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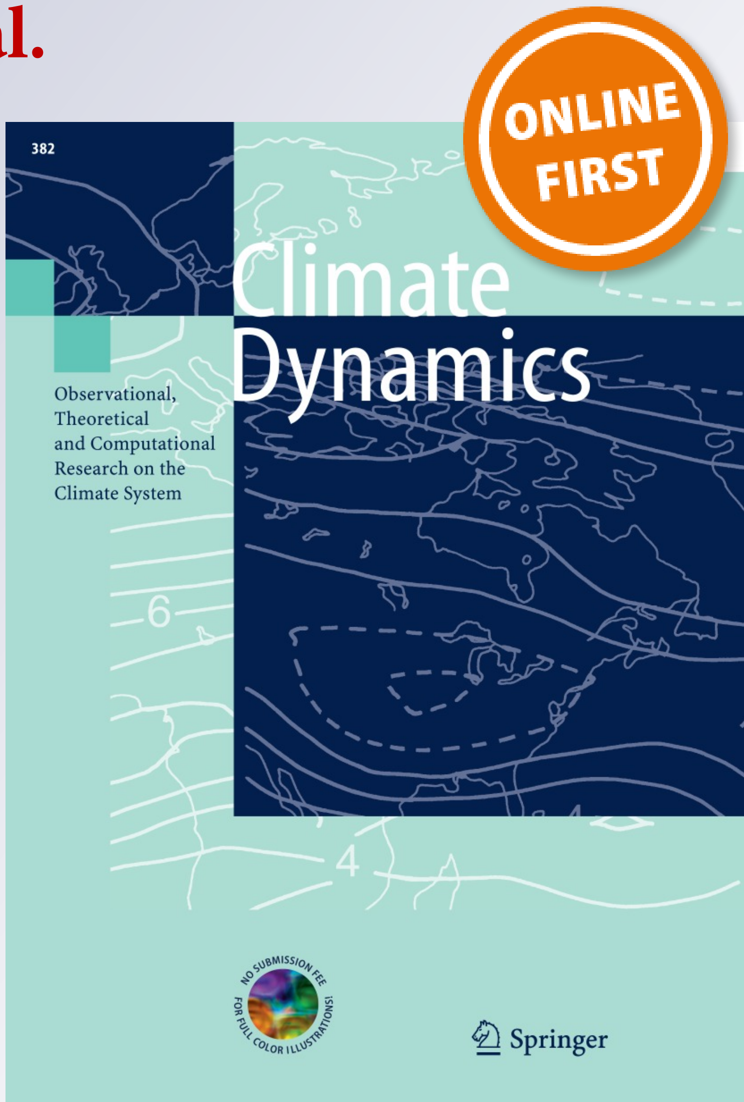

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The surface radiation budget over South America in a set of regional climate models from the CLARIS-LPB project

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Abstract The performance of seven regional climate models in simulating the radiation and heat fluxes at the surface over South America (SA) is evaluated. Sources of uncertainty and errors are identified. All simulations have been performed in the context of the CLARIS-LPB Project for the period 1990–2008 and are compared with the GEWEX-SRB, CRU, and GLDAS2 dataset and NCEP-NOAA reanalysis. Results showed that most of the models overestimate the net surface short-wave radiation over tropical SA and La Plata Basin and underestimate it over oceanic regions. Errors in the short-wave radiation are mainly associated with uncertainties in the representation of surface albedo and cloud fraction. For the net surface long-wave radiation, model biases are diverse. However, the ensemble mean showed a good agreement with the GEWEX-SRB dataset due to the compensation of individual model biases. Errors in the net surface long-wave radiation can be explained, in a large proportion, by errors in cloud fraction. For some particular models, errors in temperature also contribute to errors in the net long-wave radiation. Analysis of the annual cycle of each component of the energy budget indicates that the RCMs reproduce generally well the main characteristics of the short- and long-wave radiations in terms of timing and amplitude. However, a large spread among models over tropical SA is apparent. The annual cycle of the sensible heat flux showed a strong overestimation in comparison with the reanalysis and GLDAS2 dataset. For the latent heat flux, strong differences between the reanalysis and GLDAS2 are calculated particularly over tropical SA.

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1 Introduction

In recent years, several studies have shown that numerous sources of uncertainty affect the simulation of the radiation and energy budgets derived from climate models. These studies have emphasized that the spread among different realizations should be taken into account before drawing conclusions about the significance of the regional response to external forcings (Solman and Pessacg 2011a, b; de Elía et al. 2008, Déqué et al. 2007). In particular, studies over West Africa (Kothe and Ahrens 2010), Europe (Kothe et al. 2010; Lenderink et al. 2007) and the United States (Markovic et al. 2008) have revealed that regional climate models (RCMs), in general, present considerable uncertainties in representing the long- and short-wave components of the surface radiation budget.

In terms of climate modelling, the top of the atmosphere and surface long- and short-wave components of the Earth's radiation budget are very important elements, which describe the sources and sinks of energy in the Earth-atmosphere system (Khote et al. 2010). Their amounts determine the distribution of incoming radiation from the sun, which is transformed into sensible heat, latent heat, potential energy and kinetic energy before being re-emitted as long-wave radiant energy back to the atmosphere. The energy balance can be affected in various ways, changing the climate and associated weather (Trenberth and Fasullo 2009).

Due to the importance of the top of the atmosphere and surface radiation budget in the control of the Earth energy balance and the daily and annual cycles, it is necessary to evaluate the radiation budget simulated by regional climate models (RCMs) and to identify sources of uncertainties (Kothe et al. 2010) in order to interpret model biases. In this study, we specifically focus in the surface energy budget.

Several climate model evaluations have attributed errors in the surface radiation budget components to the cloud fraction uncertainties (Kothe and Ahrens 2010; Markovic et al. 2008; Jaeger et al. 2008). The effect of cloud plays an important role because any shift of climate is expected to affect the cloud distribution or its annual variations and consequently the downward and net short-wave radiation at the Earth's surface (Wilber et al. 2006).

In addition, Kothe et al. (2010), Kothe and Ahrens (2010), and Randall et al. (2012) have found that the uncertainties in surface albedo and surface temperature have a significant correlation with the long- and short-wave surface radiation budgets errors. In Kothe et al. (2010), they showed that the impact of the surface temperature was partly due to the clouds absorption in the atmosphere, which was strongly determined by the water vapour that is closely related with the temperature in the lower troposphere and thus correlated with the surface temperature. Over the South Atlantic Ocean, Reboita et al. (2010) evaluated a 10-year RCM simulation and showed that underestimation of 2-m air temperature was associated with larger than observed sensible heat fluxes.

In the context of the EU FP7 CLARIS LPB project (A Europe-South America Network for Climate Change Assessment and Impact Studies in La Plata Basin, 2008–2012), which aims in investigating the climate change impacts on hydroclimate and extreme events over La Plata Basin, a group of RCMs forced by the ERA-Interim reanalysis (Simmons et al. 2007) for the period of 1990–2008, have been used to simulate the South American climate at approximately 50 km horizontal resolution. This international coordinated effort provided the opportunity of performing an intercomparison exercise in terms of radiation budget over South America (SA).

Due to the important impacts that long- and short-wave radiations can exert in a wide spectrum of studies and the lack of this kind of analysis over SA, the goal of this work is to analyze the capability of a set of RCMs in representing the surface radiations budgets and to identify the associated sources of uncertainty. In order to fully explore the capability of the models in representing the surface energy budget, the heat fluxes are also evaluated. This study provides a complementary analysis in understanding the RCMs biases in terms of temperature and precipitation, identified in Solman et al. (2013).

The validation of RCMs in reproducing present climate conditions in terms of energy budget is an essential step needed to understand projected changes on individual components of the energy budget that may explain future temperature and precipitation patterns.

This paper is organized as follows: Sect. 2 describes the simulations performed and the data used for evaluation. In Sect. 3, results from the simulations and the sources of uncertainties in the radiation budget are presented. In this section also, the mean annual cycles of the short and long-wave radiation components, the latent, and sensible heat fluxes are evaluated. Finally, Sect. 4 includes the discussion and conclusions.

2 Data and simulations

2.1 Validation dataset

The short- and long-wave components of the surface radiation budget, cloud fraction, and surface albedo from RCM simulations were compared with data provided by the surface radiation budget project (GEWEX-SRB/Global Energy and Water Cycle Experiment) available at http://www.gewex.org/. GEWEX-SRB provides monthly means of satellite-based data on a 1° horizontal resolution covering the globe (Gupta et al. 2006). In this work, the release version 3.0 was used. This dataset has been used and validated in previous studies in other regions of the word and it was found that the estimated errors in the short- and long- wave radiation budgets are around 5 and 10 W m^{-2}, respectively (Gupta et al. 1999; Zhang et al. 2006, 2007, 2009; Winter and Eltahir 2011).

Near-surface air temperature was validated against the CRU (University of East Anglia Climate Research Unit, CRU TS3.1; Mitchell and Jones 2005) dataset, available at 0.5° spatial resolution.

