A comparative study of two land surface schemes in regional climate integrations over South America

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[1] A case study comparison using two different land surface models in the Regional Spectral Model (RSM) is presented here. This comparison is motivated from recent studies that show a significant impact of land surface processes on the predictability of precipitation at seasonal to interannual scales. We find in this comparative study that coupled land-atmosphere interactions using the simplified simple biosphere (SSiB) scheme and a two-layer soil (control) model with uniform vegetation fraction yield mixed results. It does not clearly indicate the superiority of one scheme over the other for this particular case. The warmer mean surface temperatures simulated by RSM-SSiB improve the seasonal (January-February-March [JFM]) simulation over Amazon River Basin, along Brazilian Highlands, over Bolivian Plateau, and over central America relative to the control model. However, the RSM-SSiB runs exhibit a strong warm bias in the surface temperature over the subtropics of South America. The mean JFM onshore easterly flow from the tropical Atlantic Ocean and the low-level jet are relatively stronger in the SSiB model. The mean JFM precipitation from the RSM-SSiB model shows an improvement over Guianan Highlands, Venezeulan Llanos, and Amazon River Basin. However, the mean JFM precipitation of the control model over the Caribbean Sea, Central America, and equatorial eastern Pacific Ocean is better than the SSiB model. *INDEX TERMS:* 1836 Hydrology: Hydrologic budget (1655); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; 9360 Information Related to Geographic Region: South America

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1. Introduction

[2] This is a sequel to a recent paper on regional climate simulation over South America [*Misra et al.*, 2002, hereafter M2002]. In the earlier paper we used a control version of the Regional Spectral Model (RSM) following *Juang and Kanamitsu* [1994]. Since then we have implemented the simplified simple biosphere (SSiB) scheme following *Xue et al.* [1991] and *Dirmeyer and Zeng* [1997, 1999], as an alternative land surface parameterization in the RSM to the existing land surface scheme of *Mahrt and Pan* [1984]. Our interest in using a more sophisticated land surface scheme in regional climate modeling stems from recent studies, which have shown a significant impact of land surface processes on the predictability of precipitation on seasonal to interannual scales [*Fennessy and Shukla*, 1996; *Paegle et al.*, 1996]. Many of these modeling studies have shown the importance of the soil wetness on the evolving climate. *Viterbo and Betts* [1999] and *Dirmeyer* [2000] using initial soil moisture conditions, calculated offline by forcing a 2-D version of the same land surface scheme as that of the general circulation model (GCM) with analyses of near surface meteorological conditions, showed substantial improvement in the climate anomalies generated from the GCM. Furthermore, recent studies have shown a critical relationship between the soil moisture and the surface fluxes which are well captured by the more advanced land surface schemes [*Dirmeyer et al.*, 2000].

[3] The first SSiB scheme developed by *Sellers et al.* [1986], and later simplified by *Xue et al.* [1991], is one of the many complex land surface schemes in existence now. One of the main motivating factors to choose this scheme over others is that the SSiB has been continuously developed in Center for Ocean-Land-Atmosphere General Circulation (COLA) and is well tested offline [*Dirmeyer*, 2000; *Dirmeyer et al.*, 2000] and in the COLA GCM [*Fennessy and Shukla*, 1996].

[4] The current GCMs lack the horizontal resolution to resolve regional orographically forced precipitation and fine scale synoptic and meso-scale systems which contribute significantly to the local climate. The current computing resources preclude the increase of the horizontal resolutions of these GCMs to very fine scales. An alternative approach that the community has adopted is the use of limited area models nested within the coarser grid resolution of the GCM. The increased horizontal resolution of the regional climate model has shown great promise in addressing seasonal predictability issues over western U.S. [*Giorgi*, 1990], over Indian monsoon region [*Ji and Vernekar*, 1997],

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over the South American region [*Tanajura*, 1996; *Chou et al.*, 2000; M2002]. M2002 show that the RSM is able to enhance the information content at intraseasonal (30–60 days) and very high frequency (3–30 days) scales over the South American region relative to the coarser National Center for Environmental Prediction (NCEP) reanalysis.

[5] Another motivating factor for this work was that South America has a considerable spatial heterogeneity in the vegetation and soil types, which could influence the local climate. The vegetation controls the transfer of moisture from the soil to the overlying atmosphere through transpiration. Furthermore, the vegetative cover insulates the ground and modulates the radiation and momentum transfer at the surface [*Dickinson*, 1983]. The vegetation type also affects the surface roughness length which can alter the distribution of the moisture flux convergence [*Sud et al.*, 1988].

[6] In the following section, we shall briefly describe the two land surface schemes which are coupled to the atmosphere of the RSM. The readers are referred to *Juang and Kanamitsu* [1994], *Juang et al.* [1997], and M2002 for details on the RSM. The results are presented in section 3 followed by conclusions in section 4.

2. Model Description

2.1. SSiB Model

[7] The SSiB is based on a simplification [*Xue et al.*, 1991, 1996] of the Simple Biosphere Scheme (SiB) proposed by *Sellers et al.* [1986]. This simplification entailed the reduction of vegetation layers from two to one with ground cover vegetation being removed, simplified stomatal resistance on root-zone soil wetness, and fluxes of heat and water between canopy and the adjacent atmosphere parameterized using a linearized version of the Monin-Obukhov theory. However, the full two stream calculation for surface radiation [*Sellers*, 1985] has been retained. The SSiB has 8 prognostic variables in canopy air space temperature, two (top and deep) soil temperatures, three soil moisture stores and two interception water stores in the canopy and ground.

[8] From the atmospheric model (RSM), SSiB receives temperature, vapor pressure and wind speed at the lowest sigma level of the RSM and precipitation rate, solar zenith angle, the rain/snow flag (based on the temperature at 850 hPa), short wave and long wave radiation flux at surface. The SSiB communicates back to RSM with sensible and latent heat fluxes, roughness and drag coefficient for momentum fluxes.

