandru et al. (2007), Miguez-Macho et al. (2005) and Seth and Giorgi (1998) for the North American region and by Seth and Rojas (2003) for South America, among others. These studies highlight that different model configurations may produce reasonable estimates of the regional climate and the choice of a particular one is somewhat arbitrary. Consequently, it seems that different model configurations can give a range of simulated regional climates and this range represents part of the intrinsic uncertainty associated to the simulated climate.

Regarding the nesting technique, the currently most common approach in regional climate simulations consists in a single initialization of the large-scale fields and frequent updates of the LBCs (Giorgi 1990), although the problems of this approach are well documented (Davies 1976; von Storch et al. 2000). The major shortcoming of this approach is that the flow developing within the RCM may become inconsistent with the driving GCM and the internal solution generated by the RCM appears to be very sensitive to the model domain size and location (Miguez-Macho et al. 2005). Recently, several studies have shown that forcing the large-scale parameters within the entire regional domain may prevent the regional simulation from drifting away from the large-scale driving fields and limits the dependence of the simulated climate to domain size and geometry (von Storch et al. 2000; Alexandru et al. 2009; Lo et al. 2008). von Storch et al. (2000) also demonstrated that the spectral nudging technique was successful in keeping the simulated states close to the driving fields at the large scales, allowing more freedom for the smaller scales and decreasing the internal variability of the simulations. However, the spectral nudging approach has several side effects, such as reducing precipitation maxima (Alexandru et al. 2009). These results suggest that a sensitivity study to the treatment of the LBCs would allow identifying one of the sources of model biases.

The sensitivity of RCMs to the choice of physical parameterizations has received considerable attention in the literature. It is generally accepted that the range of validity of the physical parameterizations may be valid only for certain regions and seasons. Moreover, RCMs are often validated for the climates where they have been originally developed, though they are intended to be used over any region of the world, such as the CORDEX international effort (http://wcrp.ipsl.jussieu.fr/SFRCDCORDEX.html). Moreover, even for a given regional domain, the same set of physical parameterizations may not be optimal over the whole area. Consequently, it is important to systematically evaluate the behavior of different parameterizations in a RCM in order to define the set of model physics that simulates the regional climate with the lowest bias, as a first step before using the model to evaluate the response to any forcing. Examination of model biases to different sets of parameterizations can provide a better knowledge of sensitivities and error bounds, providing the basis for reducing uncertainties concerning this particular shortcoming of the dynamical downscaling methodology.

Several sensitivity studies to physical parameterizations including sensitivity to the choice of cumulus parameterizations, planetary boundary layer (PBL) parameterizations, surface schemes and radiation schemes, have been carried out using different RCMs over different regions (Liang et al. 2007; Bright and Mullen 2002 for North America; Ratnam and Kumar 2005 for Southeast Asia; Fernández et al. 2007 for the Iberian Peninsula; Tadross et al. 2006 for South Africa, Seth et al. 2007; da Silva et al. 2010 for South America, among others). Most of these studies conclude that there is no single set of parameterizations that outperforms over the entire regional domain for any season and any variable. Moreover, these studies recognize that the model simulated precipitation is particularly sensitive to the cumulus and the planetary boundary layer parameterizations, though the choice of the land surface scheme is also relevant (Chen and Dudhia 2001).

Up to date, there are a limited number of studies evaluating the sensitivity of RCMs to model physics over South America (SA). In this work, we examine the sensitivity to different combinations of cumulus and PBL parameterizations and different treatments of the LBCs nesting the MM5 model (Fifth-generation Pennsylvania-State

University-NCAR non-hydrostatic Mesoscale Model; Grell et al. 1994) (reanalysis) with the aim of identifying the optimal combination of parameterizations and the best model configuration for climate studies over SA. To achieve this objective, several sensitivity experiments using the MM5 model are presented.

A sensitivity study in long-term climate simulations is an extremely demanding task. In this study we limit our analysis to evaluate the sensitivity of the MM5 regional model to simulate one of the main patterns of intraseasonal variability of precipitation during the warm season over SA: the well known South American see-saw pattern (Nogués-Paegle and Mo 1997). This pattern has a dipole structure where enhanced (reduced) rainfall over the South Atlantic Convergence Zone (SACZ) is accompanied by decreased (increased) rainfall over the subtropical plains of SA, hereafter the La Plata Basin region (LPB). Nogués-Paegle and Mo (1997) showed that this behavior is related to the strength and direction of the low level circulation. In consequence, a proper simulation of the regional circulation is one of the key elements that the regional model should capture in order to reproduce this pattern adequately. The choice of this particular pattern to perform the sensitivity study allows us to evaluate whether several sets of physical parameterizations and nesting methodologies are able to capture not only different climatic conditions over SA in terms of the spatial distribution of rainfall but also one of the dominant patterns of variability associated with well known dynamical forcing features. We focus here mainly on model performance in terms of precipitation because is one of the variables more commonly used as input for impact studies and because the period selected to perform the sensitivity experiments is characterized by a clear differential behavior in the precipitation field, not only in terms of the spatial distribution of rainfall but also in terms of the daily statistics of rainfall over the LPB and SACZ regions.

Finally, it is worth to highlight that in the context of the CLARIS-LPB (*A Europe-South America Network for Climate Change Assessment and Impact Studies in La Plata Basin*) project, a coordinated experiment of regional simulations is being performed in order to characterize the uncertainties in simulating the regional climate over SA. Some preliminary results of this intercomparison exercise are discussed in Sanchez et al. (2010). The MM5 model is one of the regional models participating in this coordinated effort and this work serves as a basis to discuss the limitations of the downscaling exercise over this region.

The structure of this paper is as follows: Sect. 2 describes the general characteristics of the model, the different experiments performed and the data used to drive the model and to evaluate the model performance. Section 3 describes the mean characteristics of the simulated period. Results are presented in Sect. 4. In Sect. 5 a discussion of the results is presented. Section 6 includes a summary of the main findings and the final conclusions.

2 Data and methods

2.1 Description of the model

The MM5 model version 3.6 was used in this study. The integration domain covers most of the South American continent, from the Equator to 50° S and from 88° to 20° W with 130 points in the west–east direction and 160 points in the south–north direction. It was configured on a Mercator projection grid with a resolution of roughly 50 km. In the vertical, 23 sigma levels were used with the model top at 50 hPa. The land-sea mask and topography have been derived from the US Navy 10-min resolution dataset. Vegetation and soil properties were obtained from USGS vegetation/land use data base. Model topography and domain are shown in Fig. 1.

Initial and boundary conditions were provided by the European Centre for Medium-range Weather and Forecasting reanalysis data set (ERA40) (Uppala et al. 2005), available at 1.125° × 1.125° resolution. Boundary conditions were updated each 6-h. Lateral boundary conditions are specified over a boundary relaxation zone covering the outermost five grid points at each side, with a relaxation constant that decreases linearly away from the outermost boundaries. Most of the maps shown hereafter exclude the buffer zones. Sea surface temperature was prescribed from the observed OISST data set (Reynolds et al. 2002) monthly mean values. The land surface model coupled to the regional model also requires additional datasets for initial conditions over land. These include soil temperature and soil moisture at four layers below the surface (0–7; 7–28; 28–100 and 100–289 cm, respectively), prescribed from the ERA40 reanalysis database.

All the simulations in this study were performed using the explicit moisture scheme by Hsie et al. (1984) which includes ice phase processes. The calculation of radiative heating or cooling in the atmosphere accounts for long-wave and short-wave interactions with explicit cloud and clear air. The radiation package calculates long-wave radiation through clouds and water vapor, based on Stephens (1978) and Garand (1983). It also accounts for short-wave absorption and scattering in clear air and reflection and absorption in cloud layers (Stephens 1984). Surface processes are represented by the Noah Land Surface Model (Chen and Dudhia 2001). The land-surface model is capable of predicting soil moisture and temperature in four layers with thicknesses of 10, 30, 60 and 100 cm, as well as canopy moisture and water-equivalent snow depth. The

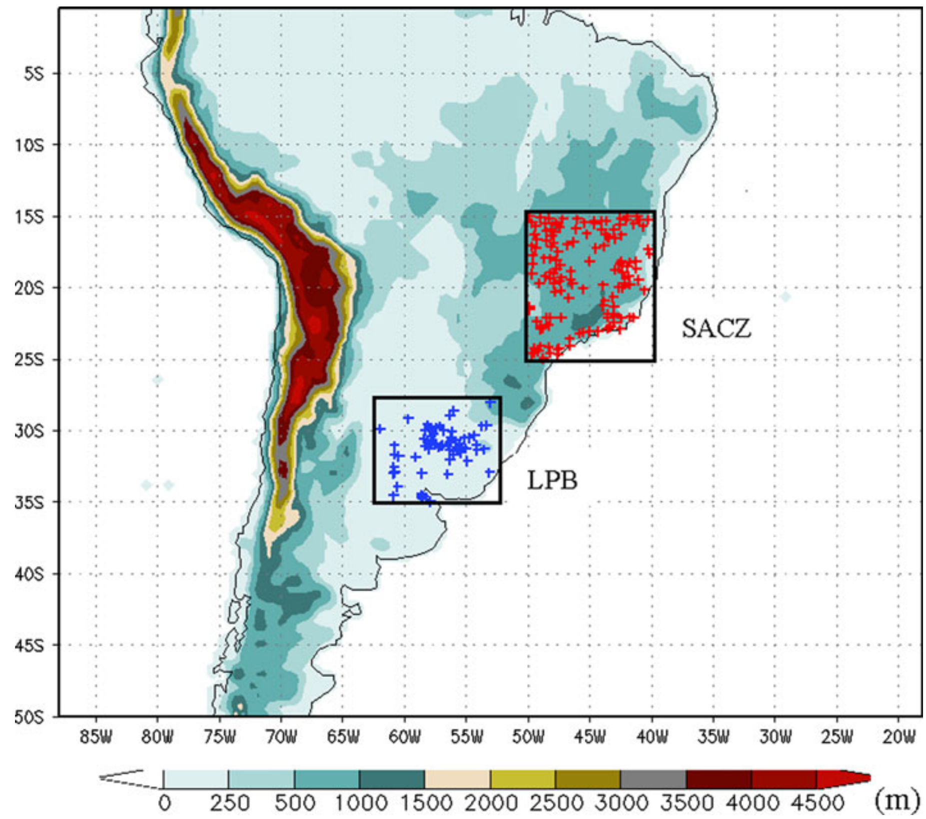

Fig. 1 Model domain and topography (*shaded*). The two *boxes* define the LPB and SACZ regions. The location of station data used in the analysis is also shown

land surface model makes use of vegetation and soil type in handling evapotranspiration, and takes into account variations in soil conductivity and the gravitational flux of moisture.