The heat fluxes were compared with the flux from NCEP-NCAR reanalysis (version 2) (Kanamitsu et al. 2002), with a 2.5° spatial resolution, and with the flux from the Global Land Data Assimilation System with Noah Land Surface Model-2 (hereafter GLDAS2, Rodell et al. 2004; http://disc.sci.gsfc.nasa.-gov/hydrology/data-holdings), with 1° spatial resolution. An ideal evaluation of the capability of models in representing the heat fluxes would use field observations. However, due to the sparse availability of this kind of data in South America, only flux data from the reanalysis and GLDAS dataset were used.

2.2 RCM simulations

The RCM simulations evaluated in this work have been performed within the CLARIS-LPB project in a coordinated framework, following the CORDEX Phase I protocol (Giorgi et al. 2009). All the models were forced by the European Centre for Medium-range Weather and Forecasting reanalysis data set or ERA-Interim (Simmons et al. 2007). The model domain covered the South American continent from 15°N to 60°S and from 90 to 20°W with approximately 50 km horizontal grid spacing. Integrations were done for the period 1990–2008.

In this study, monthly-mean values of the surface energy budget from each model were interpolated to a common 0.5° equidistant latitude-longitude grid. Due to the availability of GEWEX-SRB dataset, the period 1990–2007 is considered.

The participating RCMs were: MM5 (CIMA/CONICET, Argentina), PROMES (UCLM, Spain), REMO (MPI, Germany), RegCM3 (USP, Brazil), RCA (SMHI, Sweden), LMDZ (IPSL, France) and ETA (INPE, Brazil). Characteristics of each individual model as well as an evaluation of their capability in simulating the regional climate in terms of the climatological mean temperature and precipitation were discussed in Solman et al. (2013). Table 1 summarizes the main characteristics of each model including the land surface model, convection, explicit cloud, precipitation, and radiation schemes, and its basic references.

3 Results

3.1 Seasonal-mean surface radiation distributions

3.1.1 Surface short-wave radiation

In this section, the net short-wave and long-wave surface radiation budgets (hereafter, SWs and LWs) are evaluated, which are defined as the difference between downward and upward components, respectively.

Figure 1 shows the mean SWs for GEWEX-SRB and the mean SWs biases between the 7-member RCM ensemble mean and individual members from the GEWEX-SRB data during the austral summer (December–January–February; hereafter DJF) and the austral winter (June–July–August, hereafter JJA). The SWs mean and bias are calculated for the 1990–2007 period.

During summer, the highest values of SWs based from the GEWEX-SRB dataset (Fig. 1a, first panel) occur along the subtropical ocean of SA that is close to the coast of the continents, over the central Andes and the Altiplano (Andean Plateau). Conversely, low values of SWs occur over areas of low solar input such as the southern part of the domain and over cloudy regions as the Amazonas. During winter, high (low) values occur over tropical regions (high latitudes) due to high (low) solar input and small (large) cloud coverage (Fig. 1b, first panel).

Despite the fact that the spatial pattern of the bias for SWs during both seasons is different for each RCM, there are some particular characteristics common to all the models. In general, during summer (Fig. 1a), most of the RCMs overestimate the SWs over continental areas, with biases ranging from 20 to 40 Wm^{-2} (about 20 % of the observed values) specifically over tropical SA and over La Plata Basin (LPB). The SWs over the oceans are underestimated with biases ranging from −20 to −60 Wm^{-2} (10–25 %). A similar pattern is reflected in the ensemble mean during DJF. Among the RCMs, the RCA model differs from this pattern, showing a general underestimation of SWs over both continental and oceanic regions. However, the slight overestimation over Peru Current persists.

During winter (Fig. 1b), the RCMs underestimate SWs over the oceans with large errors over tropical latitudes reaching 100 Wm^{-2} (about 40 % of the observed values). An overestimation of SWs occurs over continental regions (close to 10 %) in most of the RCMs except in the MM5 and PROMES models. The ensemble mean presents a good agreement with the GEWEX-SRB dataset over the entire domain for JJA, which is probably due to the compensation of negative and positive errors from the individual members of the ensemble.

Table 1 Summary of regional climate models used. The models abbreviations in parenthesis are used throughout the work and figures as short names for the models

Model version	Institution	Grid type, dimensions	Convection scheme, explicit cloud and precipitation	Land surface scheme	Radiation scheme	Basic references
RCA 3.5 (RCA)	Swedish Meteorological and Hydrological Institute Sweden	Rotated lat/lon, hybrid vertical, 134 × 155 × 40, 0.5 × 0.5°	Kain and Fritsch (1990, 1993), Jones and Sanchez (2002), Rash and Kristjánsson (1998)	Samuelsson et al. (2006)	Savijarvi (1990), Sass et al. (1994)	Samuelsson et al. (2011)
REMO 2009 (REMO)	Max Planck Institute for Meteorology Germany	Rotated lat/lon, hybrid vertical, 151 × 181 × 31, 0.44 × 0.44°	Tiedtke (1989), Nordeng (1994), Roeckner et al. (1996)	Dümenil and Todini (1992), Rechid et al. (2006)	Roeckner et al. (1996)	Jacob et al. (2001, 2012)
PROMES 2.4 (PROMES)	Universidad Castilla-La Mancha Spain	Lambert conformal, pressure-based sigma, 145 × 163 × 37, 50 × 50 km^2	Kain and Fritsch (1993), Kain (2004), Hong et al. (2004)	Krinner et al. (2005), de Rosnay and Polcher (1998), Sitch et al. (2003)	Morcrette (1991)	Sanchez et al. (2007), Domínguez et al. (2010)
RegCM3	Universidade de Sao Paulo Brazil	Rotated Mercator, Terrain-following sigma, 190 × 202 × 18, 50 × 50 km^2	Grell et al. (1993), Pal et al. (2000)	Dickinson et al. (1993)	Kiehl et al. (1996)	Pal et al. (2007), da Rocha et al. (2009a, b)
MM5V3.7 (MM5)	Centro de Investigaciones del Mar y la Atmósfera Argentina	Mercator, sigma, 150 × 203 × 23, 0.5 × 0.5°	Grell et al. (1993), Hsie et al. (1984)	Chen and Dudhia (2001)	Stephens (1978, 1984), Garand (1983)	Grell et al. (1993), Solman and Pessacg (2011a)
LMDZ 4 (LMDZ)	Institut Pierre-Simon Laplace France	Irregular rectangular lat/lon, Hybrid sigma, 190 × 202 × 18	Emanuel (1991, 1993), Bony and Emanuel (2001)	Krinner et al. (2005)	Hourdin et al. (2006)	Hourdin et al. (2006), Li (1999)
ETA-CC*V1.0 (ETA)	InstitutoNacional de PesquisasEspaciais Brazil	Regular lat/lon, Eta, 123 × 245 × 38, 50 × 50 km^2	Betts and Miller (1986), Janjic (1994), Zhao et al. (1997)	Ek et al. (2003)	Fels and Schwarzkopf (1975), Lacis and Hansen (1974)	Pesquero et al. (2009), Chou et al. (2011)