[9] The fluxes in SSiB are determined as a ratio of potential difference to resistance. There are three aerodynamic resistances corresponding to the resistance between the soil surface and canopy air space; resistance between canopy leaves and canopy air space; and the resistance between canopy air space and reference height. These resistances are obtained as a function of the morphology of vegetation, soil type, wind speed and corresponding potential difference of temperature. Additionally, two more resistances, viz., bulk stomatal resistance and bare soil surface resistance are imposed to the flux of water vapor from upper soil layer and from within the canopy to the adjacent air. The readers are referred to *Sellers et al.* [1986] for the details of these resistances. The spatially varying soil parameters and spatiotemporally varying vegetation parameters are prescribed from the International Satellite Land Surface Climatology Project (ISLSCP) Initiative I land surface data set [*Meeson et al.*, 1995].

2.2. Control Soil Model

[10] The soil moisture model of *Mahrt and Pan* [1984] is a two-layer model. It consists of a thin upper layer of 5 cm thick and a thicker lower layer of 95 cm. Surface evaporation and the response to diurnal variations are related to soil moisture near the surface while storage of soil water and transpiration are related to soil moisture in the deeper layer. The hydraulic conductivity and diffusivity are not properties of the soil but rather functions of soil moisture profile near the surface. Any precipitation which cannot infiltrate or reevaporate is specified to be runoff. There are five prognostic equations corresponding to the soil moisture content, the soil temperature at the surface and at the deep layer of the soil and an equation for the canopy water content. The vegetation fraction is assumed to be constant at 0.7 and soil type does not vary spatially. The surface boundary conditions for the soil water content and temperatures are the corresponding fluxes, while deep layer drainage and prescribed deep soil temperature are the bottom boundary conditions, respectively.

[11] In both versions of the RSM, the atmospheric variables were coupled to the ground surface temperature and soil temperatures. This coupling is accomplished with implicit time integration for the dependent variables with explicit transfer coefficients. To remove occasional large amplitude oscillations in surface and soil temperatures we adopt the time filtering technique of *Kalnay and Kanamitsu* [1988]. The readers are referred to *Misra et al.* [2001] for a detailed description of the coupling of land surface schemes to the atmosphere in the RSM.

2.3. Model Configuration

[12] To facilitate comparison with the control model results presented in M2002, the configuration for the coupled RSM-SSiB model is made identical to the control run. The details of the integration are listed below:

1. Horizontal resolution: 80 km
2. Number of vertical levels: 28
3. Domain dimensions: 217 (zonal) × 112 (meridional)
4. Time step: 240 s
5. Start dates of the three integrations: 0000 UTC, 13 December of 1996, 1997, and 1998
6. End dates of the three integrations: 0000 UTC, 1 June of 1997, 1998 and 1999
7. Lateral boundary conditions: NCEP reanalysis provides time dependent fields of the prognostic variables of the model which is updated every 12 hours. The resolution of the NCEP reanalysis is 209 km (T62 spectral truncation). Any nesting (merging) exercise involves a data discontinuity in the regional model domain. However, this discontinuity is ameliorated through a sponge zone which is 10 grid points thick in the RSM along the lateral boundaries where the data relaxes smoothly to the large scale analysis at the end points of the domain from a regional model value at the beginning of the sponge zone [*Juang and Kanamitsu*, 1994].

8. Surface boundary conditions: time varying SST field are updated daily by linearly interpolating weekly *Reynolds and Smith* [1994] optimally interpolated SST data set.

3. Results

[13] We refer to the model results of M2002 as the control, and to SSiB for the results from the RSM coupled to the SSiB. The two models will be compared with available independent observations. In the absence of observations, we only emphasize the reasons behind the different features exhibited by the model simulations. We will compare the mean fields (averaged over the three simulations) of the two models. The difference in the interannual variability between the two models was found to be insignificant.

3.1. Outgoing Longwave Radiation

[14] As in the previous paper [M2002], we have examined the variance of the outgoing longwave radiation (OLR) anomalies at the intraseasonal (30–60 days) and high-frequency (3–30 days) scales. Observational studies [e.g., *Paegle and Mo*, 1997] have shown that there is a strong teleconnection between the convection over subtropical South America and tropical convection in the eastern Pacific. Furthermore, this teleconnection has important implications on the predictability of precipitation over the South Atlantic Covergence Zone (SACZ) region. In addition, M2002 indicated that there is significant change in the statistics of the weather over continental South America in going from one phase of the ENSO to another.

3.1.1. Intraseasonal Variability

[15] In (Figures 1a and 1b) we show the January-February-March (JFM) difference in the mean variance of the 30–60 days filtered OLR anomalies between the SSiB (Control) run and observations [*Liebmann and Smith*, 1996]. These differences are computed at the observational grid which is at 2.5°lat/lon grid. The figures indicate that the SSiB run improves the simulation at these intraseasonal scales over the SACZ region in the continental South America. However, the error in mean variance over the Venezuelan Llanos, the Guianan Highlands and east of Bolivian Plateau are nearly the same in both models. Outside continental South America, the SSiB model exacerbates the error in an area stretching from the Caribbean Sea over Cental America to equatorial eastern Pacific Ocean (EEPO). The errors in the rest of the domain are similar in both models.

3.1.2. High-Frequency Variability

[16] In a similar manner, we also examined the variance of the high-frequency OLR anomalies from the two models. The results of this comparison for JFM is presented in Figures 2a and 2b. From the figures it is generally seen that the two models underpredicted the variance of high-frequency OLR anomalies over most of the continental regions and tropical Atlantic Ocean. The SSiB simulation increases the variance of the high-frequency OLR anomalies over subtropical South America and northeast Brazil relative to the control, thereby bringing the simulation into better agreement with the observations. Similar to the intraseasonal scales, the SSiB model tends to increase the errors relative to the control model with higher variance especially over Central America and EEPO.

