JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, D17110, doi:10.1029/2005JD006297, 2006

Toward a South America Land Data Assimilation System: Aspects of land surface model spin-up using the Simplified Simple Biosphere

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Received 31 May 2005; revised 11 October 2005; accepted 10 May 2006; published 13 September 2006.

[1] This paper describes a spin-up experiment conducted over South America using the Simplified Simple Biosphere (SSiB) land surface model to study the process of model adjustment to atmospheric forcing data. The experiment was carried out as a precursor to the use of SSiB in a South American Land Data Assimilation System (SALDAS). The results from an 11 year long recursive simulation using three different initial conditions of soil wetness (control, wet and dry) are examined. The control run was initiated by interpolation of the NCEP/DOE Global Reanalysis-2 (NCEP/DOE R-2) soil moisture data set. In each case the time required for the model to reach equilibrium was calculated. The wet initialization leads to a faster adjustment of the soil moisture field, followed by the control and then the dry initialization. Overall, the final spin-up states using the SSiB-based SALDAS are generally wetter than both the NCEP/DOE R-2 and the Centro de Previsao do Tempo e Estudos Climaticos (CPTEC−Brazilian Center for Weather Forecast and Climate Studies) operational initial soil moisture states, consequently modeled latent heat is higher and sensible heat lower in the final year of simulation when compared with the first year. Selected regions, i.e., in semiarid northeastern Brazil, the transition zone to the south of the Amazon tropical forest, and the central Andes were studied in more detail because they took longer to spin up (up to 56 months) when compared with other areas (less than 24 months). It is shown that there is a rapid change in the soil moisture in all layers in the first 2 months of simulation followed by a subsequent slow and steady adjustment: This could imply there are increasing errors in medium range simulations. Spin-up is longest where frozen soil is present for long periods such as in the central Andes.

Citation: de Goncalves, L. G. G., W. J. Shuttleworth, E. J. Burke, P. Houser, D. L. Toll, M. Rodell, and K. Arsenault (2006), Toward a South America Land Data Assimilation System: Aspects of land surface model spin-up using the Simplified Simple Biosphere, *J. Geophys. Res.*, *111*, D17110, doi:10.1029/2005JD006297.

1. Introduction

[2] The large variations in regional climate and surface characteristics (i.e., topography, vegetation, and soil) in South America make climate and weather forecasting a challenging task [*De Goncalves et al.*, 2004; *Liebmann et al.*, 1999; *Marengo et al.*, 2002]. The exchange of heat, moisture, and momentum between the land surface and the atmosphere are all highly dependent on land surface processes and an accurate initialization of the surface stores of energy and water in fully coupled forecast models is critical. To better understand and determine the land surface energy and moisture stores for initiating prediction systems and to address land surface management issues in South America, a South American Land Data Assimilation System (SALDAS) has been created. This system is based on the concepts used in the Land Data Assimilation System (LDAS [*Rodell et al.*, 2004]) used at the NASA's Hydrology Sciences Branch at Goddard Space Flight Center (GSFC). In this study, the LDAS has been adapted to interface with the regional Eta atmospheric model [*Janjic*, 1979, 1984] that is used for weather forecasting at CPTEC (Centro de Previsão de Tempo e Estudos Climaticos), the Brazilian Center for Weather Forecasts and Climate Studies. It is therefore based on the Simplified Simple Biosphere (SSiB [*Xue et al.*, 1991, 2001]) Land Surface Model (LSM) which is used in the coupled Eta system. The results presented here are the first from a series of studies to explore the value of the SALDAS in forecasts systems. Future research will assess the impact of using

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0148-0227/06/2005JD006297$09.00

SALDAS-generated initial fields of soil moisture and soil temperature in weather and climate forecasts. This study evaluates the spin-up characteristics of SSiB when operating in the climate of South America and is similar to the evaluation of spin-up characteristics for North America, *Cosgrove et al.* [2003], who compared the behavior of several LSMs and found spin-up times showed a large spatial variation and were correlated most strongly with precipitation and temperature. Further research has been conducted by *Rodell et al.* [2005] who compared 10 methods for initializing a land surface model. They concluded that when multiple years of forcing data are not available, one of the best approaches is to use climatological average states derived from the same model for the time of year of initialization.