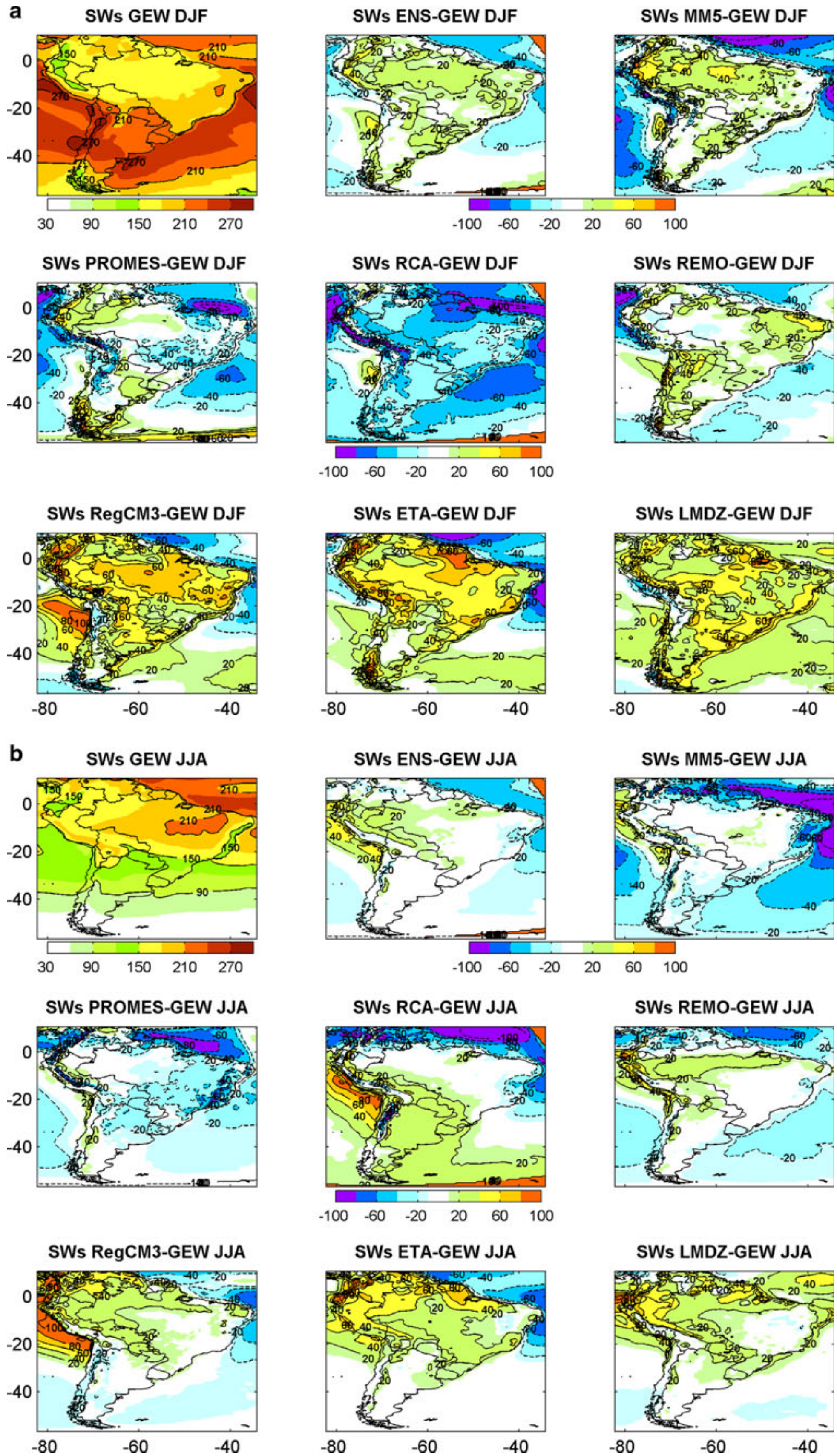
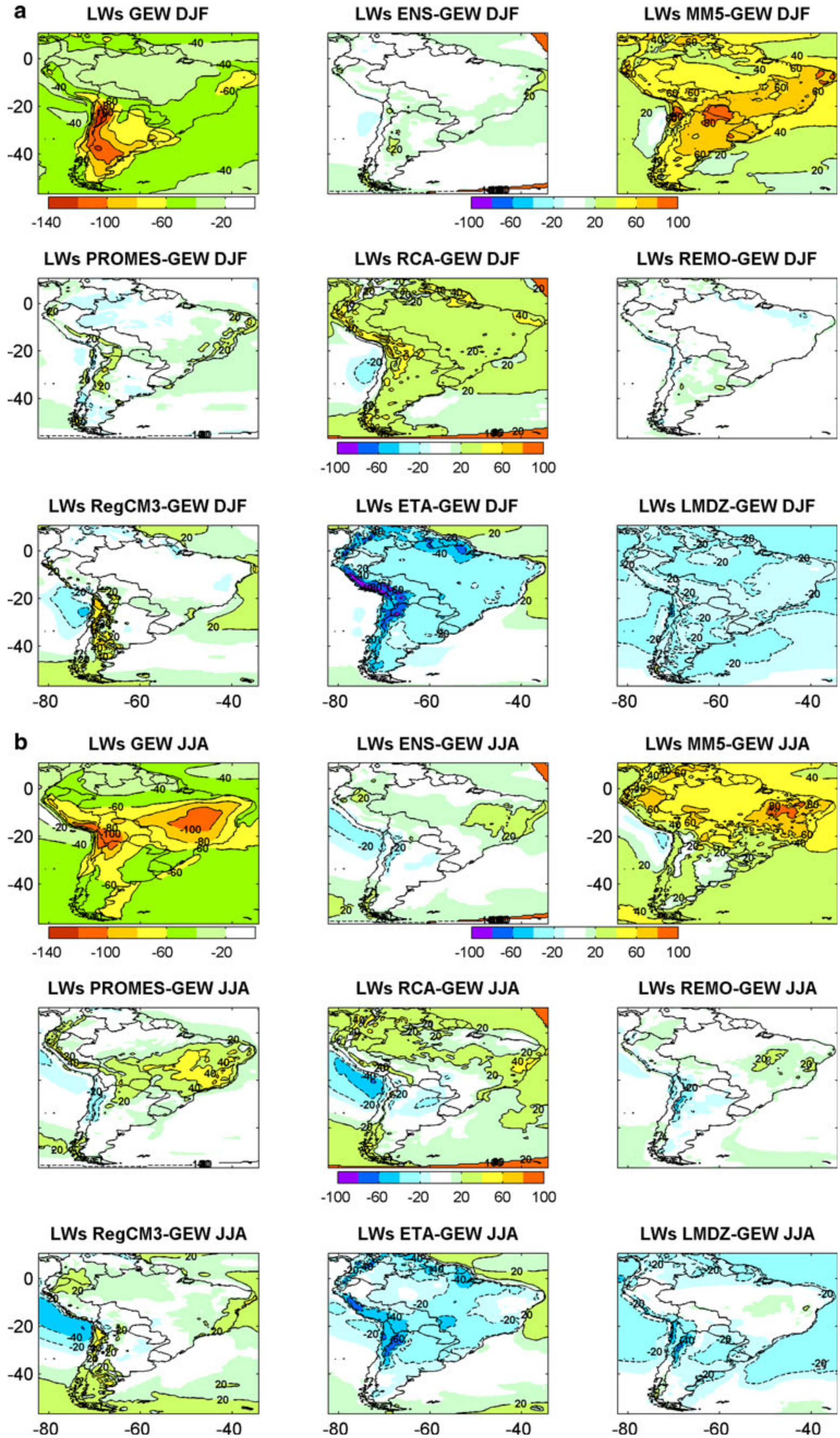


Fig. 1 **a** Climatology of the net short-wave surface radiation budget for GEWEX-SRB (GEW) during austral summer (W m^{-2}) for the period 1990–2007 (*first panel*, *top-left*). The rest of the *panels* show the differences in the net short-wave surface radiation budget (W m^{-2}) between the ensemble mean (ENS) and each RCM, and the GEWEX-SRB dataset during DJF 1990–2007. **b** Same as in **a**, but during austral winter (JJA) 1990–2007

Fig. 2 **a** Same as in Fig. 1a, but for the net long-wave surface radiation budget (W m^{-2}). **b** Same as in (**a**), but during austral winter (JJA) 1990–2007



All RCMs have difficulties in reproducing the short-wave radiation budget over the Peruvian-Chile coast and the adjacent Pacific Ocean region, i.e. a relative positive bias up to 60 %, with the exception of PROMES model. As a consequence, this pattern has been reflected in the ensemble mean during both seasons. This difficulties in representing the SWs over this region has also been found in global models (Collins et al. 2006) and it is related with a misrepresentation of the frequent stratus cloud deck over this region. Colas et al. (2011) have shown that the warm bias in the sea surface temperature may explain the lack of stratus clouds along the coast in global models over the Peruvian-Chile Current System. However, RCMs have used the prescribed sea surface temperature from the ERA-Interim reanalysis. Possible explanations for this systematic error may be related with the planetary boundary layer parameterization that fails to reproduce the stable planetary boundary layer conditions and also the representation of stratus clouds in the region. In REMO, Jacob et al. (2012), have found similar biases in upwelling regions other than the Peru/Humboldt current such as the Benguela current in Africa and they have attributed it to a possible missing coupling process between the atmosphere and the ocean.

3.1.2 Surface long-wave radiation

Figure 2 shows the 19-year mean LWs based on the GEWEX-SRB and the bias of the ensemble and individual RCMs with respect to the GEWEX-SRB dataset, during DJF and JJA.

The GEWEX-SRB dataset shows that small negative values occur over cold surfaces and over regions where cloud cover has wide coverage such as over the Amazonas during summer. The large negative values occur where surface temperature is high and/or cloud cover is minimal, such as in the subtropical deserts of Chile and east of Brazil during winter.

The ensemble mean shows a good agreement with the GEWEX-SRB dataset during both seasons (Fig. 2a, b, top middle panels). This result is associated with the fact that some models highly overestimate the LWs over the entire domain, e.g. MM5 and RCA, while others exhibit large LWs underestimation, e.g. ETA and LMDZ (about 80 % of the GEWEX-SRB). Consequently, the bias of the ensemble mean is small due to individual model error compensation. The REMO model shows the best performance in representing the LWs budget during both seasons.

It is worth to mention that for the MM5 model, the net variables of the budgets were not available as model output and they were calculated as the difference between the upward and the downward components. In this case, the upward component of the long-wave radiation has been estimated with the 2 m air temperature rather than with the surface temperature due to unavailability as model output. Considering that the long-wave radiation emitted is proportional to the temperature raised to the fourth power, the error introduced is not negligible thus explaining a large proportion of the LWs biases for the MM5 model.

3.2 Uncertainty sources

The biases found in the simulation of the SWs could be related with errors in the representation of incoming solar radiation at the Earth's surface, which are due to misrepresentation of the cloud fraction, outward short wave radiation, and surface albedo (Markovic et al. 2008; Kothe et al. 2010). Additionally, the biases detected in the simulation of LWs could be associated with errors in the surface emission due to incorrect surface temperature, and/or errors in the downward component due to inaccurate cloud fraction.