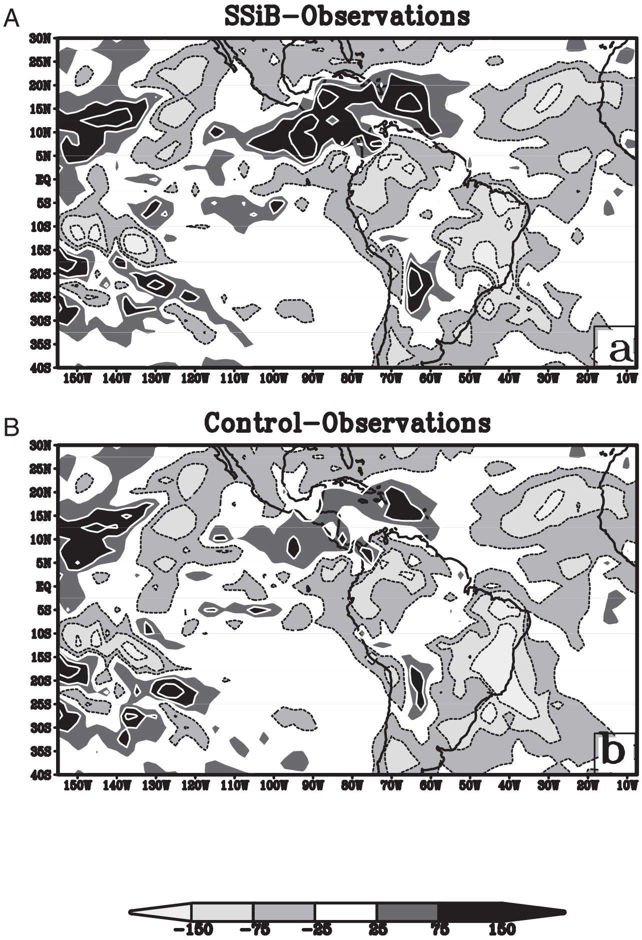

Figure 1. Error in mean variance of 30–60 days OLR anomalies for Jan-Feb-Mar of 1997 from (a) SSiB and (b) Control models. The positive values are contoured white while the negative values are contoured with dashed black lines. Units are in W^2/m^4.

3.2. Precipitation

[17] In Figures 3a–3c the mean JFM precipitation from the SSiB simulation, observations available at 2.5° lat/long grid [*Xie and Arkin*, 1996] and the control simulation are shown. At the outset, the resemblance in the simulation of mean precipitation by both model integrations is more striking than the differences between them. Both models simulate an erroneous split inter tropical convergence zone (ITCZ) over the Atlantic and Pacific Oceans, intense continental precipitation over west and northwest regions of South America, and local maxima over the Caribbean Sea and eastern Atlantic Ocean. Furthermore, both models overestimate the orographic precipitation along the Cordillera Occidental and along the Bolivian Plateau. The orientation of the precipitation band in the range of 8–16 mm day^{-1} from northeast Brazil to the northwest corner of Amazon River Basin (ARB) is very similar in both model simulations. We find that this orientation of the precipitation over the region is very similar to the orientation of the soil wetness (not shown) prescribed initially from National

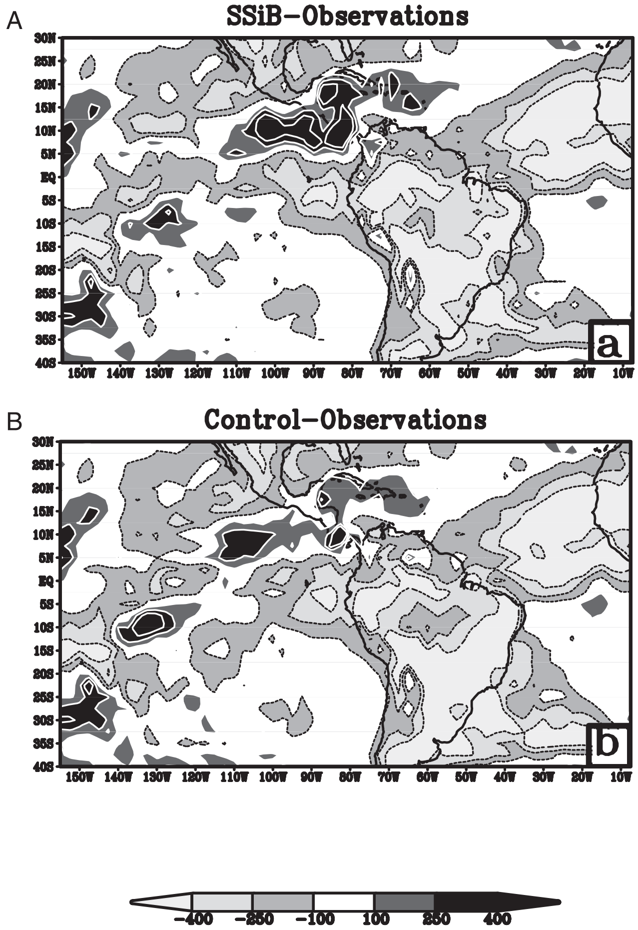

Figure 2. Same as Figure 1 but for OLR anomalies at 3–30 day scale.

Center for Environmental Prediction (NCEP) reanalysis and maintained through the integration by both models.

[18] We have plotted the errors in mean precipitation in Figure 4 for both the models. The SSiB model improves the simulation of the mean JFM precipitation relative to the control model over Venezuelan Llanos and Guianan Highlands. The SSiB model also reduces mean precipitation errors, albeit slightly, over ARB. The coupled RSM-SSiB model also deteriorates the simulation relative to the control model over the Brazilian Highlands and over Sierra De Cordoba just east of the Bolivian Plateau. Over the oceans and Central America, the precipitation errors are nearly the same in both models. As in M2002, we also examined the probability density function (pdf) of the precipitation rate [see M2002, Figures 13 and 14] in the SSiB runs (not shown). We found that the pdf of precipitation and its interannual variability in the two models were very similar. This consistency in the two different versions of the model further supports the conclusion in M2002, that the interannual variability of precipitation over South America is accompanied with a change in the number of days of heavy precipitation.