The PBL schemes account for the interaction between the atmosphere and the surface, handling the latent and sensible heat fluxes into the atmosphere, the frictional effects with the surface and the mixing processes due to turbulent eddies that controls the vertical profiles of winds, temperature and humidity within the PBL. The PBL schemes used in this study are the Mellor and Yamada (1974) scheme as used in the Eta Model (Janjic 1994), hereafter ETA and the Hong-Pan scheme as implemented in the National Center for Environmental Prediction (NCEP) medium range forecast model (hereafter MRF, Hong and Pan 1996). The ETA scheme is a local and one and a half order closure scheme. It predicts turbulent kinetic energy and has a local vertical mixing. The local formulation of the ETA PBL scheme does not allow to adequately model the deep vertical eddies and in consequence it fails in reproducing the vertical profiles of temperature and moisture within the PBL (Bright and Mullen 2002). The MRF scheme is a first-order, non-local scheme based in the Troen and Mahrt (1986) concepts. Sensitivity experiments with this scheme shows a realistic representation of large eddy fluxes within the well-mixed layer by the non-local approach under unstable conditions (Hong and Pan 1996; Bright and Mullen 2002; for experiments over North America; Tadross et al. 2006 for their study over South Africa).

The cumulus convection schemes evaluated in this study are the Kain Fritsch (herafter KF) convective scheme (Kain and Fritsch 1993), an updated version of the Kain Fritsch convective scheme, hereafter KF2 (Kain 2004); the Grell (hereafter GR) convective scheme (Grell 1993) and the Best-Miller scheme (hereafter BM) (Betts and Miller 1993).

The KF, KF2 and GR convective schemes are entraining/detraining mass flux schemes. For KF and KF2 the triggering depends on a temperature perturbation proportional to the grid-scale vertical velocity. The closure assumption is based on the removal of the convective available potential energy (CAPE). Convection rearranges mass in a column using the updraft, downdraft, and environmental mass fluxes until at least 90% of the CAPE is removed. CAPE is computed using undiluted parcel ascent. (Kain and Fritsch 1993). Once KF is activated at any time step in the model, it remains active until CAPE is consumed. The main differences between KF2 and KF are that a minimum entrainment rate is imposed, primarily to suppress convective initiation in marginally buoyant environments and the calculation of CAPE is based on the path of an entraining (diluted) parcel rather than one that ascends without dilution. (Kain 2004). KF2 includes shallow convection.

Table 1 List of the sensitivity experiments performed, indicating the cumulus scheme, PBL scheme, model version (VER) and use of grid nudging (NUD)

	Name of the experiment	Cumulus scheme	PBL scheme	Model version	Grid nudging
1	GR/ETA	Grell	ETA	3.6	No
2	KF/ETA	Kain Fritsch	ETA	3.6	No
3	BM/MRF	Best-Miller	MRF	3.6	No
4	GR/MRF	Grell	MRF	3.6	No
5	KF2/MRF	Kain Fritsch 2	MRF	3.6	No
6	KF/MRF	Kain Fritsch	MRF	3.6	No
7	KF/MRF/VER	Kain Fritsch	MRF	3.7	No
8	KF/MRF/VER/NUD	Kain Fritsch	MRF	3.7	Yes
9	GR/MRF/VER/NUD	Grell	MRF	3.7	Yes

VER indicates that model version 3.7 was used

The GR scheme as implemented in the MM5 model is a simplification of the Arakawa and Shubert scheme (Arakawa and Schubert 1974) and is based on a simple single-cloud scheme with downdraft and updraft fluxes and compensating motion determining heating/moistening profiles. The closure is based on the assumption that the change of the available buoyant energy due to convection offsets the changes due to large-scale destabilization (Grell et al. 1994). The GR scheme checks for its activation at every model time step.

The BM scheme is based on a relaxation adjustment to a reference post-convective thermodynamic profile over a given period. The triggering depends on a lifted-depth criterion which must be overcome by the large-scale vertical velocity. This scheme includes both deep and shallow convection.

2.2 Description of the sensitivity experiments

All model integrations were performed for the period October–November–December 1986, but the results for November and December will be analyzed, allowing 1 month for the model spin-up. It has been shown that 1 month is sufficient to adjust soil conditions over most of SA (Sörensson and Menéndez 2010). A detailed description of the climatic conditions during this particular period can be found in Sect. 3.

The set of experiments performed in this study covers a limited number of combinations among different physics options, nesting techniques and model versions. Concerning the physical options, this study focuses on the combination of different cumulus convection schemes: KF, KF2, GR and BM, and two different PBL schemes: ETA and MRF.

Two versions of the MM5 have been used in this work, namely version 3.6 and 3.7, respectively. Version 3.6 has been used for simulating present climate and for generating regional climate change scenarios over SA (Solman et al. 2007; Nuñez et al. 2009). Version 3.7 was released in December 2004, however, several updates were successively made to this version. We used the most lately updated version, released in October 2006 (3.7.4). It includes several code corrections with respect to previous versions, and some important modifications such as moving the calls to cumulus schemes after the calls to the PBL schemes. This change has an effect mainly on the Grell cumulus scheme that makes use of the updated PBL tendency. Other cumulus schemes are only slightly affected.

Sensitivity experiments to the nesting technique include a set of experiments in which the model is forced only through its lateral boundaries, the common procedure for regional simulations, and experiments in which grid nudging was applied to the winds above the PBL by using a Newtonian relaxation method. This method relaxes the model state toward the observed state by adding artificial tendency terms based on the difference between the two states (Stauffer and Seaman 1990). The parameters controlling the strength of the nudging are those provided by default by the MM5 model. This set of experiments is aimed to evaluate the impact of nudging to constrain the circulation within the regional model domain.

A summary of the sensitivity experiments performed is listed in Table 1. As can be noted, not all the possible combinations of physics options, nesting techniques and model versions, have been carried out. This is mainly due to the sensitivity experiments were designed in order to find the model set up that represent South American climate with the lowest bias. Consequently, progressive changes were made in order to achieve this objective.

2.3 The data

The data used to evaluate the circulation patterns are provided by the ERA40 reanalysis data set. The model precipitation is compared with several precipitation datasets.

Monthly precipitation data provided by the Climate Research Unit from the University of East Anglia (CRU) on a 0.5° grid is used to evaluate the spatial distribution of the precipitation. Additionally, two gridded daily precipitation datasets were used. One of them is a dataset for SA on a 1° resolution (Silva et al. 2007), hereafter CPC-SA. This database was derived based on daily gauge data over SA. We also used a daily precipitation dataset on a 2° global grid (Nijssen et al. 2001), hereafter CPC-NIJSSEN, based on global station observations from the Climate Prediction Center (CPC).

Daily rainfall accumulations from 135 and 89 stations scattered over SACZ and LPB regions, respectively, were also used. The location of the stations is shown in Fig. 1. The station data was provided by several agencies from Argentina, Brazil and Uruguay and compiled by the CLARIS-LPB Project. Due to poor station data coverage over the entire South American continent, the station data was used to evaluate the daily precipitation statistics over the LPB and SACZ regions only. In order to compare daily statistics of station precipitation data with modeled precipitation, the station data was first averaged onto a 0.5° grid, then the daily statistics were calculated and finally the results were averaged over the LPB and SCAZ areas. For the SACZ region we calculated areal averages from 25° to 15°S, 50° to 40°W. For the LPB region, the box was defined from 35° to 28°S and from 62° to 52°W.

The use of different observational datasets of precipitation allows quantifying the level of uncertainty in the observations but also permits to put the spread among the sensitivity experiments in the context of the observational spread.

3 Period description

The simulated period was characterized by contrasting conditions, with anomalous wet (dry) conditions over LPB (SACZ) during November and anomalous dry (wet) conditions over LPB (SACZ) during December. This behavior can be seen in Fig. 2 which displays the monthly precipitation for November, December and the difference (November–December). The pattern of the difference (November–December) resembles the most important

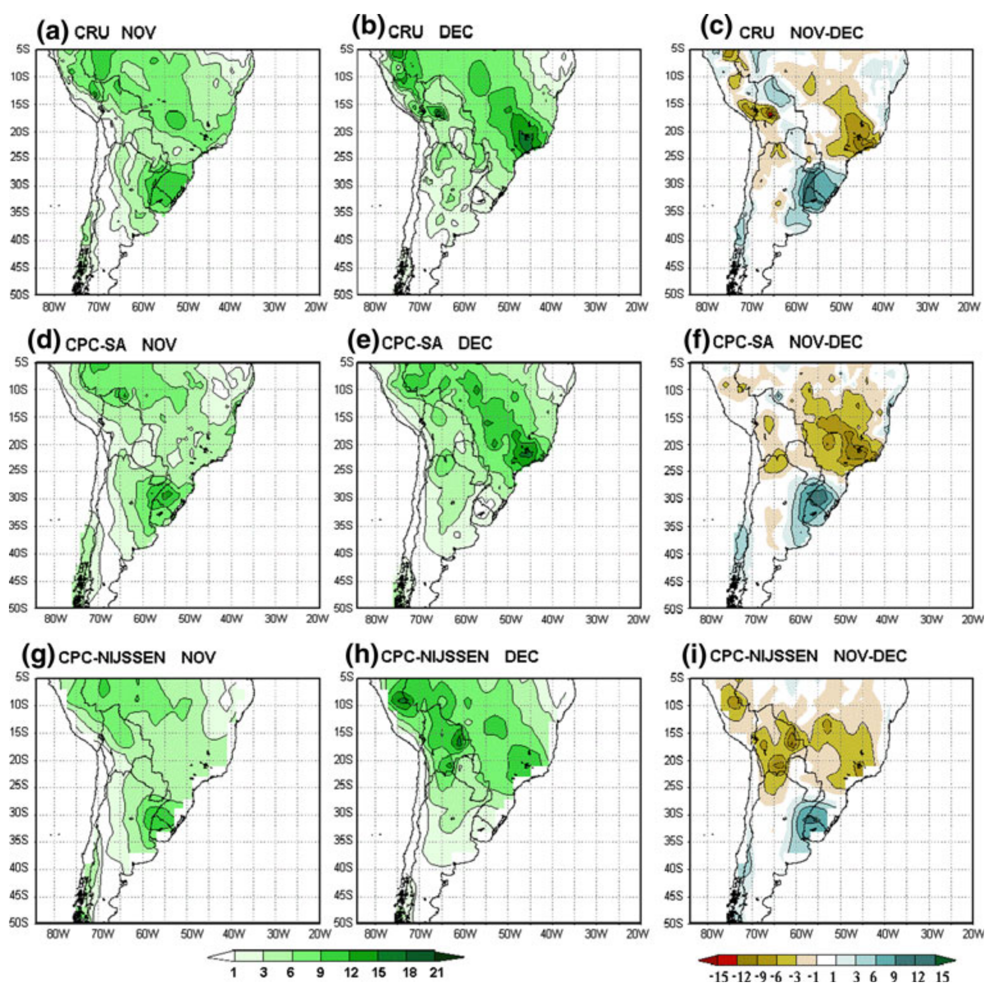

Fig. 2 Monthly precipitation (in mm/day) for November 1986 (*left panels*), December 1986 (*center panels*) and the intraseasonal signal (November 1986–December 1986—*right panels*), as depicted by CRU (**a**, **b** and **c**); CPC-SA (**d**, **e** and **f**) and CPC-NIJSSEN (**g**, **h** and **i**), respectively