Consequently, the biases in the albedo, temperature, and cloud fraction may be considered as the main sources of uncertainty in the simulated components of the surface radiation budget. In this context, the observed mean values and the RCMs ensemble mean and individual model biases for albedo, 2 m air temperature, and cloud fraction during austral summer and winter are shown in Figs. 3, 4, and 5, respectively. Figures 3, 5 show the relative differences in percentage for albedo and cloud fraction, respectively, which is calculated with respect to the GEWEX-SRB dataset. Figure 4 shows the absolute difference in 2 m air temperature with respect to the CRU dataset. Note that due to availability of model output, some of the model biases are missing. The detailed characteristics of the individual figures will be discussed shortly after relating the uncertainty sources to the radiation components.

Comparing these biases (Figs. 3, 4, 5) with those biases in the SWs and LWs (in Figs. 1, 2), it is clear that there is some coherency between the patterns of the biases. For example, regions showing overestimation (underestimation) of cloud fraction also show underestimation (overestimation) of the SWs and the opposite for LWs (as for the Peruvian coast). Additionally, some regions where the albedo values are overestimated (Fig. 3) also show that the SWs are underestimated (Fig. 1). However, the relation between these variables is not simply linear since several nonlinear factors may also have an impact on the errors of the SWs and LWs.

The extent to which these uncertainty sources impact on the errors of the radiation budgets have been quantified following the method used in Kothe and Ahrens (2010, and references quoted therein). These authors have proposed that the squared Pearson correlation coefficients between the uncertainty sources (errors in albedo, cloud fraction, and temperature) and the radiation components (SWs and

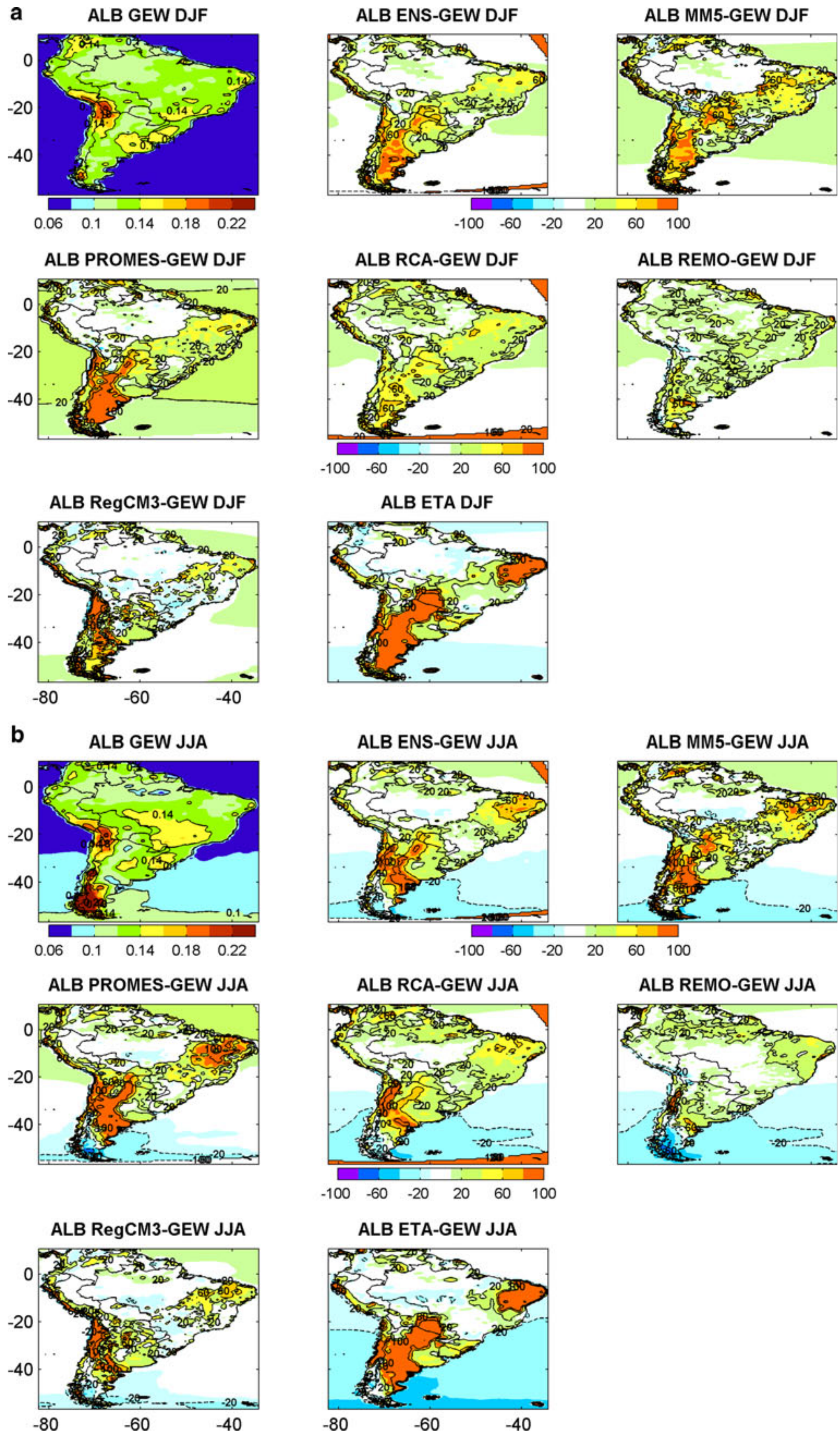


Fig. 3 **a** Climatology of the surface albedo for GEWEX-SRB (GEW) during austral summer (fraction) for the period 1990–2007 (*first panel*, *top-left*). The rest of the *panels* show the relative differences in the surface albedo (%) between the ensemble mean (ENS) and each RCM, and the GEWEX-SRB dataset during DJF 1990–2007. **b** Same as in (**a**), but during austral winter (JJA) 1990–2007