[3] The process of a model adjustment to forcing fields (i.e., model spin-up) can severely bias land surface simulations and, if not properly recognized and understood, could potentially degrade the value of LDAS-calculated initiation fields, therefore compromising associated weather and climate simulations. *Xue et al.* [2004] showed that with improved initial soil moisture and vegetation maps, the intensity and location of the summer precipitation over East Africa and West Asia in a coupled Global Circulation Model that included SSiB were also improved. To better understand how the spatial and temporal climate and land surface complexities over South America affect SSiB spin-up, the results of three 11 year long simulations where analyzed. Forcing data for the same 365-day period in 2001–2002 was recursively applied for 11 years in experiments initialized with different soil water contents: completely dry (DRY), fully saturated (WET), and a control run (CTR) which was initiated from the NCEP/DOE Global Reanalysis 2 (NCEP/DOE R-2 [*Kanamitsu et al.*, 2002]).

2. SSiB Land Surface Scheme

[4] The Simplified Simple Biosphere land surface scheme (SSiB [*Xue et al.*, 1991]) used in the CPTEC Eta model simulates biophysical processes by modeling vegetation explicitly and is a simplified version of the Simple Biosphere model (SiB [*Sellers et al.*, 1986]). The SSiB scheme has three soil layers with depths that vary according to the vegetation type, and one canopy layer. Their status is defined by eight prognostics states (i.e., soil wetness in the three soil layers; the temperatures of the canopy, ground surface, and deep soil layer; the liquid water stored on the canopy; and the snow stored on the ground). Vertical eddy flux transfer is calculated using the Mellor-Yamada second-order closure scheme [*Mellor and Yamada*, 1982]. Three aerodynamic resistances are specified, namely the resistance between the soil surface and the canopy air space (*rd*); the resistance between the canopy and the canopy air space (*rb*); and the resistance between the canopy air space and the reference height (*ra*). The SSiB forcing variables (taken from the lowest modeled level of the Eta model when operating in coupled mode) are precipitation, downward shortwave radiation, downward longwave radiation, temperature, humidity, and wind speed. The output variables include surface albedo; sensible heat flux; latent heat flux (transpiration and evaporation from intercepted water and the soil); momentum flux; ground heat fluxes; skin temperature; surface runoff; groundwater runoff; carbon dioxide flux; and net photosynthesis rate. SSiB requires the specification of 23 parameters for 13 ecosystems (i.e., broadleaf-evergreen; broadleaf deciduous trees; mixed forest; needleleaf evergreen trees; needleleaf deciduous trees; savanna; perennial grassland; broadleaf shrubs with ground cover; broadleaf shrubs with bare soil; tundra; desert; crops; and permanent ice). In the present study, the default values of these 23 parameters given by *Xue et al.* [1991] were used for each ecosystem. Snowmelting and freezing are also taken into account in SSiB [*Xue et al.*, 2003]. If the canopy/ground temperature is below freezing, the water stored on the canopy is frozen and accumulates there as snow and ice. If the canopy/ground temperature rises above freezing, accumulated snow begins to melt and the water becomes runoff. Studies have been made with SSiB coupled to a General Circulation Model (GCM) to investigate the impact of land surface changes on the atmospheric circulation, precipitation and moisture flux in the Sahel [*Xue*, 1993; *Xue and Shukla*, 1993]; and to study the influence of seasonal variations in crop parameters on the U.S. hydrological cycle [*Xue et al.*, 2001] and the southeast Asia monsoon [*Xue et al.*, 2004]. These studies suggest that the resulting changes in the surface energy budget and hydrological cycle can have a significant impact on regional climate simulations [*Xue et al.*, 1996].

3. Observed Climatologies

[5] Data used for comparison with the spin-up states were those currently used to initialize models at CPTEC and the NCEP renanalysis-2 data. At CPTEC, a monthly soil moisture climatology derived from global model simulations forced with observations, monthly average temperature and precipitation climatologies [*Mintz and Serafini*, 1992; *Mintz and Walker*, 1993] are used for the purposes of weather and climate simulations. A simple 15-cm bucket model [*Manabe*, 1969] is used with *Thornthwaite* [1948] evaporation, and soil moisture is derived on a global $4 \times 5°$ latitude-longitude grid. The soil moisture data provided by *Mintz and Serafini* [1992] were recently evaluated by *Robock et al.* [1998], as part of the Atmospheric Model Intercomparison Project (AMIP) and were found to be noticeably different from available observations. These data, linearly interpolated to a daily time step [*Willmott et al.*, 1985], are currently used in both the operational Global Circulation Model [*Cavalcanti et al.*, 2002] and the Eta regional model [*Chou et al.*, 2002] at CPTEC.