3.3. Surface Temperature

[19] In Figure 5a we show the observations of the mean surface temperature [*Ropelewski et al.*, 1985] averaged over JFM 1997, 1998, and 1999 (data void regions are denoted by the blank spaces in the figure). The resolution of the gridded surface temperature observations is approximately 300 km. In Figures 5b and 5c we plot the mean surface temperature errors from the SSiB and the control model, respectively. In the mean, the warmer surface temperatures from the SSiB simulation improves the simulation over Central Amazon, along Brazilian Highlands and over central America. However, the warm bias over subtropical regions of the Pampas and in the Gran-Chaco area are exacerbated by as much as 6°C in the SSiB runs. The NCEP reanalysis surface temperatures (not shown) also exhibited a

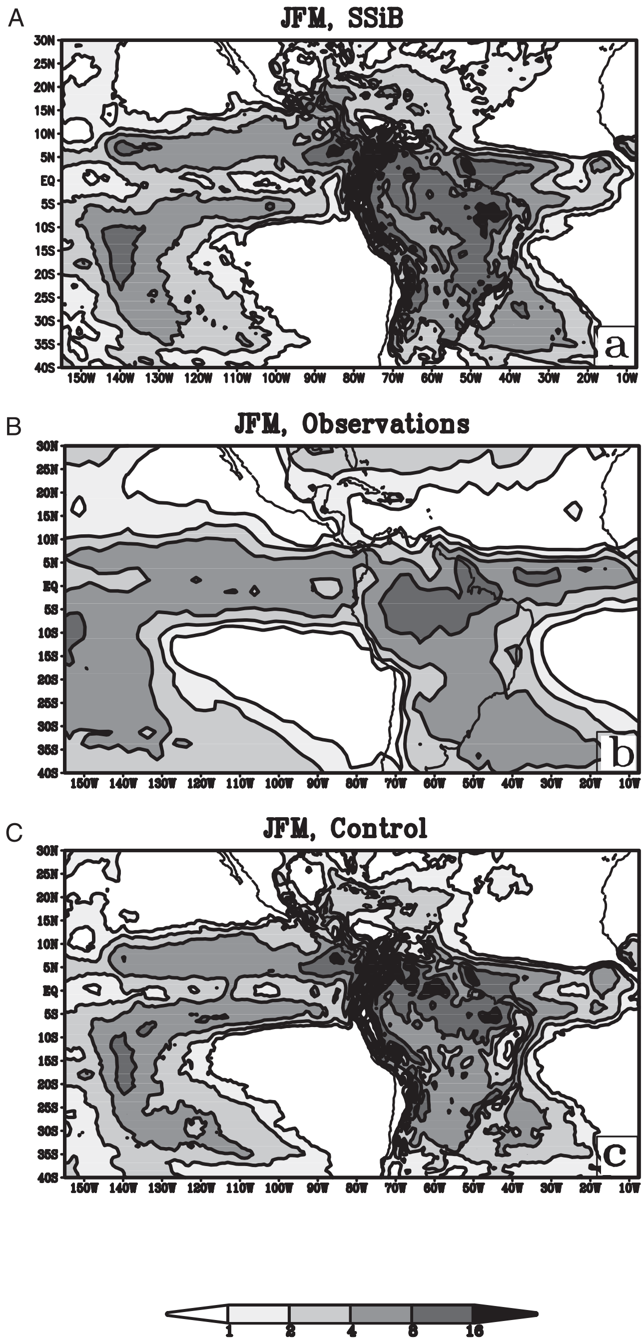

Figure 3. JFM mean precipitation from (a) SSiB run, (b) Observations, and (c) Control. The units are in mm/d.

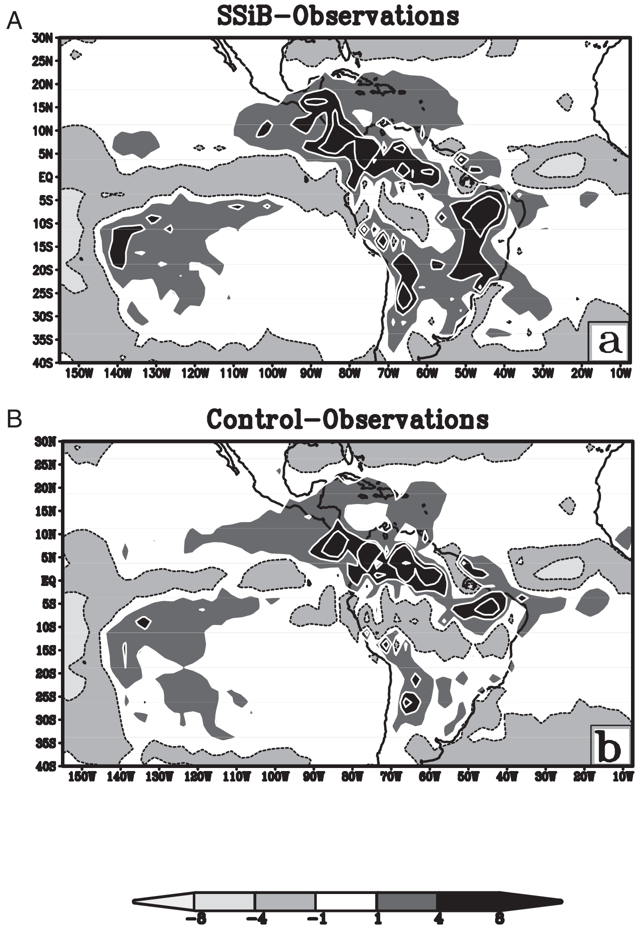

Figure 4. Error in mean JFM precipitation from (a) SSiB run and (b) Control models. The units are in mm/d.