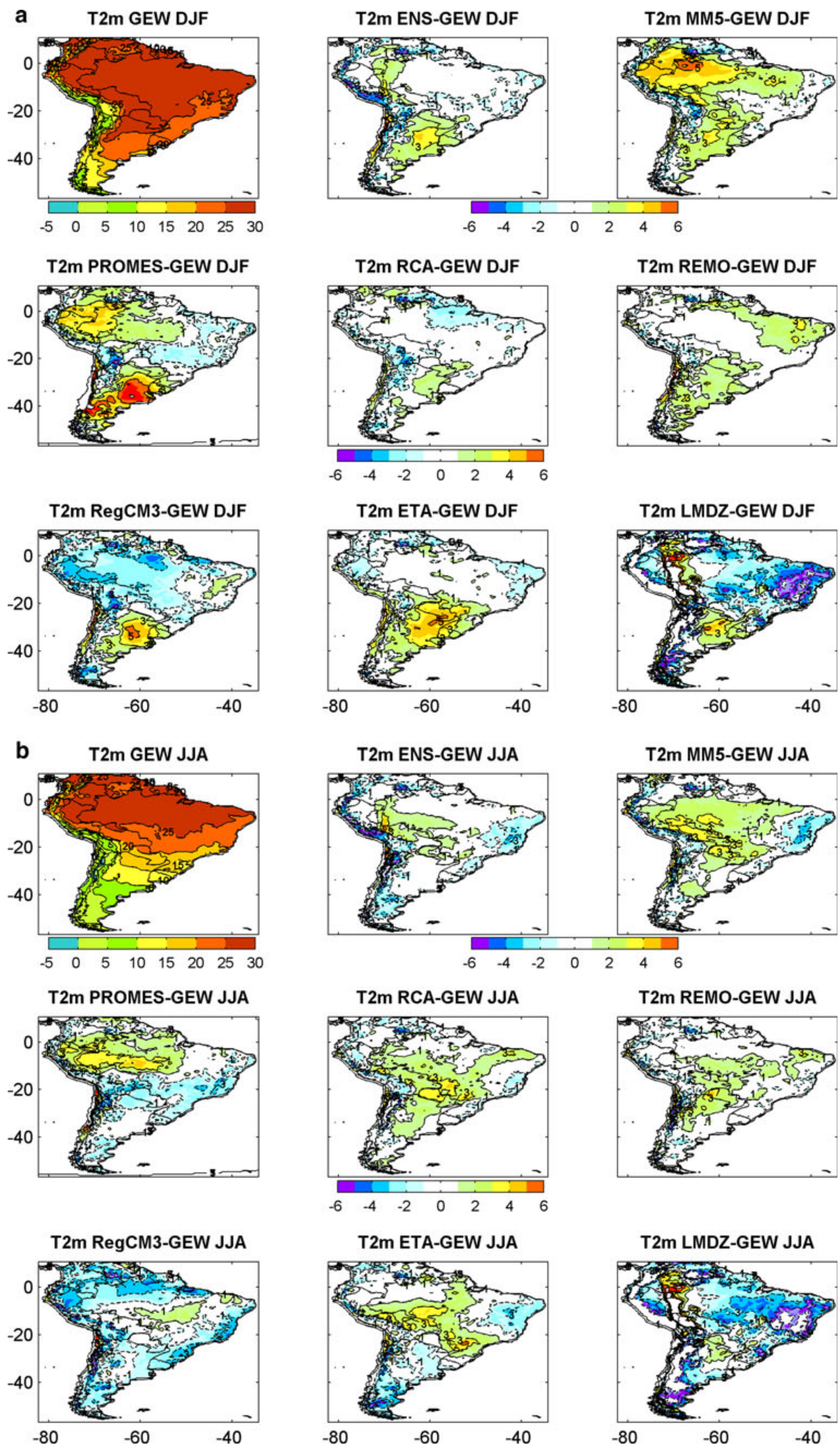
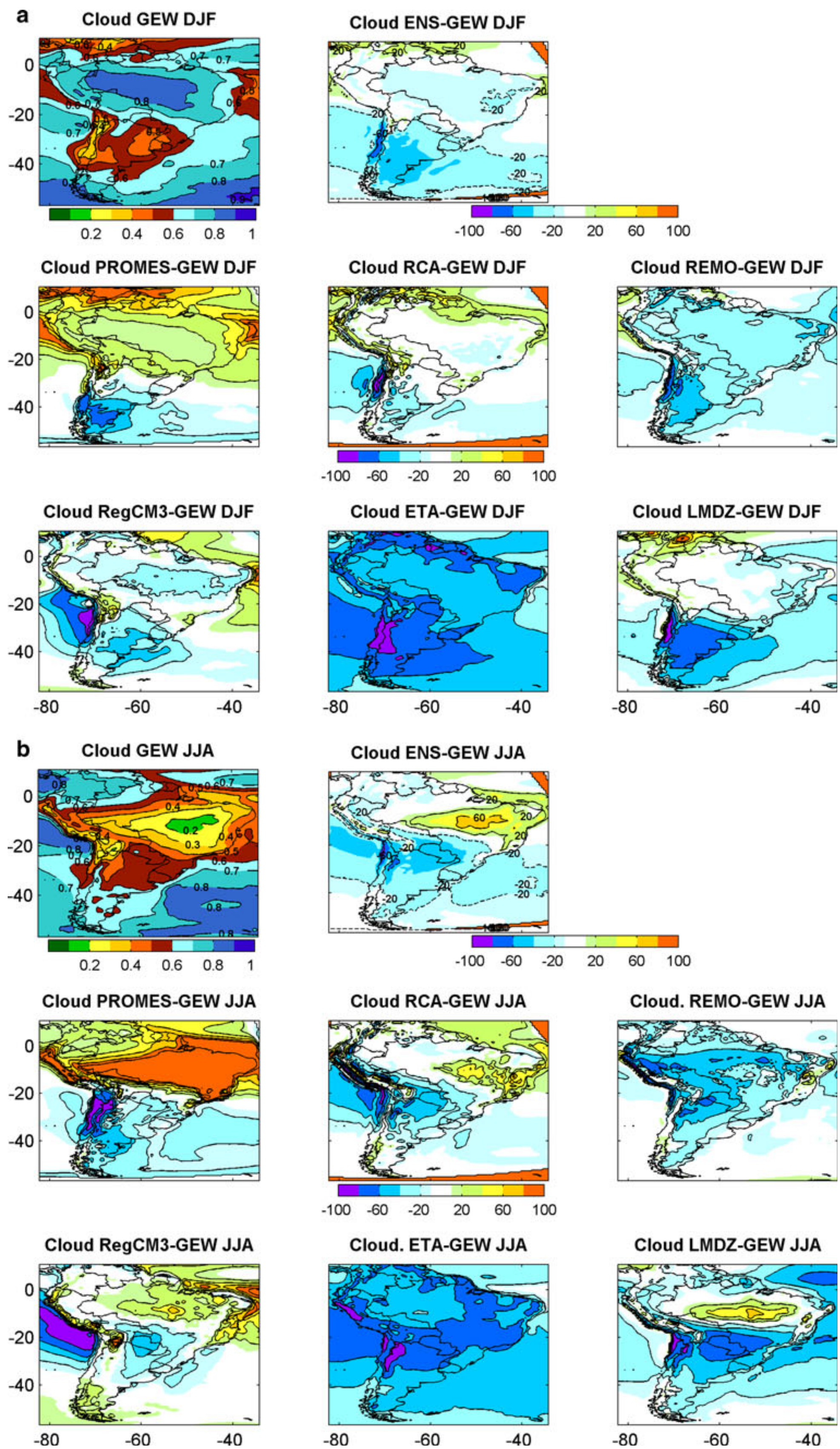


Fig. 4 **a** Climatology for the 2-m temperature (°C) for the CRU dataset during austral summer for the period 1990–2007 (*first panel*, *top-left*). The rest of the *panels* show the differences in the 2-m temperature (°C) between the ensemble mean (ENS) and each RCM, and the CRU dataset during DJF 1990–2007. **b** Same as in (**a**), but during austral winter (JJA) 1990–2007

Fig. 5 **a** Same as in Fig. 3a, but for the total cloud fraction (%). **b** Same as in (**a**), but during austral winter (JJA) 1990–2007



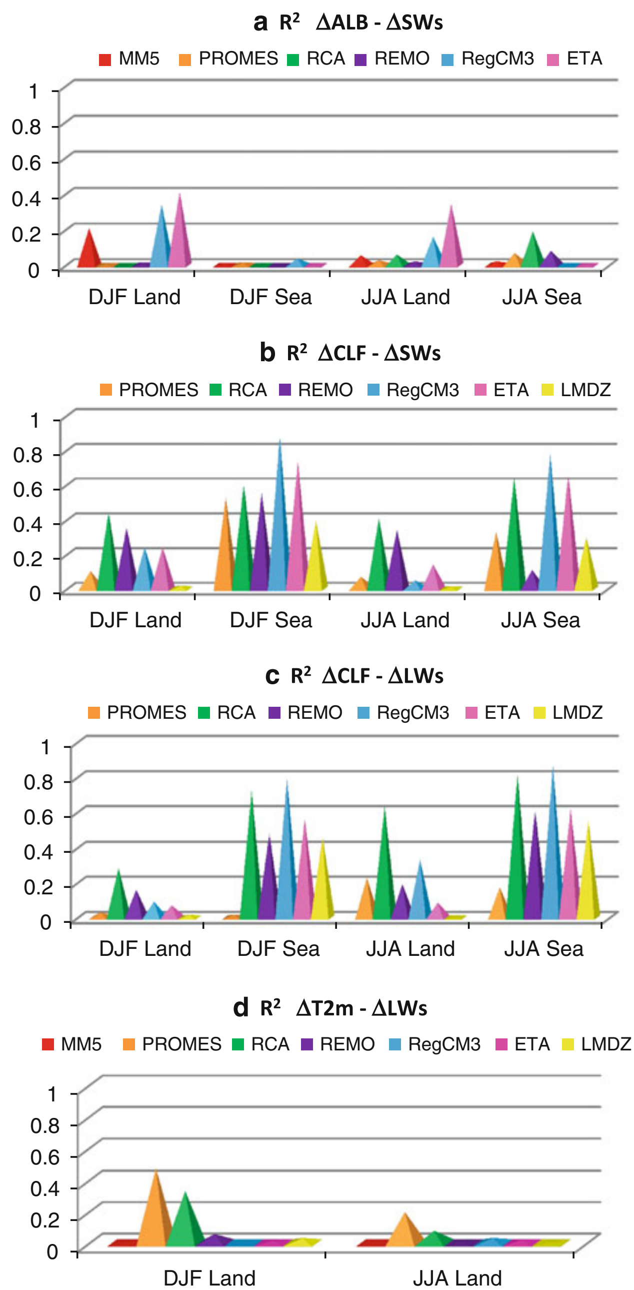


Fig. 6 Spatial average over land and ocean regions of the explained variances of the net short-wave radiation budget errors due to uncertainties in **a** albedo and **b** total cloud fraction; and for the net long-wave radiation budget error due to uncertainties in **c** total cloud fraction and **d** 2 m temperature

LWs) are measures of the explained variances of the error in the components of the radiation budget due to each of these uncertainty parameters. This method, which assumes a linear relationship between both variables, means that the Pearson correlation coefficient specifies the proportion of the variability of one of the two variables (in this case, the errors in the parameters and the errors in the LWs and SWs) that is linearly accounted for or described by the other (Wilks 1995). Based on Figs. 1 and 2, large differences between the sign of the biases for both SWs and LWs over the continental and the oceanic regions, particularly for SWs, have been detected. Because of this reason, the explained variances have been calculated as the spatial average over continental and oceanic regions, separately during summer and winter (Fig. 6). The individual uncertainty sources (Figs. 3, 4, 5) are discussed in parallel with the results for the explained variances (Fig. 6). The impacts of albedo and cloud fraction are relevant for SWs (Fig. 6a, b) while the cloud fraction and 2 m temperature for LWs (Fig. 6c, d).