[6] The NCEP–NCAR reanalysis (R-1) is a 40-year record of global analyses of atmospheric fields where land surface, ship, rawinsonde, buoy, aircraft, satellite, and other data are quality controlled and assimilated using a data assimilation system that is kept unchanged over the reanalysis period 1957–96 [*Kistler et al.*, 2001]. The model used is the global system implemented operationally at the NCEP on 11 January 1995, except that the horizontal resolution is T62 (about 210 km). The NCEP/DOE Reanalysis-2 (R-2) soil moisture analysis is used to initiate the CTR run in this study. This analysis is based on the precipitation constructed from satellite data and rain gauges, radiation forcing computed from atmospheric analysis, and near surface atmospheric analyses. It is an updated 6-hourly global analysis series from 1979 to the present and corrects known pro-

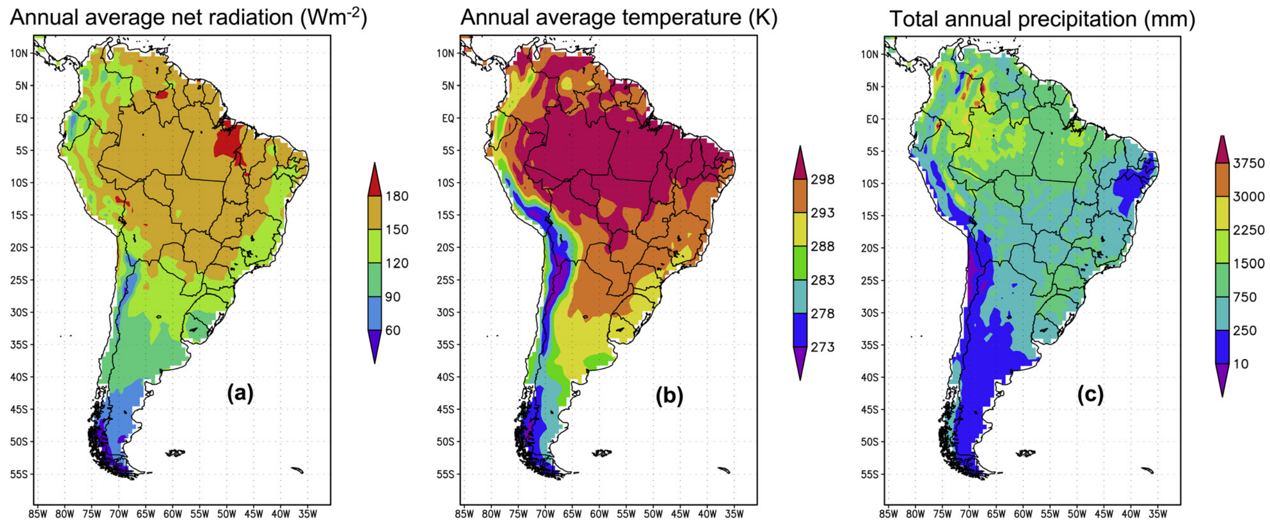

Figure 1. Average annual (a) net radiation in W m^{-2}, (b) temperature in K, and (c) total annual precipitation in mm from March 2001 to March 2002.

cessing errors in the NCEP–NCAR reanalysis (R-1) and uses an improved forecast model and data assimilation system. Because there is limited soil moisture variation over periods less than a month, the soil moisture fields used for initializing the CTR run in this study are the monthly average values from NCEP/DOE-R2.

4. Experiment Design and SALDAS Configuration

[7] The experiment consisted of three simulations using different soil wetness initial conditions: the first, a control run (CTR) initialized with NCEP reanalysis-2 soil moisture fields; the second, with the soil completely dry (DRY); and the third, with a fully saturated soil moisture content (WET).