similar warm bias over this region. The amplitude of this bias is further amplified in the SSiB simulations. In addition to the biases in the lateral boundary conditions, it is found that SSiB, relative to other land surface schemes, has a tendency to partition the total energy at the surface with higher sensible and lower latent heat fluxes [*Dirmeyer et al.*, 2000]. The difference in the mean surface fluxes for the JFM season between the SSiB and control models are shown in Figure 6. The sensible heat flux from the SSiB runs in the subtropics of South America is about 50 W m^{-2} higher than the control and the latent heat flux is correspondingly less by about the same amount. This relative reduction in surface evaporation (thereby reducing surface cooling) and an increase in sensible heat flux in the SSiB model may have resulted in the warm bias over this subtropical region. The surface temperature errors in the rest of the continental regions of the model domain are similar in both models.

3.4. Low-Level Circulation

[20] The low-level jet (LLJ) is a significant feature of the monsoon system of South America. It serves as a conduit for the supply of moisture into the subtropics from the ARB. Observational studies [*Wang and Paegle*, 1996] indicate that moisture flux uncertainties in subtropical South America in the various analyses is nearly on the order of 50%. They find that this uncertainty is largely contributed from the meridional component of the wind due to the substantially different LLJ in the analyses.

[21] In Figure 7a we illustrate the mean JFM 850 hPa circulation field from the SSiB model, while in Figure 7b we display its difference with respect to the control model. It is seen from the figure that the mean LLJ along the eastern slopes of the Andes Mountains is at least 4 m/s stronger than the control model, especially just east of the Bolivian Plateau. Furthermore, in the mean, the SSiB simulation shifts the LLJ slightly to the north and makes it more northwesterly than the control near the Bolivian Plateau. This weakens the prevailing easterly associated

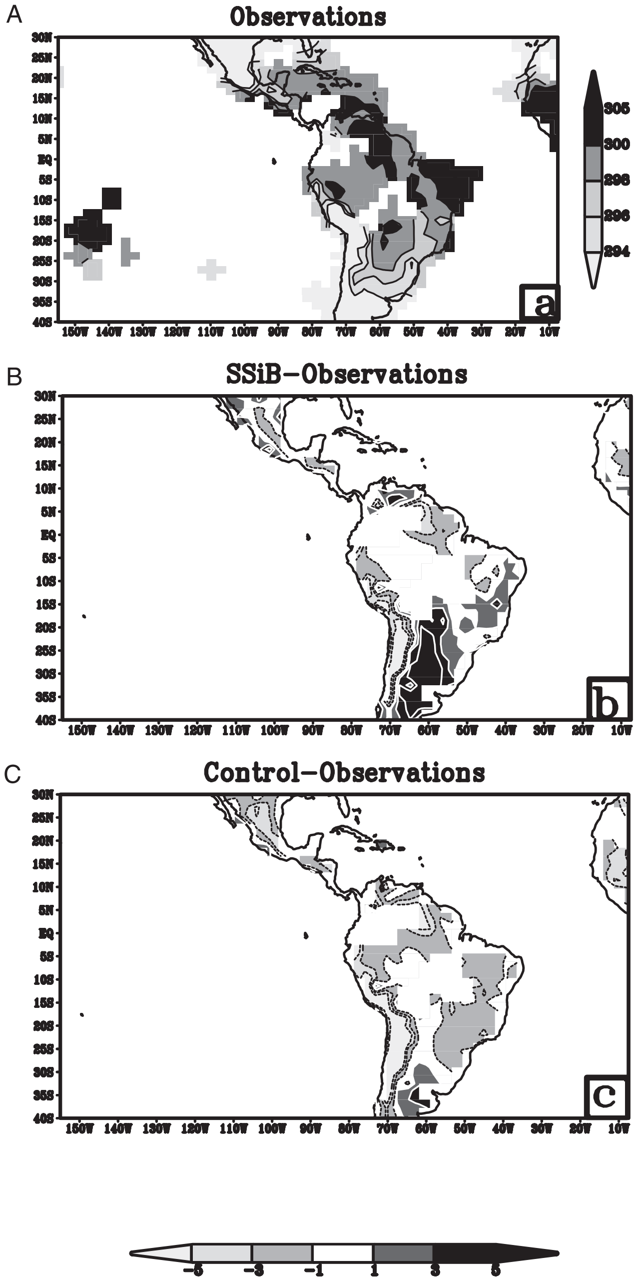

Figure 5. (a) Mean JFM surface temperature from observations. Mean JFM surface temperature errors from (b) SSiB and (c) Control models. The units are in K.