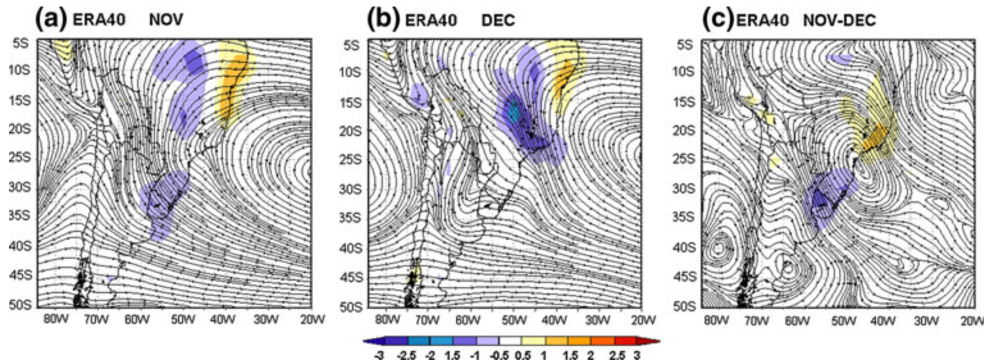

Fig. 3 Moisture flux (streamlines in kg m^{-1} s^{-1}) and moisture flux convergence vertically integrated from 925 to 500 hPa (shaded in kg s^{-1}) from the ERA40 reanalysis dataset for **a** November 1986; **b** December 1986 and **c** November–December 1986

intraseasonal variability pattern of precipitation over SA during the warm season, the well-known see-saw pattern, discussed in the literature (Nogués-Paegle and Mo 1997).

Though all datasets capture the contrasting conditions during November and December over the target areas, there are some differences in the magnitude and location of the regions with maximum rainfall not only for the individual months but also for the intraseasonal signal. In particular, CRU data overestimates the precipitation over the SACZ, compared with CPC-SA and CPC-NIJSSEN databases during November and December. The differences among the gridded precipitation datasets may be due to different reasons. The spatial resolution, the method used to interpolate station data to the regular grid and the number of stations included in the analysis, among others. All these factors contribute to a certain level of uncertainty in the observational datasets that should be taken into account when model simulations are compared against observations.

The moisture flux at lower levels of the atmosphere and its convergence can explain the differential behavior in the precipitation pattern. Figure 3 summarizes the moisture flux vertically integrated from surface to 500 hPa and the moisture flux convergence, from the ERA40 reanalysis dataset for November 1986; December 1986 and the difference between the 2 months. During November, the northwesterly low level jet (LLJ) that extends from the western Amazon Basin southeastward across eastern Bolivia and Paraguay, has a strong southward component, consequently, the moisture flux at lower levels converges over the LPB region. Conversely, during December, the LLJ and the low level moisture flux acquire an eastward direction over southeastern Brazil, and moisture flux converges over the SACZ area. In the anomalous pattern displayed in the November–December field it is quite clear that the positive rainfall anomalies over the LPB are associated with an anomalous anticyclonic circulation over the subtropical Atlantic Ocean, which reinforces the subtropical anticyclone and a cyclonic circulation over southern SA. These circulation anomalies reinforce the northwesterly flow and enhance the moisture transport towards the LPB region, in agreement with previous studies (Liebmann et al. 2004; Solman and Orlanski 2010; da Silva et al. 2010).

It is clear from Fig. 3 that the moisture flux convergence is a key feature inducing the anomalous precipitation pattern. Consequently, the sensitivity experiments will be evaluated taking into account the differential behavior in the precipitation field during November and December but also the differential behavior in the moisture flux field.

4 Results

4.1 The spatial distribution of the monthly mean precipitation and moisture flux

We concentrate first on the sensitivity experiments in which different combinations of PBL and cumulus schemes were performed with the MM5 model version 3.6. Table 2 summarizes the monthly precipitation averaged all over the model domain (SA) and over the target areas, LPB and SACZ, for November, December and November–December as depicted by the sensitivity experiments and observational datasets. The pattern correlation coefficient, calculated with respect to the CRU monthly precipitation field, is also shown. Model simulated precipitation was interpolated to the CRU grid considering the nearest grid point and land-only points were included in the analysis. Figure 4 displays the spatial distribution of simulated rainfall for some selected experiments only, those with the worst and best performance, respectively, in terms of the set of model metrics over SA displayed in Table 2. Accordingly, results from the GR/ETA experiment and the KF/ETA were selected as the worst and best simulations, respectively. Figure 5 shows the difference between November and December for every sensitivity experiment.

Though all the experiments are able to capture the differential behavior of the precipitation field during

Table 2 Mean precipitation averaged all over the model domain (SA) and over the target areas, LPB and SACZ, for November, December and November–December 1986 (mm/day) as depicted by the sensitivity experiments and observational datasets

	SA			LPB			SACZ		
	Nov	Dec	Nov–Dec	Nov	Dec	Nov–Dec	Nov	Dec	Nov–Dec
Experiments									
GR/ETA	1.4	1.6	−0.2	5.2	2.2	3.0	0.4	1.8	−1.4
	(0.16)	(0.13)	(0.50)						
KF/ETA	4.7	5.6	−0.9	3.5	0.9	2.6	3.1	8.2	−5.1
	(0.58)	(0.68)	(0.42)						
BM/MRF	2.5	3.0	−0.5	6.1	2.4	3.7	1.3	6.5	−5.2
	(0.19)	(0.26)	(0.48)						
GR/MRF	2.3	2.9	−0.6	4.4	1.5	2.9	2.2	5.4	−3.2
	(0.25)	(0.38)	(0.39)						
KF2/MRF	6.4	6.9	−0.5	2.4	0.9	1.5	7.8	11.5	−3.7
	(0.53)	(0.64)	(0.24)						
KF/MRF	5.4	6.2	−0.8	3.0	0.7	2.3	5.9	10.4	−4.5
	(0.55)	(0.67)	(0.41)						
KF/MRF/VER	5.6	6.0	−0.4	2.8	0.7	2.1	6.2	10.1	−3.9
	(0.54)	(0.68)	(0.39)						
KF/MRF/VER/NUD	5.3	6.2	−0.9	6.6	1.0	5.6	2.6	8.3	−5.7
	(0.57)	(0.67)	(0.58)						
GR/MRF/VER/NUD	2.9	3.7	−0.8	5.9	2.4	3.5	1.2	6.7	−5.5
	(0.37)	(0.57)	(0.51)						
Observations									
Station data				10.7	1.5	9.2	3.8	9.1	−5.3
CPC NIJSSEN	4.5	5.6	−1.1	8.4	2.1	6.3	4.7	9.0	−4.3
CPC-SA	3.9	4.6	−0.7	8.1	2.0	6.1	3.9	9.1	−5.2
CRU	4.8	5.0	−0.2	8.6	2.3	6.3	5.9	10.7	−4.8

The pattern correlation coefficient, calculated with respect to the CRU monthly precipitation field, is shown in brackets

November–December 1986 (Fig. 5) there are some characteristics that are worth to remark.

The simulations performed using the GR scheme in combination with either ETA or MRF PBL schemes; strongly underestimate rainfall all over the model domain during November and December (Table 2). This systematic underestimation is particularly remarkable over tropical areas, as can be noted from Fig. 4. This underestimation is partially corrected when using the MRF PBL. The pattern correlation coefficients corresponding to these simulations for November and December certainly denote a very poor quality of the simulations in terms of reproducing rainfall patterns for each individual month. Though the correlation coefficient for the intraseasonal signal for the GR/ETA experiment is large, inspection of Fig. 5 indicates that this experiment underestimates strongly the amplitude of the intraseasonal signal, mainly over the SACZ area.

Possible reasons for the systematic underestimation of rainfall over tropical areas with the GR scheme can be associated with the assumptions underlying this parameterization. The GR cumulus scheme is activated in the model every time-step, consequently, the model tends to develop convective cumulus to reduce the instabilities as fast as the large scale produce them, producing short-lived clouds with relative small amounts of convective rainfall. Moreover, in the GR scheme convection is activated after a lifting depth trigger is reached, which is prescribed to 50 hPa in the MM5 model. This parameter controls the decision point that determines whether deep convection occurs. Yang and Arrit (2002) found that the amount of convective precipitation was sensitive to this parameter using the RegCM3 regional model over North America and showed that larger values of the lifting depth allows for more frequent activation of the scheme.

The improvement of GR/MRF experiment over tropical areas may be due to the non-local formulation of the MRF PBL scheme, which tends to produce a warmer and deeper convective boundary layer than the local formulation of the ETA PBL scheme, which allows for larger eddy fluxes

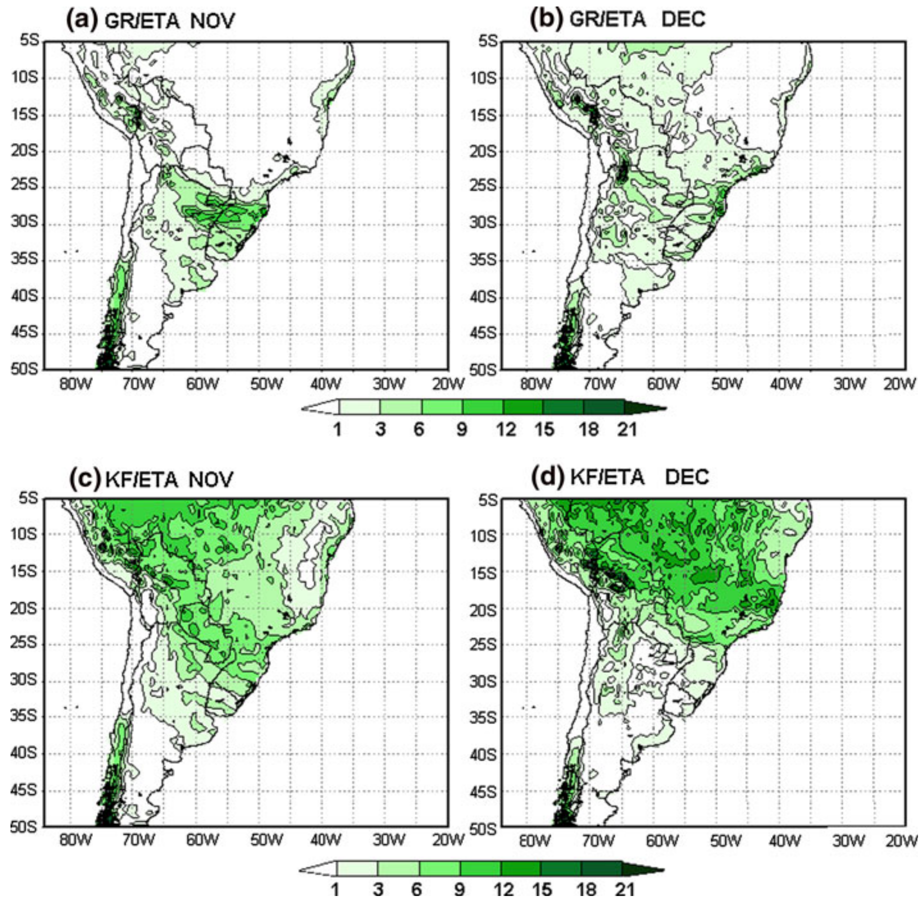

Fig. 4 Monthly precipitation (in mm/day) for the experiment with the worst (*top panels*) and best (*bottom panels*) performance during November and December 1986, respectively, based on metrics displayed in Table 2. **a** and **b** for GR/ETA; **c** and **d** for KF/ETA. Monthly precipitation larger than 1 mm/day is *shaded*

within the well-mixed layer and improved representation of moisture and temperature profiles within the PBL. These results are consistent with the original investigation of Hong and Pan (1996) and Tadross et al. (2006).