[8] An uncoupled, two-dimensional array using SSiB set up on a 40 km $\times$ 40 km grid across South America (between 50°S–12°N and 85–30°E) was run for 11 years using forcing data for the period from 17 March 2001 to 16 March 2002 recursively. 17 March 2001 was selected as the starting date for the repeated annual cycle because the year-to-year difference in meteorological forcing variables were least for this particular date, and the resulting recursive forcing data consequently had a smoother year end transition. The atmospheric forcing data used to force SSiB was derived from the global operational weather forecast model at NCEP [*Derber et al.*, 1991], the Global Data Assimilation System (GDAS), which provides 6-hourly, 0.25° global coverage for precipitation, downward shortwave and longwave radiation, temperature, relative humidity, wind speed and atmospheric pressure. Figure 1 shows average annual net radiation (Figure 1a), average annual temperature (Figure 1b), and total annual precipitation over the study region (Figure 1c). There are large climatic variations over South America. The annual average net radiation ranges from less than 60 W m^{-2} in the extreme south, to over 180 W m^{-2} in parts of the Amazon basin. Similarly for temperature, the Amazon basin has an annual average temperature of approximately 300 K and the south of the continent has an annual average temperature around 280 K. The average annual temperature is below freezing in parts of the central Andes (north of Chile and Argentina and southwest Bolivia) and the Peruvian Andes. This can affect the water balance particularly during snowmelt [*Mocko et al.*, 1999; *Slater et al.*, 2001; *Xue et al.*, 2003]. Many southern areas and the western and eastern edges of the continent have a very low annual precipitation (less than 700 mm per year). Precipitation is particularly low (less than 10 mm per year) in the lowlands north of Chile (Atacama desert). However, the Amazon basin has an annual precipitation which often exceeds 3000 mm per year.

[9] The vegetation classification (Figure 2) used in SSiB was taken from the University of Maryland (UMD) global, 1-km, AVHRR-based, 13-class vegetation database [*Hansen et al.*, 2000]. The broadleaf tress in the Amazon basin are the dominant ecosystem in the north, whereas in the south the vegetation is much sparser and dominated by shrubs, ground cover and bare soil. The vegetation parameters were held constant throughout the simulations, except for LAI, greenness fraction, and vegetation cover fraction which varied monthly. Figure 2 also shows the three 5 $\times$ 5 degree regions over which further analysis was carried out. These regions are in different climate regimes: Their vegetation and soil characteristics are given in Table 1 and their annual atmospheric conditions for the study period in Table 2.

[10] The selected region in semiarid northeastern Brazil, hereinafter called NE, is predominantly covered with broadleaf trees mixed with bare soil. (Note that in SSiB, the type of soil present at each location is defined from a look up table.) The NE region received a relatively low total accumulated precipitation of 413 mm during the period studied. The selected region in the Central area of the continent (CE) is in the Mato Grosso state in Brazil. This region received significantly more total accumulated precipitation during the period studied than NE, which is in part due to convective activity. The predominant vegetation in CE is tropical forest and soil characteristics are very similar to the NE region. The third selected region covers