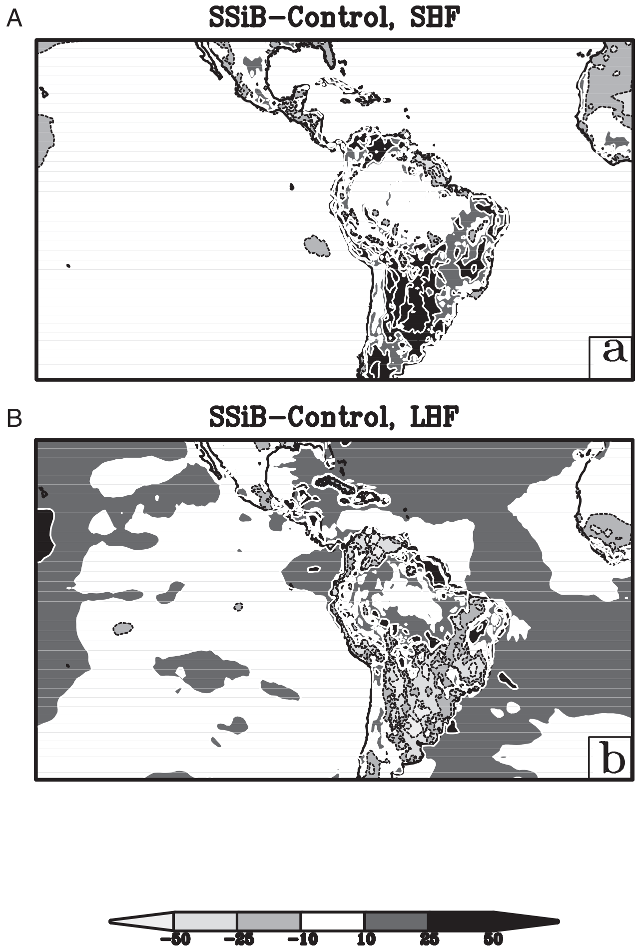

Figure 6. Mean seasonal (JFM) difference of (a) sensible heat flux (SHF) and (b) latent heat flux (LHF) between the SSiB and Control models. The positive values are contoured white and negative values are contoured with dashed black line. The units are in W m^{-2}.

with the anticyclone circulation of the south Atlantic subtropical high. The enhanced onshore easterly flow from the tropical Atlantic simulated by the SSiB run becomes more northerly near the eastern slopes of the Andes Mountains, which then contributes to the intensification of the LLJ despite a slight weakening of the subtropical high over the south Atlantic Ocean. It was shown in M2002 that the interannual variability of the LLJ was modulated by variability in the strength of the subtropical high over the south Atlantic Ocean. In addition, the SSiB simulation has the mean surface pressure just east of the Andes Mountains that is slightly lower than the control simulation (not shown), which, in turn, modulates the easterly onshore flow from the Atlantic. The easterly over eastern Pacific Ocean are relatively weaker in the SSiB run. The differences in the low-level circulation between the two models are comparably smaller over the rest of the domain.

3.5. Moisture Budget

[22] From our previous discussion it follows that the low-level flow is notably different in the two models over the South American region. This has implications on the moisture budget over the area. In Figures 8a–8f we show the components of the atmospheric moisture budget averaged over the JFM season over all three simulations of 1997, 1998 and 1999 over ARB, Gran-Chaco (GRAN), Pampas (PAM), ITCZ over Atlantic (ITCZ), Nordeste (NOR) and SACZ. The outlines of these regions are shown in Figure 9. Furthermore, the difference (diff) in the seasonal means between the two model simulations (SSiB-control) is also depicted in Figure 8. The moisture flux convergence (MFC) is obtained as a residual in these budget computations. It is clear from the figure that the moisture budget over the tropical areas of ARB and ITCZ over the Atlantic (Figures 8a and 8d) has the least difference between the two models. However, further south over GRAN and PAM (Figures 8b and 8c) the moisture flux convergence over the JFM season in the SSiB runs are relatively high compared to the control by about 1.8 and 0.5 mm/d respectively. Over GRAN, this results in an increase in precipitation in the JFM season, despite a small reduction in the surface evaporation (SE) relative to the control run.

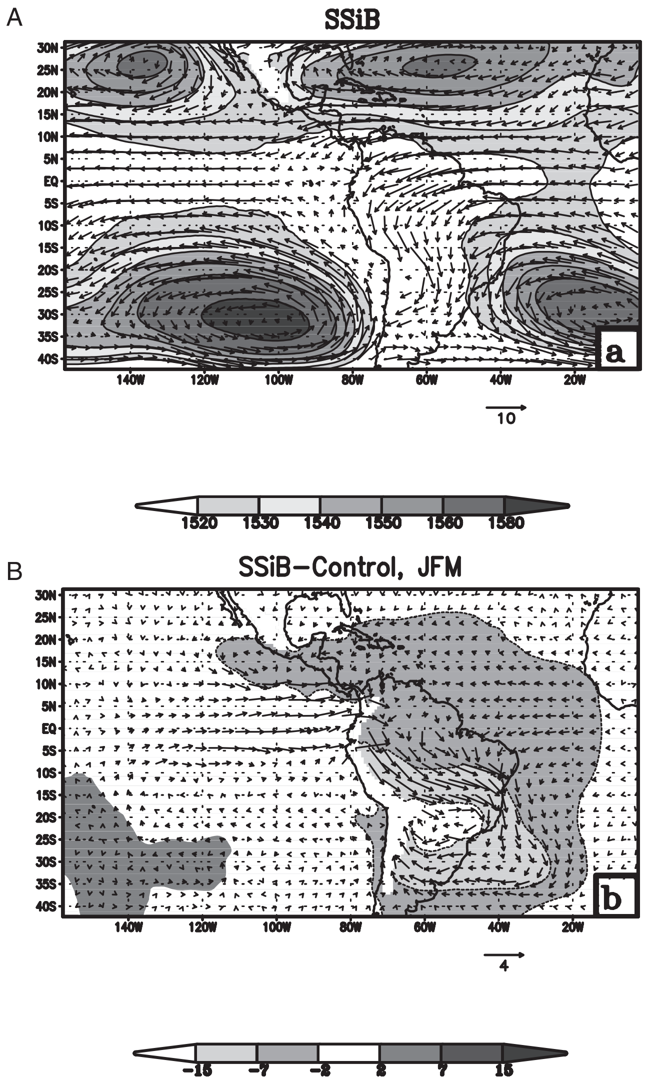

Figure 7. (a) Mean JFM 850 hPa circulation field superposed over 850 hPa heights from the SSiB model and its (b) difference with the corresponding mean control simulation. The height field are in m and winds are in m/s.