The BM scheme also shows a poor performance for the individual months as for the intraseasonal signal shown in Fig. 5, mainly due to a strong underestimation of rainfall over tropical areas (not shown). The convective triggering formulation may be not sufficient to activate the scheme, leaving a more instable environment, indicating a deficiency in adequately representing the extent of convective activity in tropical regions, in agreement with results from Gochis et al. (2002).

Simulations using KF in combination with MRF and ETA PBL schemes and KF2 simulate large rainfall amounts over most areas of tropical SA compared with those using GR and BM, but fail in simulating the precipitation maximum over Uruguay and over southern Brazil during November (Fig. 4). Using KF and KF2 (not shown) the model systematically simulates a band of maximum precipitation shifted northward (located over southeastern Brazil and eastern Paraguay) compared with the observations. During December, when rainfall is enhanced over the SACZ area, simulations using KF reproduce reasonably well both the spatial pattern and the rainfall amount. The experiments using KF with either ETA or MRF are quite similar, though the experiment KF/MRF systematically increases (reduces) precipitation compared with KF/ETA over SACZ (LPB), probably due to the greater ability of the MRF scheme to develop deeper vertical eddies, which are important to start convection, particularly over the SACZ region (see Table 2). The experiment using KF2 strongly overestimates rainfall over tropical regions.

The differences in the triggering mechanisms and the closure assumptions among GR, BM and KF cumulus schemes may explain why the KF scheme systematically produces more rainfall over tropical regions, where the vertical instabilities are more likely to pass the triggering threshold. Furthermore, the release of CAPE during a period of time once convection is triggered, allows for convective events lasting longer. Nevertheless, given the complexity of nonlinear interactions between various physical processes, it is extremely difficult to identify which formulation in each parameterization is likely to fully explain the differences in the results.

Concerning the intraseasonal signal displayed in Fig. 5, the experiments using KF (KF/ETA and KF/MRF) and KF2/MRF reproduce reasonably well the location of the negative anomaly over the SACZ area, though the

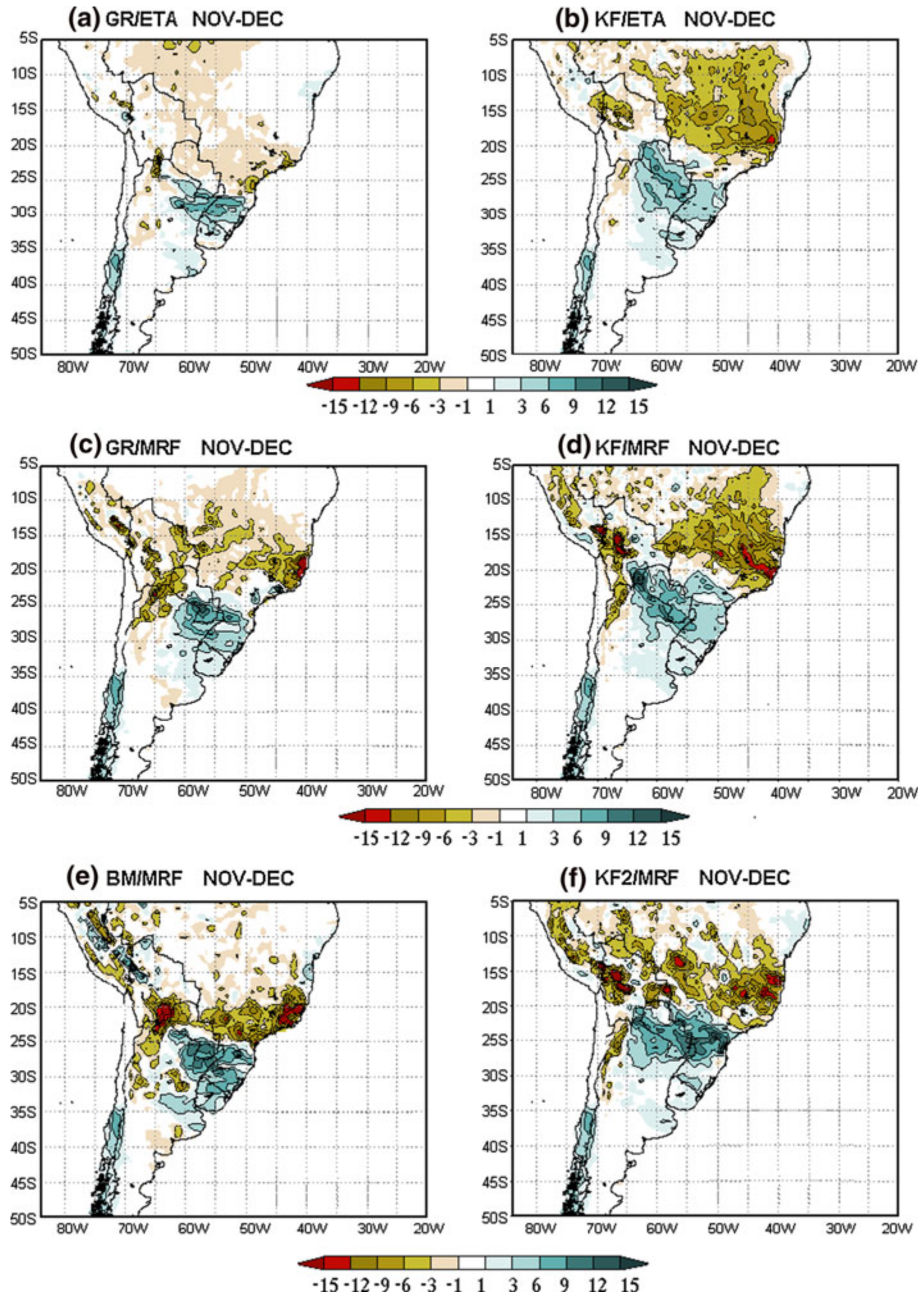

Fig. 5 Difference between November and December 1986 precipitation (in mm/day) for the sensitivity experiments: **a** GR/ETA, **b** KF/ETA, **c** GR/MRF, **d** KF/MRF, **e** BM/MRF and **f** KF2/MRF. Negative values (below −1 mm/day) are shaded in *blue* and positive values (above 1 mm/day) are shaded in *brown*

amplitude is slightly overestimated. However, these experiments fail in reproducing the location of the positive anomaly over the LPB region, which is shifted northwards compared with the observations. Conversely, the experiments using GR (GR/ETA and GR/MRF) and BM/MRF are capable of reproducing the location and intensity of the positive anomaly over the LPB region but fail in reproducing the negative anomaly over the SACZ area.

Overall, the simulation of rainfall is very sensitive to the PBL and convective schemes selected in the model, moreover, no single experiment perform the best over the whole domain and during the two selected months analyzed. It is interesting to note from Table 2 and Fig. 4 that the experiments using the KF (GR) scheme systematically represent better the precipitation pattern over tropical (subtropical) areas though underestimate rainfall over the subtropics (tropics).

Similar sensitivity experiments using the MM5 model were performed over other regions in the world. Ratnam and Kumar (2005) evaluated the sensitivity to cumulus parameterization in the simulation of the Indian Monsoon during two contrasting years (wet and dry, respectively) and found that using the BM scheme less (more) rainfall was simulated during the dry (wet) period and using the GR (KF) scheme rainfall was underestimated (overestimated) during both periods. Tadross et al. (2006)

performed a set of sensitivity experiments to cumulus and PBL schemes over southern Africa for two contrasting years and found that using the BM (KF) scheme the model systematically underestimates (overestimates) rainfall. In a very complete sensitivity study performed over the Iberian Peninsula, Fernández et al. (2007) performed several 5-years simulations using different combinations of physical parameterizations. They found that using the KF (GR) scheme summer precipitation is generally overestimated (underestimated). Overall, comparing the results summarized in Fig. 4 and Table 2 with these studies, it seems that the sensitivity to cumulus schemes using the MM5 model for different regions of the world seem to have a similar behavior.

Figure 6 displays the moisture flux and moisture flux convergence for the experiments KF/MRF and GR/MRF, respectively. These two experiments are displayed for brevity, because they summarize the main differences in the simulated moisture flux between the experiments using KF and the experiments using other cumulus schemes. Results from KF/ETA and KF2/MRF are similar to KF/MRF while results from BM/MRF and GR/ETA are similar to GR/MRF (not shown). During November, both KF/MRF and GR/MRF simulations reproduce the general characteristics of the circulation pattern, however, in KF/MRF the moisture flux acquires a cyclonic curvature over northern Argentina (at around 20°–25°S, 60°–65°W) which is not realistic (Fig. 3). In both simulations the moisture flux convergence is located out of the LPB region. The simulation using KF/MRF shows that the moisture flux converges over eastern Paraguay and southeastern Brazil where a large amount of precipitation is simulated. For the simulation using GR/MRF the moisture flux converges mainly over northeastern Argentina–southeastern Paraguay in agreement with the maximum precipitation simulated over that area. During December, the simulation using KF/MRF completely misrepresents the low level circulation over southeastern SA, with a spurious cyclonic circulation over northern Paraguay. However, the moisture flux convergence is located at a similar position compared with ERA40. The simulation using GR/MRF captures reasonably well the circulation pattern and the moisture flux convergence over the SACZ area, but its intensity is strongly underestimated. The difference between November and December summarizes the capability of these experiments in reproducing the intraseasonal variability pattern of the low level circulation. It is clear that though the anomalous anticyclonic circulation over the eastern coast of SA centered at 25°S, 50°W is fairly well reproduced, the pattern of moisture flux convergence is poorly represented by either the simulations using KF/MRF or GR/MRF.

In summary, the misrepresentation of the precipitation field using GR or KF cumulus schemes may be associated not only with particular details concerning how each parameterization works but also on how the interaction between the dynamics and physical processes are dealt with in the model.