Figure 3 (a, b, first panels) shows the spatial structure of the albedo based on the GEWEX-SRB dataset during austral summer and winter, respectively. The variations are associated mainly with the land cover of the region (e.g. lower values over the forest regions such as the Amazonia and the Chaco Forest; and high values of the snow-capped southern Andes Mountains particularly during winter). The range of the albedo values over South America in this dataset is similar with another satellite estimates from MODIS (Rechid et al. 2006). Figure 3 also shows the ensemble mean and individual model biases, which illustrates a high overestimation of the albedo over Argentina and tropical SA during both seasons (reaching maximum values of 100 %). Also, the RCMs have underestimated the albedo over the oceanic regions south of 20°S during winter. The areal averages of albedo biases (not shown) have indicated that they are much larger over land than over oceanic regions during both seasons.

The explained variance of SWs attributable to albedo (Fig. 6a) indicates that the impact of the albedo uncertainties is low for most of the models (less than 5 %), except for the ETA, RegCM3, and MM5 models (ranging from 20 to 40 %). Moreover, the impact of errors in albedo seems to be slightly stronger over land than over oceans. It is worth to mention that the values of explained variance for SWs due to albedo uncertainties found over SA are similar to the values found over Europe and lower than the values calculated over West Africa (Kothe et al. 2010 and Kothe and Ahrens 2010, respectively). Most land surface schemes of the RCMs use surface albedos without temporal variations and these values are prescribed by tabulated values only depending on land cover type, so it is a simple parameter in RCMs (Rechid et al. 2006). Consequently for the models with high values of explained variance due to albedo, a better representation of albedo values may yield the possibility of improving the simulated radiation budgets at surface, as was discussed in Kothe et al. (2010).

The bias for the 2 m air temperature (Fig. 4) shows that during summer all the RCMs systematically overestimate the temperature over LPB and this behavior is reflected in the ensemble mean. During winter, the RCMs ensemble mean shows a good agreement with the observations over LPB due to the bias for each model is low (less than 1 °C). Over tropical SA during both seasons, even when the bias of the ensemble is small (less than 1 °C), the uncertainty is relatively high, which is due to individual model biases (ranging from −3 to 3 °C). This behavior has been noted previously in Solman et al. (2013).

It is important to note that the surface-planetary boundary layer-atmosphere system is strongly connected. However, as described by Jaeger et al. (2008), the system does not present a clear "causality direction", which means that one can explain errors in 2-m temperature due to errors in the radiation budget or vice versa. In this study, we focus on quantifying the impact of errors in temperature on errors in LWs (Fig. 6d).This analysis is performed only for continental regions where CRU temperature data is available.

Results displayed in Fig. 6d indicate that the temperature errors in most models have a weak impact on the LWs errors, with explained variances lower than the 10 %. Only PROMES and RCA models have uncertainties in the simulation of temperature explain a larger amount of the SWs variance (45 and 35 %, respectively, during summer and less than 15 % during winter). The explained variance due to errors in temperature is also similar to those values calculated over Europe and lower than the values detected over West Africa (Kothe et al. 2010; Kothe and Ahrens 2010, respectively).

The biases in the total cloud fraction (Fig. 5) suggest that most of the models underestimate this variable over continental areas during DJF with the exception of the PROMES model, which shows a strong overestimation of the maximum of cloud fraction over the entire tropical SA region. During winter, every model depicts negative biases over LPB and oceanic regions. Positive biases over the tropical SA are apparent for most of the models, where a systematic overestimation of the cloud during winter occurs (Fig. 5b, first panel). The ETA model shows a strong underestimation over the entire domain during both seasons, consistent with the underestimation of LWs discussed above.

The explained variances of the SWs and LWs errors due to the uncertainty in cloud fraction are displayed in Figs. 6b, c, respectively. The explained variances indicate that the cloud fraction is the largest source of uncertainty for the errors in both SWs and LWs. For the long-wave (short-wave) this variable explains around of 20 and 55 % (30 and 50 %) over land and oceanic regions, respectively. The values of explained variances for SWs due to uncertainties in cloud fraction are similar to the values found for West Africa and Europe (Kothe et al. 2010; Kothe and Ahrens 2010).

Overall, results show that errors in cloud fraction have the largest impact on errors of both SWs and LWs. This result agrees with the findings for Europe (Kothe et al. 2010) where errors in cloud fraction have been the most relevant source of uncertainty in the simulated radiation budget. However, Kothe and Ahrens 2010 have shown that over West Africa errors in temperature (albedo and cloud fraction) are the main source of uncertainty in the simulated LWs (SWs). In summary, the relative importance of the impact of different sources of uncertainty has a strong geographical dependence.

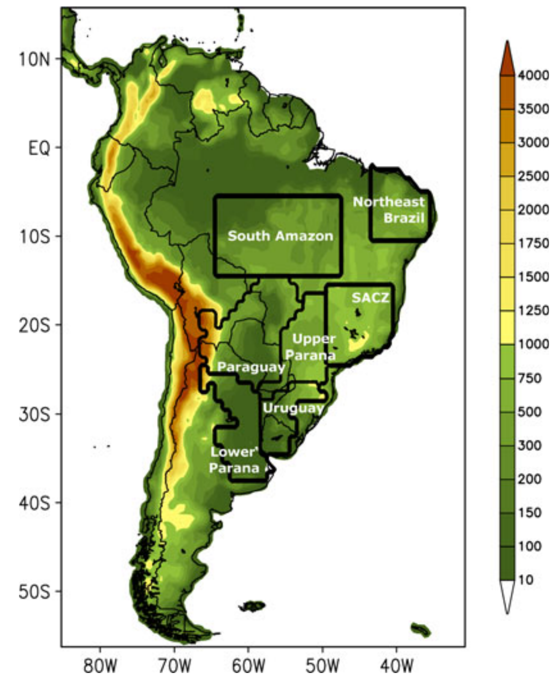


Fig. 7 Model domain and topography (*shaded*) (m). *Boxes* defined the selected regions for the analysis

3.3 Mean annual cycle

In this section, the annual cycles of the SWs, LWs and heat fluxes for each RCM are evaluated and compared with observations from GEWEX-SRB, NCEP-NCAR reanalysis and GLDAS2 datasets for further analysis of the energy budget over SA.

The mean annual cycles are analyzed over seven regions that have been defined in the context of the CLARIS LPB-Project, which are in terms of hydro-meteorological features (Solman et al. 2013). The regions are shown in Fig. 7, which include South Amazon (South-AMZ), Northeast Brazil (NE-Brazil), South Atlantic Convergence Zone (SACZ), and the sub basins of LPB (Paraguay, Low-Paraná, Up-Paraná, and Uruguay).

Most of the RCMs capture the general characteristics of the mean annual cycle of SWs and LWs based from the GEWEX-SRB dataset over the seven regions (Figs. 8, 9). However, it is important to remark that some models

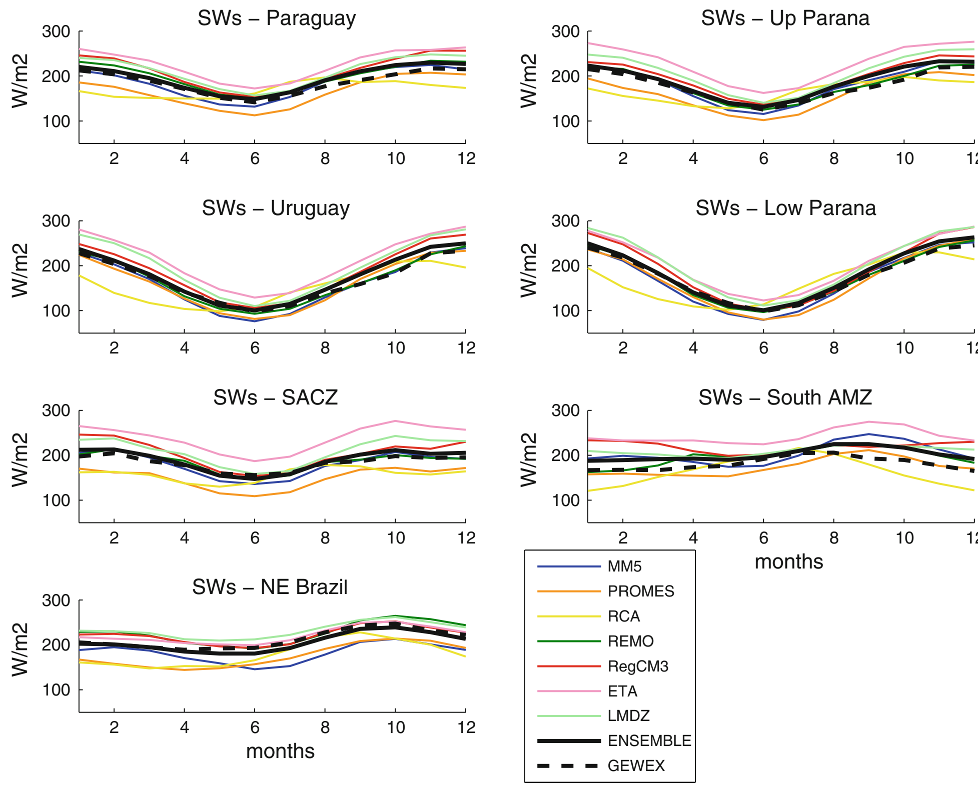


Fig. 8 Annual cycle of the net short-wave surface radiation budget (W m^{-2}) for the ensemble mean of RCMs, individual RCMs, and the GEWEX SRB dataset, area averaged over the regions defined in Fig. 7