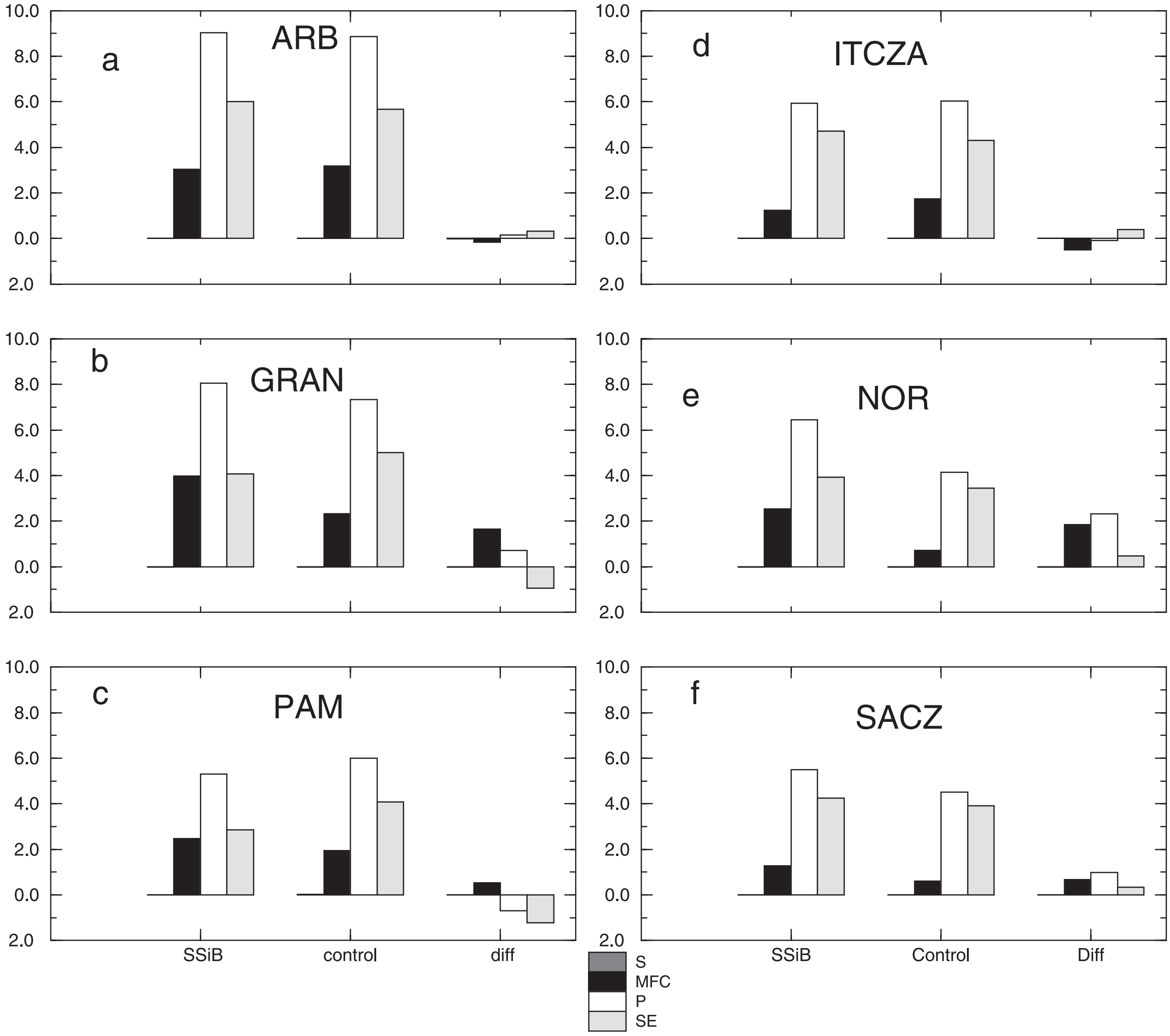

Figure 8. The moisture budget for JFM from the control and SSiB versions of RSM averaged over all 3 simulations of 1997, 1998, and 1999 over (a) Amazon River Basin (ARB), (b) Gran-Chaco (GRAN), (c) Pampas (PAM), (d) ITCZ over Atlantic (ITCZ), (e) Nordeste (NOR), and (f) SACZ. The moisture budget components are storage (S), moisture flux convergence (MFC), precipitation (P), and surface evaporation (SE). “diff” corresponds to SSiB-control. The units are in mm/d.

However, over PAM, the increase in moisture flux convergence is not sufficient to offset the decrease in surface evaporation in the SSiB runs, resulting in slightly less precipitation than the control run. In the NOR region, the increased intensity of onshore flow in the SSiB model has resulted in an increased moisture flux convergence accompanied by a small increase in surface evaporation. This has significantly enhanced the precipitation over the NOR region in the SSiB runs relative to the control run. Likewise in the SACZ region, there is a increase in moisture flux convergence and surface evaporation in the SSiB runs relative to the control resulting in more precipitation in the coupled RSM-SSiB model.

[23] Drawing an overall picture from the differences in the mean low-level circulation and the moisture budget between the models, it can be said that the relative strengthening (weakening) of the easterlies in the tropical Atlantic (Pacific) Ocean in the SSiB model, modulates the moisture flux convergence and surface evaporation sufficiently to cause a change in the mean austral summer seasonal precipitation relative to the control model. This results in a general improvement of the precipitation simulation in the SSiB model east of the Andes mountains (central ARB, Venezeulan Llanos, Guianan Highlands), while it deteriorates the simulation west and north of the Andes Mountains (Central America, EEPO, Caribbean Sea).