These results motivated three additional sensitivity experiments: to model version, and to the treatment of LBCs using the KF/MRF and the GR/MRF schemes. From Table 2, it is worth to note that the KF/MRF/VER experiment has a similar performance compared with KF/MRF and KF/ETA. The spatial distribution of precipitation (not shown) is actually very similar, particularly compared with KF/MRF. However, it is noticeable from Table 2 and Fig. 7, that the experiments using grid nudging, KF/MRF/VER/NUD and GR/MRF/VER/NUD (see Table 1 for reference), improve the main shortcomings of the experiments using GR/MRF and KF/MRF, respectively. The KF/MRF/VER/NUD experiment improves the simulation of the maximum rainfall over the LPB region during November and the intraseasonal signal of precipitation both concerning the spatial distribution and the intensity of the rainfall anomalies, compared with other sensitivity experiments. The GR/MRF/VER/NUD experiment improves the model performance compared with the GR/MRF simulation over both tropical and subtropical SA. The improvement over tropical areas may be due to the GR scheme is called after the MRF PBL scheme in the updated version of the model, leading to more frequent activation of the cumulus scheme; however, it still underestimates rainfall amounts. The improvement in reproducing rainfall over subtropical regions in both GR/MRF/VER/NUD and KF/MRF/VER/NUD experiments is largely due to the improvement in the simulated pattern of moisture flux and moisture flux convergence, as can be noted from Fig. 6. These results agree with the findings in Lo et al. (2008) who showed that applying nudging significantly improves the precipitation simulation.

In summary, it is clear that the monthly average rainfall over LPB is underestimated by every sensitivity experiment mainly during November. For SACZ, every experiment underestimates the total precipitation amount during November and December with the exception of those experiments using the KF and KF2 cumulus convective schemes. The experiments using grid nudging improve the performance of the model over most of SA.

4.2 Daily precipitation statistics

The period selected to perform the sensitivity experiments to different regional model's set up and parameterizations is interesting because of various reasons, largely discussed in previous sections. However, it is worth to remark that the anomalous behavior of the precipitation over LPB and SACZ during the austral warm season associated with the

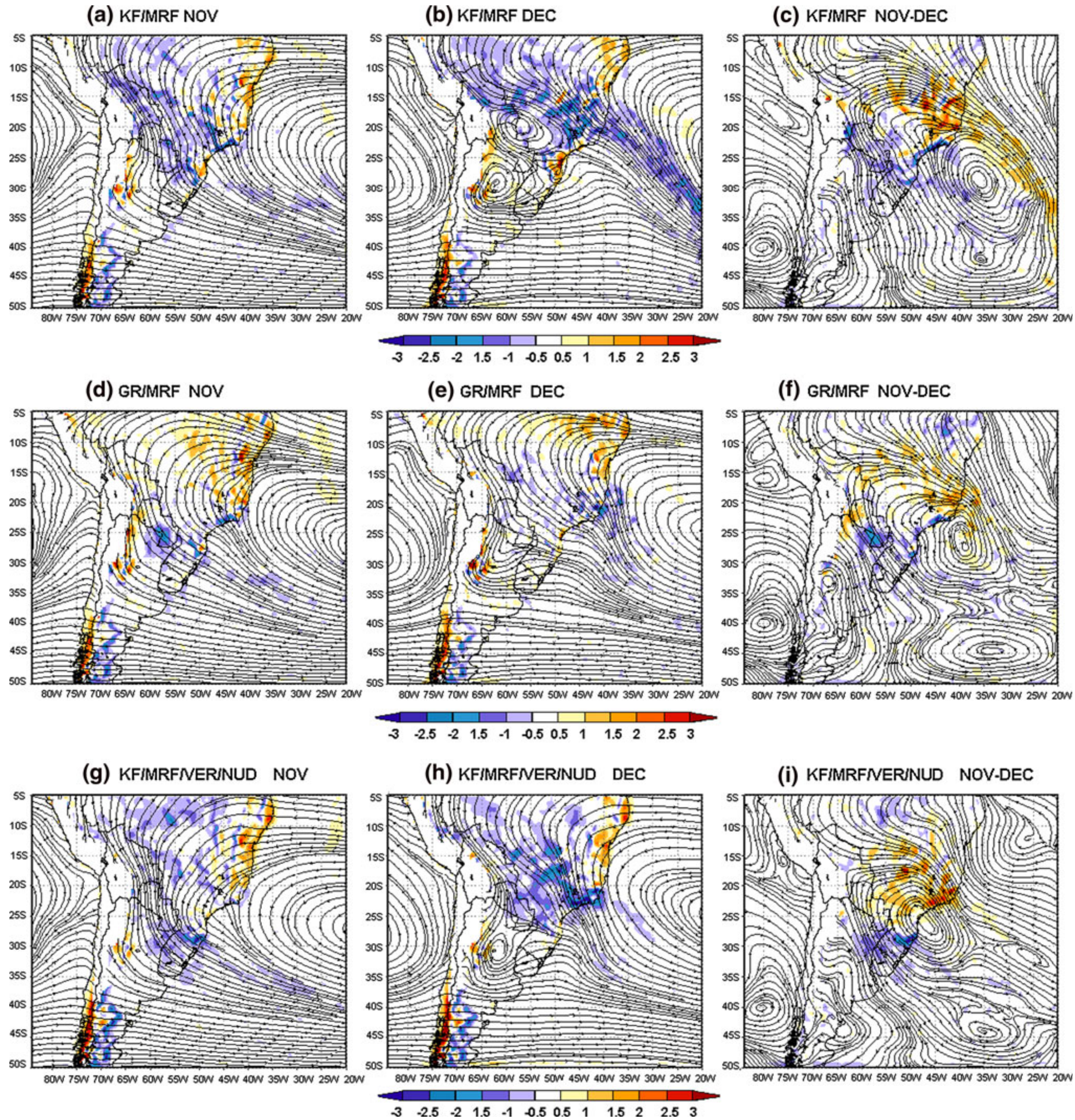

Fig. 6 Same as Fig. 3 but for the experiments KF/MRF (**a**)–(**c**); GR/MRF (**d**)–(**f**) and KF/MRF/VER/NUD (**g**)–(**i**), respectively

intraseasonal variability pattern is mainly related to the behavior of the convective activity and, consequently, the occurrence of moderate to heavy individual precipitation events (Liebmann et al. 2004; Silva and Berbery 2006). Consequently, our discussion in this section focuses on evaluating the performance of the set of experiments in terms of daily precipitation statistics over LPB and SACZ in order to understand the biases in the simulation of monthly rainfall discussed previously.

We concentrate first on the evaluation of model performance in terms of the wet day frequency. The number of days with precipitation larger than 1 mm was calculated at each grid point and then averaged over the LPB and SACZ areas for each experiment. Figure 8 displays the results for both experiments and observations. Alternating wet (dry) and dry (wet) conditions for November and December, respectively, over LPB (SACZ) are clearly evident in terms of the wet day frequency from observations. However,

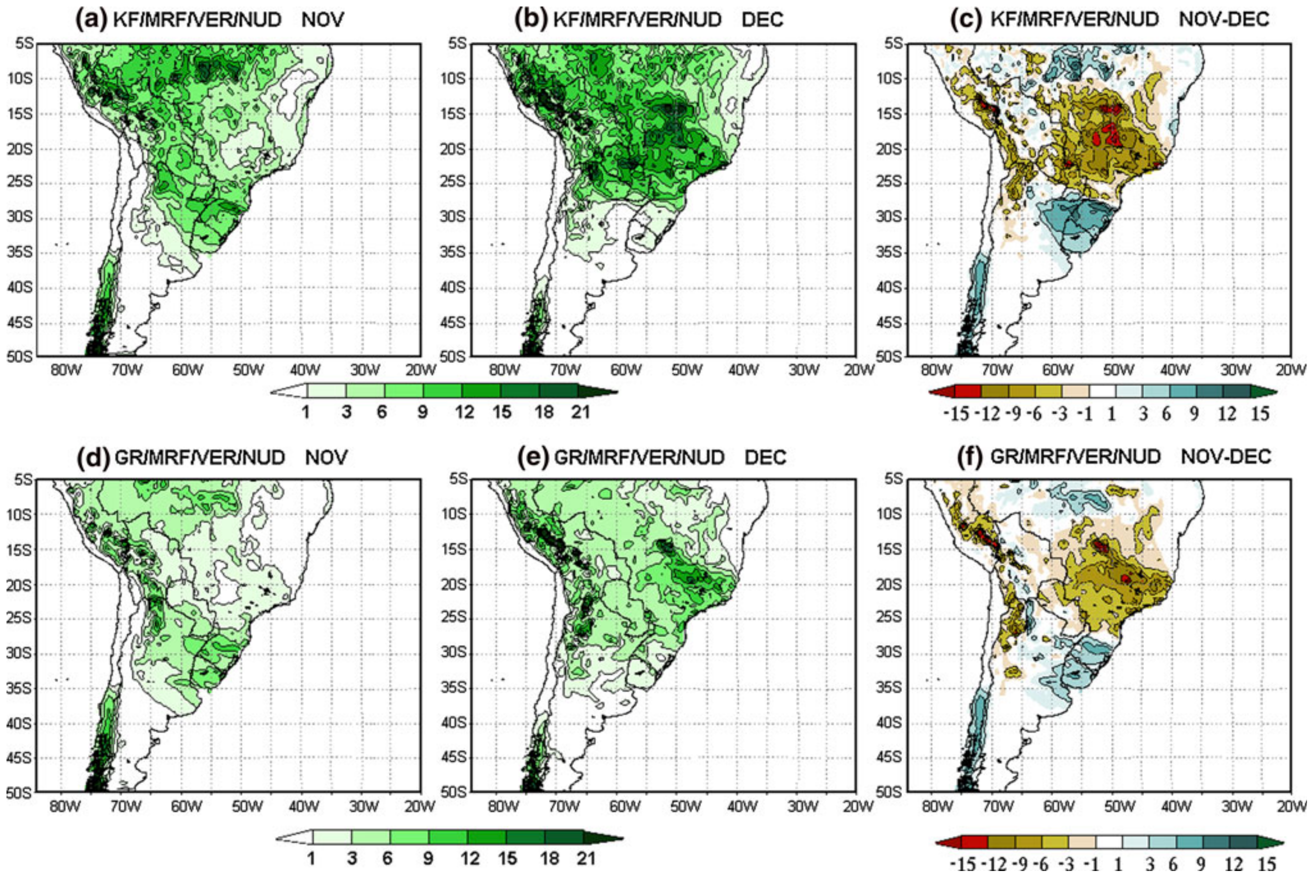

Fig. 7 Same as Fig. 2 but for the experiments using KF/MRF/VER/NUD (**a**)–(**c**) and GR/MRF/VER/NUD (**d**)–(**f**), respectively

there are large differences among the gridded observational datasets and station data. It is worth to remark that the CRU dataset displays the largest values of wet day frequency over SACZ compared with the other observational datasets.

Every sensitivity experiment captures the contrasting behavior over the LPB and SACZ regions during November and December. Over the LPB region, there is a general good agreement between the wet day frequency depicted by the experiments and observations, suggesting that the systematic underestimation of the total rainfall amount may be due to the underestimation of amount of precipitation for individual rainy events. In particular, the differences among each experiment and the station data are within the same range compared with the differences among different observational datasets. For the SACZ region the experiments using KF show the best agreement with observations. However, the spread among the sensitivity experiments is smaller than that in the observational datasets, making it difficult to draw a conclusion about the experiment that outperforms in terms of this particular metric.