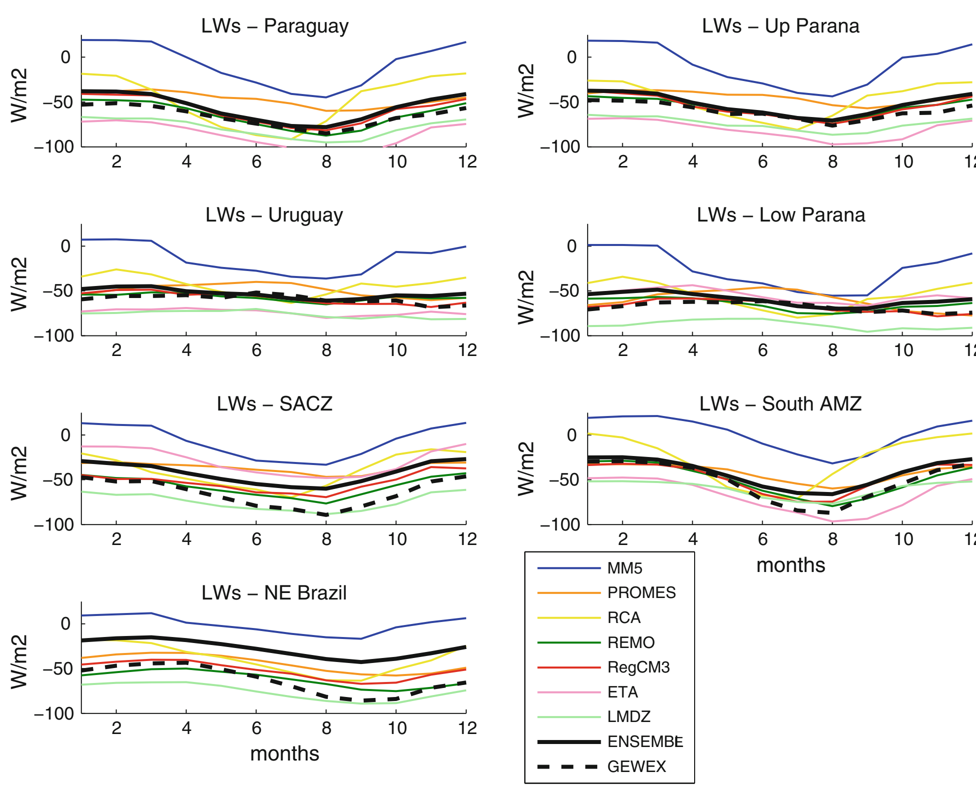


Fig. 9 Same as in Fig. 8, but for the net long-wave surface radiation budget (W m^{-2})

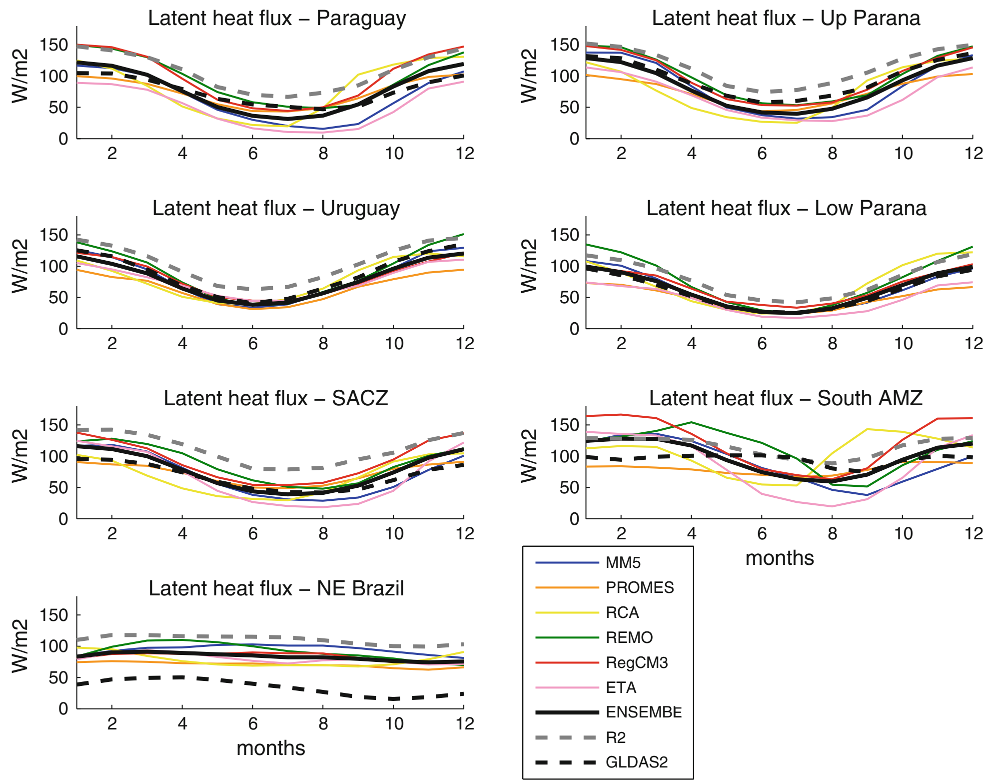


Fig. 10 Annual cycle of the the latent heat flux (W m^{-2}) for the ensemble mean of RCMs, individual RCM, the NCEP-NOAA reanalysis (R2), and the GLDAS2 dataset, area averaged over the regions defined in Fig. 7

present particular biases in these components. For the SWs (Fig. 8), the RCA model (yellow curve) shifts the minimum earlier compared with the GEWEX-SRB dataset over all regions, while the ETA model (pink curve) overestimates the SWs in all regions during all the months. It is relevant to remark also that for regions located over tropical SA (NE-Brazil, SACZ, and South-AMZ), the RCMs display the largest differences in simulating the annual cycle of SWs.

Figure 9 shows the mean annual cycles of LWs. It is noted that there is a large spread between RCMs in reproducing both the magnitude and the shape of the GEWEX-SRB dataset. The PROMES model (orange curve) fails in reproducing the annual cycle of LWs over the regions within LPB. The RCA model overestimates the LWs maximum during summer in all the regions. The LMDZ model (light green curve) shows a systematic underestimation all along the year over each region. The MM5 model (blue curve) shows a strong overestimation, probably due to the fact that the upward component of the LWs was calculated with the 2 m air temperature rather than the surface temperature as was discussed in Sect. 3.1.

Note that observations of net long wave radiation made in southern Amazonia during the ABRACOS field experiment (Culf et al. 1996) show annual values varying from -33.8 W m^{-2} in January and -68.1 W m^{-2} in September 1990–1991. These observations during summer are similar to the values calculated for the GEWEX-SRB dataset over S-AMZ. During winter, the observations showed lower values for the net long-wave radiation than the GEWEX-SRB dataset. In fact, the net long-wave radiation values observed during September are closer to the net long wave radiation during austral winter derived from the GEWEX-SRB.

Figures 10 and 11 show the mean annual cycles for the latent and sensible heat fluxes, respectively. The figures depict the ensemble mean, each RCM, the NCEP-NOAA reanalysis, and the GLDAS2 dataset at seven different subregions. Note that the LMDZ model is not shown in Fig. 10 due to data unavailability. The mean annual cycles based on the NCEP-NOAA and the GLDAS2 dataset for both latent and sensible heat fluxes are well represented in the RCM ensemble over most of the analyzed regions. However, the models systematically overestimate the sensible heat fluxes all year long compared to the NCEP-NOAA and GLDAS2 datasets. Note that the mean annual cycles of the sensible heat flux based on the ensemble are similar to the mean annual of the 2 m temperature discussed in Solman et al. 2013. In terms of latent heat fluxes, large differences between both datasets are depicted especially over tropical regions. Based on the reanalysis, the models systematically underestimated the latent heat flux over the seven regions. On the other hand, the differences between the RCMs and GLDAS2 are high over tropical regions whereas over subtropical regions such as the LPB, the models have presented a good agreement with this dataset.