4. Conclusions

[24] In this paper, we have made a comparison of two land surface schemes on the evolving regional climate simulation over South America. This examination was accomplished by comparing a control version of the RSM which had the *Mahrt and Pan* [1984] land surface scheme

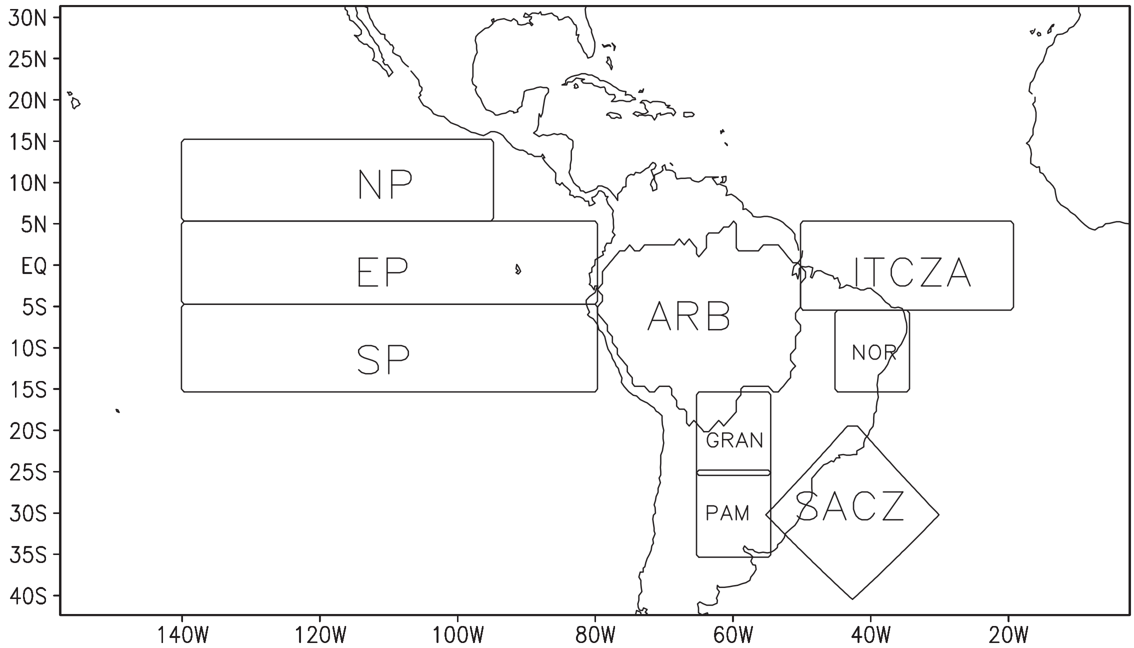

Figure 9. Outline of the Amazon River Basin (ARB), ITCZ over Atlantic (ITCZA), Nordeste (NOR), SACZ, Pampas region (PAM), Gran Chaco area (GRAN), South Pacific (SP), equatorial Pacific (EP), and North Pacific (NP). This is based on *Misra et al.* [2001].

with coupled RSM-SSiB model simulations. Among the many differences between the two schemes, the most striking is that the control RSM had a homogeneous vegetation and soil distribution while in SSiB there are 12(6) different vegetation (soil) types defined.

[25] This comparison of the two land surface schemes coupled to a regional atmospheric model (RSM) yielded mixed results which does not clearly indicate the superiority of one scheme over the other. At intraseasonal sales, the SSiB model showed some relative improvement in the SACZ region while it deteriorated the simulation (even at high frequency) compared to the control model over the Caribbean Sea, Central America and equatorial eastern Pacific Ocean (EEPO). At high frequencies (3–30 days) the variance described by the SSiB model over subtropical South America and northeast Brazil was seen as a improvement over the control model. The mean JFM precipitation simulation over Guianan Highlands, Venezeulan Llanos and Amazon River Basin is better in the SSiB model. However, it exacerbates the mean JFM precipitation errors over the Brazilian Highlands and east of Bolivian Plateau over Sierra De Cordoba.

[26] The comparison of surface temperature between the two models revealed that the removal of the cold bias of the control model improved the simulation over ARB, along Brazilian Highlands and over Central America relative to the control model. However, the SSiB model exhibited too warm a surface temperature in the subtropical latitudes over Pampas and Gran-Chaco area. This may be related to a similar bias in the driving NCEP reanalysis combined with inherent feature of SSiB to produce lower latent heat flux and higher sensible heat flux for a given atmospheric condition.

[27] The analysis of the differences in low-level circulation in the two models showed that the mean onshore easterly flow from the Atlantic Ocean and the mean northerly low-level jet (LLJ) are stronger in the SSiB simulation. This results in an overall increase in moisture flux convergence over Nordeste, the Gran Chaco area, Pampas and SACZ region. The relatively lower latent heat flux, and yet higher seasonal precipitation, for the SSiB runs over the subtropical region (Gran Chaco area) is due to this increase in moisture flux convergence, which compensates for the reduced surface evaporation. However, over the Pampas region, the decrease in surface evaporation was slightly greater than in Gran-Chaco area, resulting in a decrease in the precipitation over the area relative to the control. In addition, this enhanced onshore easterlies from the tropical Atlantic Ocean which then become northerly near the eastern slopes of the Andes Mountains further contributes to the strengthening of the LLJ despite the weakening of the mean subtropical high over the south Atlantic Ocean in the SSiB model relative to the control simulation.

[28] We acknowledge that some of these differences may be due to internal dynamics of the model; however given that we are taking seasonal means, averaging over 3 simulations together and using "perfect" (NCEP reanalysis) boundary conditions we believe the differences in the seasonal climate of the two models are largely due to the different treatment of land surface processes.

[29] In incorporating a more comprehensive land surface scheme such as SSiB, a more descriptive climatology of the region is obtained. Furthermore, it makes it feasible to study the sensitivity of regional climate to land use and land cover change.

[30] Although, we have compared a regional model with two different land surface schemes, this study is limited by a small sample size of multiseasonal simulations. Furthermore, in this study the influence of the SSiB scheme on the regional climate may have been modulated by the NCEP

reanalysis lateral boundary conditions which uses the *Mahrt and Pan* [1984] scheme. We are presently analyzing seasonal integrations from this coupled RSM-SSiB model nested into a GCM which also has SSiB as its land surface scheme as well as other similarities in atmospheric physics.

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