In order to identify how individual rainy events are simulated, frequency diagrams of daily precipitation were built, taking into account the frequency of occurrence of rainy events within several intervals, representing light (1–5 mm day^{-1}), moderate (5–30 mm day^{-1}), and heavy (more than 30 mm day^{-1}) precipitation days, in a similar way as in Menéndez et al. (2010). The results are displayed in Fig. 9.

The contrasting behavior of precipitation over LPB and SACZ during November and December can be distinguished from the frequency distribution of rainfall rates as depicted by the observational datasets, however, several discrepancies among different observational datasets are apparent. For LPB (Fig. 9a, b), the wet period (November) is characterized by higher frequencies of moderate and heavy precipitation events compared with the dry period (December) in which higher frequencies of occurrence of light precipitation events occurs. The station data displays higher (lower) frequencies of heavy (light) precipitation events, compared with CPC-SA and CPC-NIJSSEN, probably due to the gridded precipitation datasets systematically overestimate (underestimate) the number of light (heavy) precipitation events as a consequence of the spatial interpolation and the number of the station data used. Recall that the CPC-NIJSSEN and CPC-SA are on a 2° and 1° regular lon-lat grid, respectively, and the station data is on a 0.5° lon-lat grid, comparable to the model resolution.

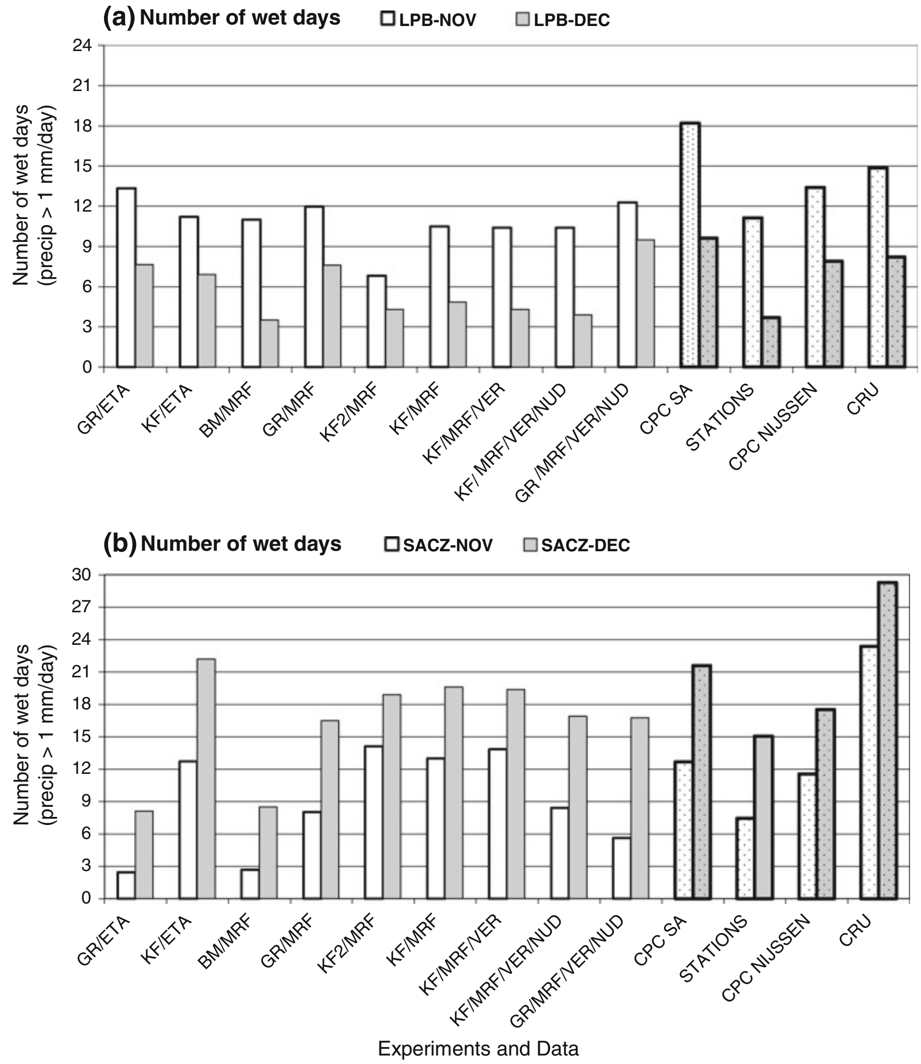

Fig. 8 Number of wet days (precipitation larger than 1 mm/day) during November 1986 and December 1986 for LPB (**a**) and SACZ (**b**) as depicted by the sensitivity experiments and the observational datasets

Concerning the sensitivity experiments, almost all the experiments capture the frequency distribution of rainfall rates over LPB. Moreover, most of the experiments overestimate the frequency of light precipitation events and underestimate the frequency of moderate rainy events when compared with any observational dataset. The heavy precipitation events are fairly well simulated. These results agree with those presented in Menéndez et al. (2010) in which an intercomparison of different regional models over SA were evaluated.

For the SACZ area the observational datasets show that the dry (wet) period is characterized by higher frequencies of light (moderate) precipitation events. As for the case of LPB, station data has more days with heavy precipitation and less days with light precipitation compared with the gridded datasets. The sensitivity experiments show good agreement with observations, with the exception of the experiments using the GR convective scheme, which systematically overestimate (underestimate) the frequency of light (moderate and heavy) precipitation.

The experiment using KF/MRF/VER/NUD seems to perform the best, in terms of the daily precipitation statistics over both the LPB and SACZ regions.

It is important to keep in mind that the period for the evaluation of model performance spans only over 2 months, and the number of rainy events may be not large enough. However, results reported here agree with those presented by Boberg et al. (2009a) who evaluated the ability of different RCMs in reproducing the rainfall distribution over Europe for a 30-year period. They found that most of the RCMs overestimate (underestimate) the frequency of days with light (heavy) precipitation rates.

5 Discussion: which is the best model set up for simulating regional climate over SA?

One of the aims of this study is to find the best model set up and configuration to perform long-term simulations using the MM5 model over SA. In order to achieve this objective,

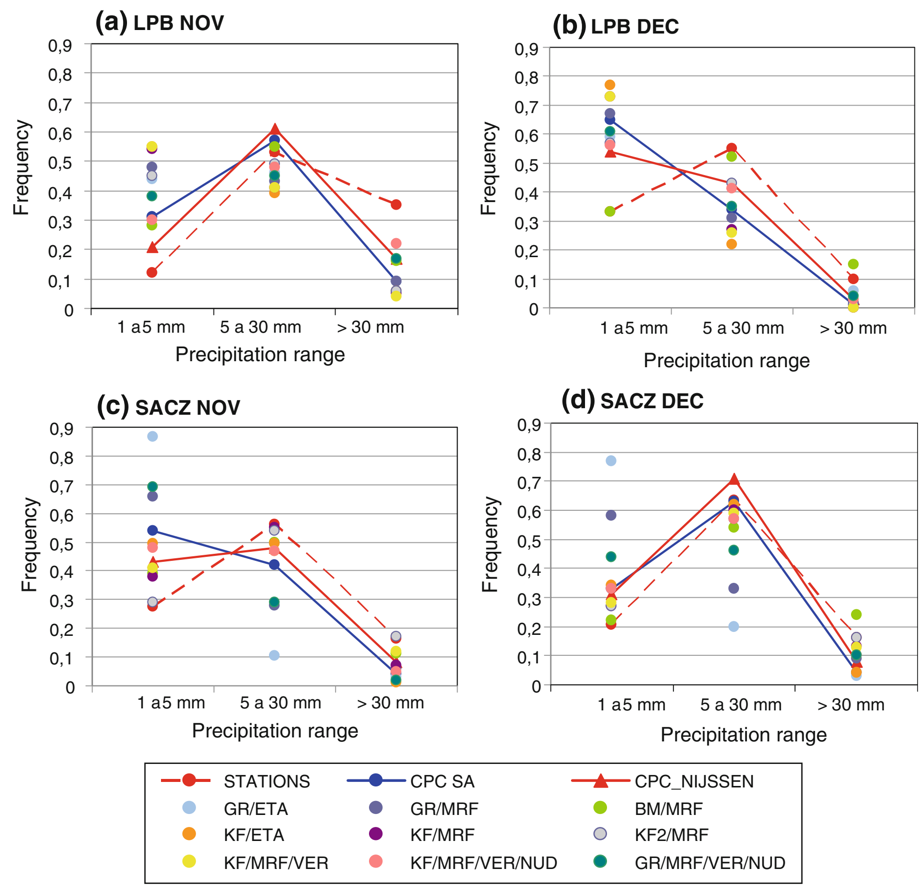

Fig. 9 Frequency distribution of precipitation for light (1–5 mm), moderate (5–30 mm) and heavy (more than 30 mm) daily rainy events for LPB (**a**, **b**) and SACZ (**c**, **d**) during November and December 1986, as depicted by observations and sensitivity experiments

if this is possible, several measures of model performance in terms of both the spatial patterns and daily statistics of rainfall are quantified in this section.

The relative difference between the simulated monthly precipitation for November and December at each grid point and CRU was calculated and Fig. 10a shows the experiments depicting the smallest relative difference, only if the relative difference was less than 25% at each grid point during the 2 months. The first thing to note is that there are several regions for which no experiment fulfills the condition of relative errors being less than 25% for the whole period. Moreover, for those regions where this threshold is satisfied, no single experiment fulfills the quality criteria. However, it is clear that over tropical SA, the experiments using KF/MRF, KF/MRF/VER and KF/MRF/VER/NUD satisfy the quality criteria more broadly and over subtropical areas, there is a prevalence of the experiments using GR/MRF/VER/NUD and KF/MRF/VER/NUD. Overall, it seems that no single set of parameterizations is capable of reproducing with the lowest error the climate conditions over the whole South American continent. These results are similar to those obtained by Fernández et al. (2007) who also showed that depending on which variable is being evaluated, the idea of finding the optimal model configuration seems to be a difficult task.

The conclusion drawn from Fig. 10a suggests that an ensemble of the sensitivity experiments may perform better than any individual experiment. The ensemble approach using multiple model formulations has been proved to be useful for climate prediction (Palmer et al. 2005) and for modeling regional climate (Yang and Arrit 2002; Menéndez et al. 2010). The ensemble mean, calculated as the mean of every sensitivity experiment has been included in Fig. 10b. It is clear that there is a widespread predominance of the ensemble fulfilling the quality criteria, indicating, as expected, that the ensemble of experiments depicts superior skill compared with any individual simulation, probably due to compensating errors of individual simulations.