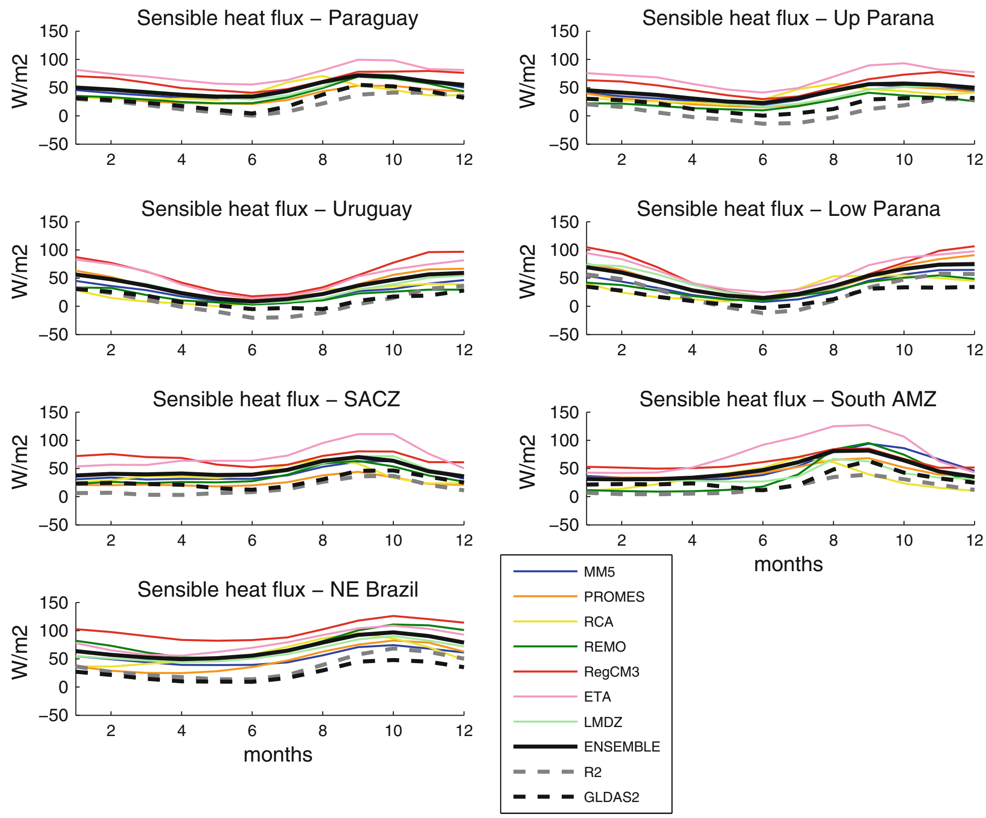


Fig. 11 Same as in Fig. 10, but for the sensible heat flux (W m^{-2})

These results lead to differences in the energy partition, which contribute to errors in the Bowen coefficient that lead to significant impacts, e.g.in the soil-atmosphere interaction processes. These results are in agreement with the large overestimation of sensible heat fluxes found over the South Atlantic Ocean associated with the cold bias in the RegCM3 model (red curve) as discussed by Reboita et al. (2010).

The South-AMZ region is where the models present the largest errors (ranging from −80 to 40 %) and the largest spread, which is mainly for the latent heat flux. This result may be related with the variety of land-surface models used including the various prescribed vegetation cover in the individual RCMs evaluated in this study. Moreover, the land–atmosphere interaction is particularly strong over tropical SA and may impact on the model performance (Sörensson et al. 2010). In South-AMZ, observations measured during the Rondonia Boundary Layer Experiment (RBLE-II), field experiment during July 1993 (Nobre et al. 1996), show values of 30 W m^{-2} for sensible heat and 100 W m^{-2} for the latent heat, which are similar to the mean July values from the reanalyses and GLDAS2. Additionally, during the LBA (Large-Scale Biosphere–Atmosphere Experimentin Amazonia) field experiment, the measures of the heat fluxes over 3 flux tower stations located in the S-AMZ (da Rocha et al. 2009a, b) are similar to the values for the NCEP-NOAA and GLDAS2 datasets, but the reanalysis did not reproduce well the seasonality of the sensible heat flux in comparison with these local observations, in which an underestimation of the second maximum during March–April occurs.

Over LPB, a good agreement between the simulation of the latent heat flux from RCMs and the GLDAS2 values can be seen. However, all the models systematically underestimate the latent heat flux in comparison with the reanalysis, especially during winter months. This result may explain, in part, the systematic underestimation of precipitation of these RCMs during JJA, as was discussed in Solman et al. (2013). During summer, the spread among models in simulating both the latent and sensible heat fluxes is large. The variety of land-surface schemes and the strong land-atmospheric coupling over this region (Sörensson et al. 2010) may be associated with this behavior.

4 Discussion and conclusions

In this study, the net short- and long-wave surface radiations budgets over South America are analyzed using an ensemble of seven regional climate simulations performed in the context of CLARIS-LPB Project for the period 1990–2007. Additionally, the uncertainty sources in the simulation of the radiation budgets and the mean annual cycles of the components of the energy budget are explored.

Most of the RCMs overestimate the net short-wave radiation over tropical SA and LPB and underestimate it over the ocean during both summer and winter. The errors in the short-wave radiation budget over land areas are associated with uncertainties in the simulated cloud fraction and, to a lesser extent, with uncertainties in surface albedo. Over ocean regions, the net short-wave radiation budget underestimation is largely explained by uncertainties in cloud fraction.

Concerning the net long-wave surface radiation budget, there is no clear error patterns since individual models show different model behavior; some have depicted overestimation over the entire domain while others have depicted underestimation during both seasons. The long-wave radiation errors are explained in a large proportion by errors in the simulation of cloud fraction especially over the ocean.

It is important to highlight the significant role that cloud fraction plays in modulating both the short- and long-wave radiation components. Cloudiness is fundamental in the interaction between the soil and the atmosphere, connecting the energy and water budgets. However, the cloudiness continues to be the major uncertainty source in the climate models (IPCC 2007; Jaeger et al. 2008).

In addition, a proportion of the errors in the net short-wave radiation are explained by errors in albedo. As was discussed previously, for many models the surface albedo is a prescribed parameter, consequently one way to improve model performance may be by simply adjusting the prescribed values of albedo to observed values.

The annual cycles of the energy budget over the seven selected regions indicates that most of the RCMs reproduce well the main characteristics of the net short- and long-wave radiation budgets in terms of timing and amplitude. But two models (RCA and PROMES) have completely misrepresented the annual cycles. In the tropical regions, the models' errors and spread are larger than in the subtropical region (LPB). These results are consistent with the findings in Solman et al. (2013), where they have shown that the reliability in simulating mean climate over tropical regions is lower compared with the LPB region.

All models have shown a systematic overestimation of the sensible heat flux in all sub-regions. For the latent heat flux, large differences are observed between the datasets used to validate the RCMs, particularly over tropical areas. All RCMs have presented underestimation of the latent heat flux in comparison with the reanalysis whereas a good agreement with the GLDAS2 dataset over LPB region is depicted. It is important to bear in mind that only the NCEP-NOAA reanalysis and GLDAS2 dataset are used for quantifying model bias for the latent and sensible heat fluxes due to the scarce local observations for these variables (da Rocha et al. 2009a, b). Therefore, these results should be taken with care. These systematic errors in both latent and sensible heat fluxes from the RCMs drive the biases in the Bowen ratio which indicates how the energy reaching the surface is partitioned. Over tropical areas, the simulated Bowen ratio is greater than 1 indicating that the evaporative cooling near the surface is insufficient and the modelled sensible heating is overestimated, in contrast with the reanalysis. This result suggests that the RCMs may have difficulties in representing the surface processes and consequently, the land–atmosphere interaction.

The analysis of the model performance in terms of energy budget allows us to better understand the biases in the simulated climate, mainly temperature and precipitation, which has been identified in Solman et al. (2013). They have shown that the RCMs ensemble is warmer and dryer over the tropical regions than over the LPB region in regard with observations dataset, during the summer season. During the winter season, the models overestimate (underestimate) temperature over the South Amazon region (SACZ) and underestimate rainfall over northern SA and LPB.

We have shown that the models tend to overestimate the net short-wave radiation for the austral summer over the tropical regions, mainly due to an underestimation of cloud fraction. Models also overestimate the sensible heat flux. Both features lead to a small positive bias in the total energy budget (e.g. 7 W m^{-2} for the South-AMZ region), which is consistent with the small positive temperature bias in that region. The underestimation of cloud fraction and latent heat flux is also consistent with the models being dryer than observations. In the LPB region, cloud fraction is strongly underestimated and the albedo is overestimated by almost every model, in which the cloud fraction effect is more dominant than albedo, leading to an overestimation of the net short-wave budget. As for the tropical region, the sensible heat flux is overestimated and the total energy budget is highly overestimated. These results may explain the biases in temperature andprecipitation over LPB. Further analysis for understanding precipitation biases should also include the evaluation of the water budget, in which the moisture flux convergence plays a relevant role, but this is out of the scope of this work.

The highest temperature bias for the winter months over South Amazon seems to be dominated by the large overestimation of the sensible heat flux. A systematic underestimation of cloud fraction in each model is consistent with dryer conditions over LPB. However, precipitation bias is also related with other mechanisms, such as the moisture flux convergence and synoptic activity, which are important mechanisms for this region.

It is also important to highlight that small biases in the simulated temperature and precipitation for some models, may be due to compensation of errors in the individual components of the energy budget. This means that some models may perform well but for the wrong reasons. For example, RCA model reproduces summer temperature with a small bias (less than 1 °C), however, this model underestimates both the net short- and long-wave radiation budgets, yielding a small bias in the total energy budget.

Finally, the analysis of the energy budget allows the evaluation of models in reproducing the underlying physical mechanisms and in identifying the uncertainty sources of the individual components of the energy budget. This analysis may help in the improvement of specific physical parameterizations, such as cloud schemes, planetary boundary layer and land-surface schemes, which will certainly lead to a better quality in simulating the climate.

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