Focusing on the LPB and SACZ regions, it is worth to perform also a quantitatively evaluation in terms of the different metrics of model performance of daily precipitation statistics. As already stated in previous sections, every statistical metric of daily precipitation is characterized by a large observational uncertainty (see Figs. 8, 9). Consequently, an ensemble of the observations was calculated and compared with every sensitivity experiment, in terms of three precipitation metrics averaged over the target regions: the monthly precipitation, the wet day frequency and the frequency distribution of rainfall rates. The

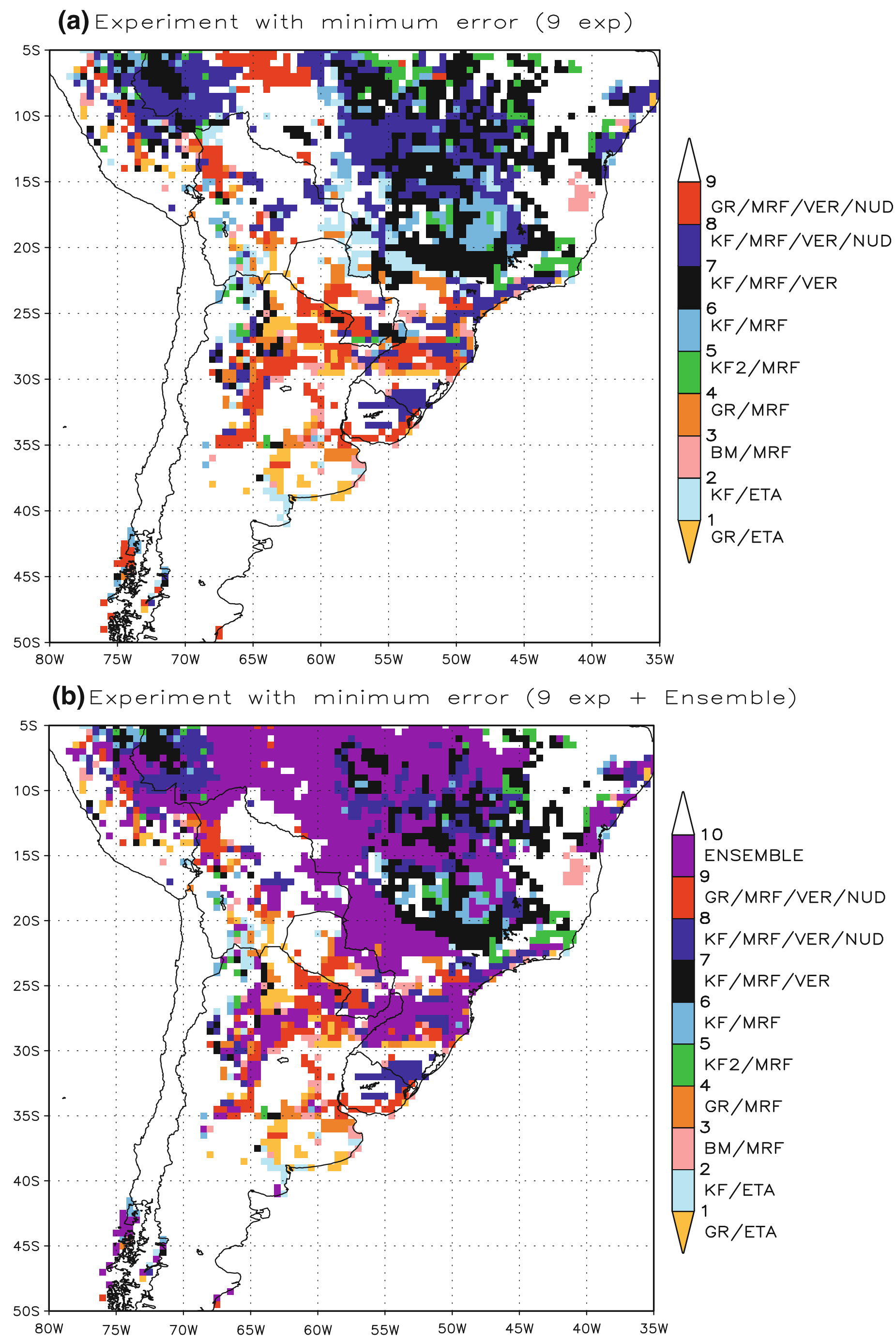

Fig. 10 **a** Experiment depicting the minimum relative error of monthly precipitation for November and December, only if the relative error was less than 25% compared with CRU, considering the experiments listed in Table 1. **b** Same as **a** but including the ensemble of experiments

difference between each experiment and the ensemble of observations was computed for LPB and SACZ for November and December and the experiments depicting relative differences of less than 25% for the 2 months for the set of metrics are indicate in Table 3.

In agreement with the results presented in Fig. 10, no experiment outperforms taking into account every evaluation measure in neither LPB nor SACZ areas. However, the experiments using KF/MRF seem to fulfill the quality criteria more often, considering the set of metrics in Table 3, particularly for the SACZ region, while the experiment GR/MRF/VER/NUD, agrees better with the ensemble of observations over LPB. These results reinforce the ideas stated in previous sections, indicating that the best parameterization combination cannot generally be set. However, these results may contribute for designing an experimental set up to simulate regional climate over SA with the MM5 model. Though the best model set up depends on the region, the experiments using grid nudging seem to perform better compared with those experiments in

Table 3 Experiments depicting a difference with respect to the ensemble mean of observations of less than 25% for November and December in terms of the monthly precipitation, the number of wet days and the frequency of occurrence of light (1–5 mm), moderate (5–30 mm) and heavy (>30 mm) precipitation events over LPB and SACZ

Sensitivity Experiment	Mean		Wet days		Precipitation range (mm)					
					1 to 5		5 to 30		> 30	
	LPB	SACZ	LPB	SACZ	LPB	SACZ	LPB	SACZ	LPB	SACZ
GR/ TA										
KF/ETA										
BM/MRF										
GR/MRF										
KF2/MRF										
KF/MRF										
KF/MRF/VER										
KF/MRF/VER/NUD										
GR/MRF/VER/NUD										
ENSEMBLE EXP										

which the regional circulation is not controlled within the model domain.

The ensemble of experiments satisfies the quality criteria considering different metrics of model evaluation over SACZ and LPB, however, some of the individual experiments share similar biases and the ensemble does not improve the performance compared with any individual experiment.

6 Summary and conclusions

In this study several sensitivity experiments with the MM5 model were performed, with the aim of identifying the best model set up and configuration for climate studies over SA. The experiments were 3-month length, comprising the period October–November and December 1986, characterized by contrasting conditions in terms of both precipitation and low-level circulation over LPB and SACZ, resembling one of the main modes of intraseasonal precipitation variability over SA during the warm season., the well known dipole pattern (Nogués-Paegle and Mo 1997). The sensitivity experiments included different combinations of cumulus and planetary boundary layer schemes, and different treatments of the lateral boundary conditions in which constraints to the regional circulation within the regional model domain were considered. All simulations were nested into ERA40 reanalysis. The study focused mainly on evaluating the capability of the sensitivity experiments in simulating the spatial pattern of rainfall and low-level circulation during November, December and the difference between November and December, with special emphasis on the daily precipitation statistics over the LPB and SACZ regions.

We concentrated first on evaluating the sensitivity to two planetary boundary layer schemes (ETA and MRF) in combination with four cumulus schemes (GR, BM, KF and KF2). Overall, every experiment was able to capture the contrasting behavior of the precipitation pattern over the LPB and SACZ regions; however, large differences in the simulated spatial distribution of rainfall during the 2 months were apparent, suggesting that the ability in simulating precipitation is very sensitive to the choice of the PBL and cumulus schemes used in the model. The experiment using the ETA PBL in combination with the GR cumulus scheme completely underestimates rainfall over tropical latitudes of SA. Though the GR scheme in combination with the MRF PBL scheme improves the simulation of rainfall compared with the GR/ETA experiment, the underestimation over tropical SA is still apparent. Conversely, using the KF cumulus scheme in combination with either ETA or MRF PBL schemes, the model captures better the spatial distribution of rainfall over tropical areas, particularly over SACZ, but underestimates rainfall over the subtropical plains. These results agree with those presented in Liang et al. (2007) using the MM5 model over North America. Experiments using the MRF PBL scheme in combination with BM and KF2 cumulus schemes depict large negative biases over tropical and subtropical areas, respectively.

Inspection of the simulated low level circulation pattern and the moisture flux convergence, the key dynamical forcing associated with the anomalous precipitation pattern during the simulated period, showed that every experiment misrepresent to some extent the differential behavior of the low level circulation leading to anomalous rainfall over LPB and SACZ during November and December. These results motivated additional sensitivity experiments in which grid nudging of the winds above the PBL was used with the GR and the KF cumulus schemes in combination with the MRF PBL scheme. The experiments using grid nudging of the winds show and overall improvement in the quality of the simulations mainly because the spatial distribution of the moisture flux controls to a large extent the precipitation pattern evaluated in this study. However, the experiment that outperforms still depends on the area of interest, being the GR/MRF/VER/NUD for subtropical latitudes and the KF/MRF/VER/NUD for tropical regions, in agreement with Miguez-Macho et al. (2005) and Lo et al. (2008) who found similar results using different regional climate models over North America.

Taking into account the strong impact of the moisture flux on precipitation during the warm season over SA, it is expected that this approach may lead to better results also for long-term climate simulations performed with the MM5 model over large domains as the one used in this study. It is worth to remark that in most of the RCM intercomparison exercises, such as those performed for the European region (e.g., PRUDENCE; Jacob et al. 2007 and ENSEMBLES; Boberg et al. 2009b) no model used nudging techniques within the regional domain. Furthermore, this approach may be considered controversial due to the lack of freedom of the large-scale circulation and the detrimental effect on extreme precipitation events (Alexandru et al. 2009), though recent results by Colin et al. (2010) show that the use of the spectral nudging technique is not detrimental to the modeling of heavy precipitation.

The evaluation of model performance in terms of daily precipitation statistics deserves a particular discussion. The evaluation of model performance requires a reference dataset to contrast the simulations. Moreover, in most of the cases, the reliability of the observational dataset is out of discussion. Though subtle discrepancies among the gridded observational datasets used in this work were highlighted when the spatial distribution of monthly rainfall were presented, the spread among observations became larger when daily precipitation statistics were analyzed over the LPB and SACZ areas, particularly for the wet day frequency and, to a lesser extent, for the rainfall rate distribution.

In terms of the frequency of rainy days over LPB and SACZ the spread in observations was found to be as large as the spread among the sensitivity experiments, making in difficult to draw a conclusion about the experiment that outperforms in terms of this particular metric. However, every experiment captures the contrasting behavior over LPB and SACZ during November and December. This metric suggests that the underestimation of rainfall is generally related with the underestimation of the amount of rainfall of individual rainy events. This conclusion suggests that improvements in the cumulus schemes are necessary to represent the intensity of rainfall more accurately. This result also arises from the evaluation of the distribution of rainfall rates. Overall, almost every sensitivity experiment overestimates (underestimates) the frequency of light (moderate) precipitation events.

The results presented show that there is no single experiment that outperforms over the entire domain taking into account every evaluation measure. However, some of the sensitivity experiments arise as more reliable for some regions only. These results are similar to those found in Fernández et al. (2007), who raised the question: Do the best parameterization exist? Apparently, the answer is no. However, it is still possible to take advantage of these results which suggest that an ensemble of simulations using one single model with different physical parameterizations may be one possibility to improve the quality of regional climate simulations.

The conclusions drawn in this study are based on a particular season. However, the skill of regional climate simulations is regime-dependent, as shown in Fernández et al. (2007) and Menéndez et al. (2010), consequently, a similar analysis based on longer simulations is expected to result in more general recommendations in order to set up a regional model for climate studies over SA.

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References

Alexandru A, de Elia R, Laprise R (2007) Interanual variability in regional climate downscaling at the seasonal scale. Mon Wea Rev 135:3221–3238

Alexandru A, de Elia R, Laprise R, Separovic L, Biner S (2009) Sensitivity study of regional model simulations to large-scale nudging parameters. Mon Wea Rev 137:1666–1686

Arakawa A, Schubert W (1974) Interaction of a cumulus cloud ensemble with the large scale environment. Part I. J Atmos Sci 31:674–701

Betts AK, Miller MJ (1993) The Best Miller scheme. In: Emanuel KA, Raymond DJ (eds) The representation of cumulus convection in numerical models of the atmosphere. Amer Met Soc, 246 pp

Boberg F, Berg P, Thejll P, Gotowski W, Christenen J (2009a) Improved confidence in climate change projections of precipitation evaluated using daily statistics from the PRUDENCE ensemble. Clim Dyn 32:1097–1106

Boberg F, Berg P, Thejll P, Gotowski W, Christenen J (2009b) Improved confidence in climate change projections of precipitation further evaluated using daily statistics from the ENSEMBLES models. Clim Dyn. doi:10.1007/s00382-009-0683-8

Bright D, Mullen S (2002) The sensitivity of the numerical simulation of the southwest monsoon boundary layer to the choice of PBL turbulence parameterization in MM5. Weather Forecast 17:99–114

Chen F, Dudhia J (2001) Coupling and advanced land surface hydrology model with the Penn State-NCAR MM5 modeling system. Part I: model implementation and sensitivity. Mon Weather Rev 129:569–585

Colin J, Deque M, Radu R, Somot S (2010) Sensitivity study of heavy precipitation in limited area model climate simulations: influence of the size of the domain and the use of the spectral nudging technique. Tellus 62A:591–604

da Silva M, da Rocha RP, Ynoue RY (2010) Climatic simulations of the eastern Andes low-level jet and its dependency on convective parameterizations. Meteorol Atmos Phys 108:9–27

Davies HC (1976) A lateral boundary formulation for multi-level prediction models. Q J R Meteorol Soc 102:405–418

de Elía R, Caya D, Côté H, Frigon A, Biner S, Giguère M, Paquin D, Harvey R, Plummer D (2007) Evaluation of uncertainties in the CRCM-simulated North American climate. Clim Dyn 30:113–132

Denis B, Laprise R, Caya D, Côte J (2002) Downscaling ability of one-way nested regional climate models: the Big-Brother Experiment. Clim Dyn 18:627–646

Fernández J, Montávez JP, Sáenz J, González-Rouco JF, Zorita E (2007) Sensitivity of the MM5 mesoscale model to physical parameterizations for regional climate studies: annual cycle. J Geophys Res 112:D04101. doi:10.1029/2005JD00664

Garand L (1983) Some improvements and complements to the infrared emissivity algorithm including a parameterization of the absorption in the continuum region. J Atmos Sci 40:230–244

Giorgi F (1990) On the simulation of regional climate using a limited area model nested in a general circulation model. J Clim 3:941–963

Giorgi F, Bi X, Pal J (2004) Mean, interannual variability and trends in a regional climate change experiment over Europe I. Present day climate (1961–1990). Clim Dyn 22:733–756

Gochis D, Shuttleworth W, Yang Z (2002) Sensitivity of the modeled North American monsoon regional climate to convective parameterization. Mon Weather Rev 130:1282–1298

Grell GA (1993) Prognostic evaluation of assumptions used by cumulus parameterizations. Mon Weather Rev 12:764–787

Grell GA, Dudhia J, Stauffer DR (1994) A description of the fifth generation Penn System/NCAR Mesoscale Model (MM5). NCAR Tech Note NCAR/TN–398 + 1A, 107 pp

Hong S, Pan H (1996) Non-local boundary layer vertical diffusion in a medium-range forecast model. Mon Weather Rev 124:2322–2339

Hsie EY, Anthes RA, Keyser D (1984) Numerical simulation of frontogenesis in a moist atmosphere. J Atmos Sci 41:2581–2594

Jacob D, Bärring L, Christensen O, Christensen J, Castro M, Déqué M, Giorgi F, Hagemann S, Hirschi M, Jones R, Kjellström E, Lenderink G, Rockel B, Sánchez E, Schär C, Seneviratne S, Somot S, van Ulden A, van den Hurk B (2007) An inter-comparison of regional climate models for Europe: model performance in present-day climate. Clim Change 81:31–52. doi: 10.1007/s10584-006-9213-4

Janjic ZI (1994) The step-mountain eta coordinate model: further development of the convection, viscous sublayer, and turbulent closure schemes. Mon We Rev 122:927–945

Kain JS (2004) The Kain–Fritsch convective parameterization: an update. J Appl Meteorol 43:170–181

Kain JS, Fritsch JM (1993) Convective parameterization for meso-scale models: the Kain–Fritsch scheme. In: The representation of cumulus convection in numerical models. Meteor. Monogr. No. 24. Amer Meteor Soc, pp 165–170

Liang XZ, Xu M, Kunkel K, Grell G, Kain J (2007) Regional climate model simulations of US–Mexico summer precipitation using the optimal ensemble of two cumulus parameterizations. J Clim 20:5201–5207

Liebmann B, Kiladis G, Vera C, Saulo C, Carvalho L (2004) Subseasonal variations of rainfall in South America in the vicinity of the low-level jet east of the Andes and comparison to those in the South Atlantic convergence zone. J Clim 17:3829–3842

Lo JCF, Yang ZL, Pielke R (2008) Assesment of three dynamical climate downscaling methods using the Weather Research and Forecasting (WRF) model. J Geophys Res 113:DO9112. doi: 10.1029/2007JD009216

Mellor GL, Yamada T (1974) A hierarchy of turbulence closure models for planetary boundary layers. J Atmos Sci 31:1791–1806

Menéndez CG, de Castro M, Boulanger J-P, D'Onofrio A, Sanchez E, Sörensson AA, Blazquez J, Elizalde A, Jacob D, Le Treut H, Li ZX, Núñez MN, Pessacg N, Pfeiffer S, Rojas M, Rolla A, Samuelsson P, Solman SA, Teichmann C (2010) Downscaling extreme month-long anomalies in southern South America. Clim Change 98:379–403. doi:10.1007/s10584-009-9739-3

Miguez-Macho G, Stenchikov G, Robock A (2005) Regional Climate Simulations over North America: interaction of local processes with improved large-scale flow. J Clim 18:1227–1246

Misra V, Dirmeyer PA, Kirtman BP (2003) Dynamic downscaling of seasonal simulations over South America. J Clim 16:103–117

Nijssen B, Schnur R, Lettenmaier DP (2001) Global retrospective estimation of soil moisture using the variable infiltration capacity land surface model, 1980–93. J Clim 14:1790–1808

Nogués-Paegle J, Mo KC (1997) Alternating wet and dry conditions over South America during summer. Mon Weather Rev 125:279–291

Nuñez MN, Solman S, Cabré MF (2009) Regional climate change experiments over Southern South America. II: climate change scenarios in the late twenty first century. Clim Dyn 32:1081–1095

Palmer TN, Doblas-Reyes FJ, Hagedorn R, Weisheimer A (2005) Probabilistic prediction of climate using multi-model ensembles: from basics to applications. Phil Trans R Soc B 360:1991–1998. doi:10.1098/rstb.2005.1750

Ratnam JV, Kumar KK (2005) Sensitivity of the simulated monsoons of 1987 and 1988 to convective parameterization schemes in MM5. J Clim 18:2724–2743

Reynolds R, Rayner N, Smith T, Stokes D, Wang W (2002) An improved in situ and satellite SST analysis for climate. J Clim 15:1609–1625

Sanchez E, Berbery E, Solman S, García-Ochoa R, Samuelsson P, Remedio A, Jacob D, Rojas M, Sörensson A, Menendez C, Porfirio da Rocha R, Castro M, Pessacg N, Marengo J, Chan Chou S, Li L, Le Treut H (2010) Present climate validation of an ensemble of regional climate models over South America forced by 1989–2008 ERAinterim reanalysis. Eos Trans. AGU, 91(26), Meet Am Suppl Abstract GC33A-02

Seth A, Giorgi F (1998) The effects of domain choice on summer precipitation simulation and sensitivity in a regional climate model. J Clim 11:2698–2712

Seth A, Rojas M (2003) Simulation and sensitivity in a nested modeling system for South America. Part I. Reanalysis boundary forcing. J Clim 16:2437–2453

Seth A, Rauscher S, Qian J, Pal J (2007) RegCM3 regional climatologies for South America using reanalysis and ECHAM global model driving fields. Clim Dyn 28:461–480

Silva V, Berbery H (2006) Intense rainfall events affecting the La Plata Basin. J Hydrometeorol 7:769–778

Silva V, Kousky V, Shi W, Higgins W (2007) An improved gridded historical daily precipitation analysis for Brazil. J Hydrometeorol 8:847–861

Solman S, Orlanski I (2010) Subpolar high anomaly preconditioning precipitation over South America. J Atmos Sci 67:1526–1542

Solman S, Nuñez M, Cabré MF (2007) Regional climate change experiments over southern South America. I: present climate. Clim Dyn 30:533–552

Sörensson A, Menéndez C (2010) Summer soil-precipitation coupling in South America. Tellus A 23:5–7. doi:10.1111/j.1600-0870.2010.00468.x

Stauffer DR, Seaman NL (1990) Use of four-dimensional data assimilation in a limited-area mesoscale model. Part I: Experiments with synoptic-scale data. Mon Weather Rev 118:1250–1277

Stephens GL (1978) Radiation profiles in extended water clouds: II. Parameterization schemes. J Atmos Sci 35:2123–2132

Stephens GL (1984) The parameterization of radiation for numerical weather prediction and climate models. Mon Weather Rev 112:826–867

Tadross M, Gutowski W, Hewitson W, Jack C, New M (2006) MM5 simulations of interannual change and the diurnal cycle of southern African regional climate. Theor Appl Climatol 86:63–80

Troen IW, Mahrt L (1986) A simple model of the atmospheric boundary layer; sensitivity to surface evaporation. Bound Layer Meteorol 37:129–148

Uppala SM et al (2005) The ERA-40 re-analysis. Q J R Meteorol Soc 131:2961–3012. doi:10.1256/qj.04.176

von Storch H, Langenberg H, Feser F (2000) A spectral nudging technique for dynamical downscaling purposes. Mon Weather Rev 128(10):3664–3673

Yang Z, Arrit R (2002) Test of a perturbed physics ensemble approach for regional climate modeling. J Clim 15:2881–2896