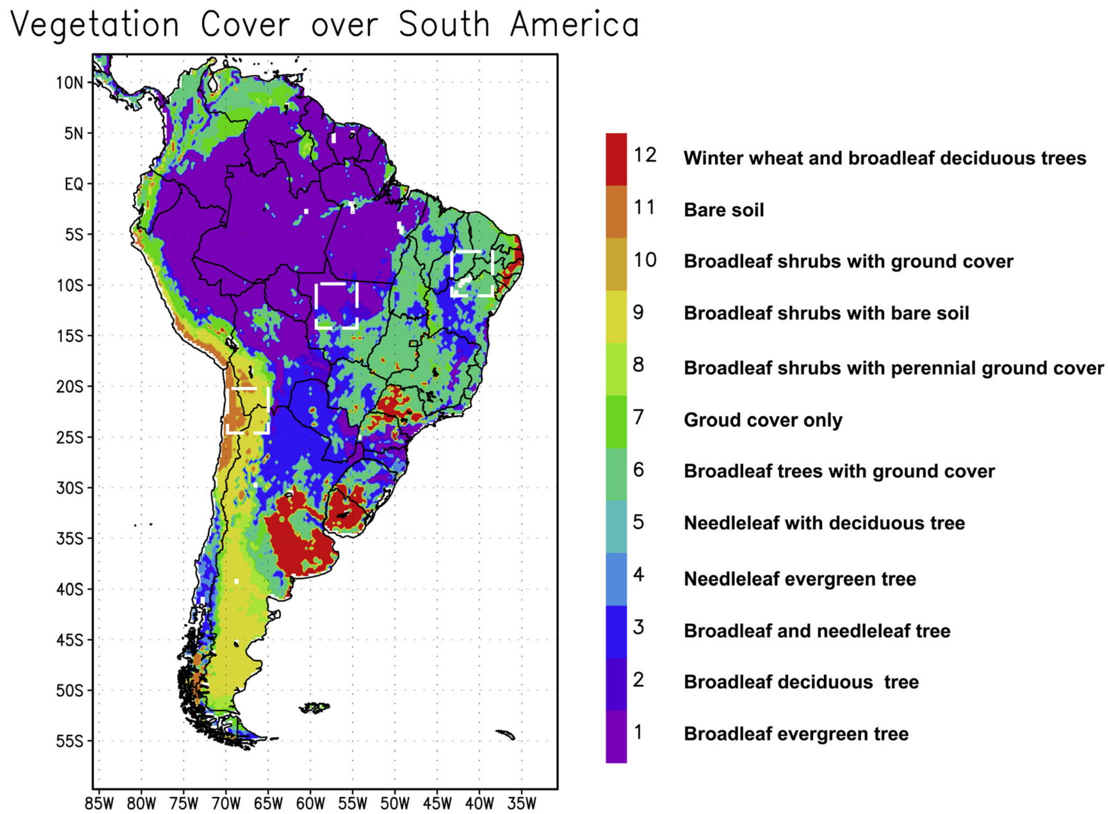

Figure 2. Vegetation cover classification over South America. Type 1 is tropical rain forest, type 2 is broadleaf deciduous trees, type 3 is broadleaf and needleleaf trees, type 4 is needleleaf evergreen trees, type 5 is needleleaf deciduous trees, type 6 is broadleaf trees with ground cover, type 7 is grassland, type 8 is broadleaf shrubs with ground cover, type 9 is broadleaf shrubs with bare soil, type 10 is dwarf trees with ground cover, type 11 is desert, and type 12 is crops.

the Andes (AN), a mountainous region where the mean temperature is below freezing for a significant proportion of the year, and the Atacama desert, which is at a lower elevation but which has very low accumulated precipitation (less than 10 mm). Taken together, this corresponds to an area where the mean annual temperature is just above freezing and the precipitation is low. It is predominantly covered with broadleaf shrubs mixed with bare soil.

[11] The criterion often used to define when a model has achieved soil moisture equilibrium in a recursive run is when the percentage change in the average monthly soil moisture from one year to the next reaches a specified value, the percentage change (*PC*) being given by

$$PC = 100\frac{M_1 - M_2}{M_2}, \quad (1)$$

where $M1$ is the monthly average soil moisture for the previous year and $M2$ the monthly average soil moisture for the current year. *Henderson-Sellers et al.* [1993] suggest a *PC* value of 0.01% defines when an LSM to reaches equilibrium, while the SSiB modeling group [*Yang et al.*, 1995] suggested a *PC* value of 1%. This study uses both the 0.01% and 1% thresholds, along with the intermediate value of 0.1%. The time necessary for each run to reach the threshold is a measure of the minimum required spin-up period for the model. All the spin-up experiments (i.e., CTR, WET and DRY) converged, over varying lengths of time, to the same preferable final states, demonstrating that the model final states are independent of the initial states. These final spin-up states were compared with soil moisture climatology currently used at CPTEC and with the NCEP reanalysis-2 soil moisture fields. To investigate associated changes in the modeled land surface interaction with the atmosphere, surface fluxes were computed and compared

Table 1. Surface (SUR), Root (ROO) and Subsurface (SUB) Depths, for the First and Second Vegetation Types (TYPE) with Higher Coverage (COV), in the NE, CE and AN Regions

	TYPE	COV, %	SUR, m	ROO, m	SUB, m	POR	TYPE	COV, %	SUR, m	ROO, m	SUB, m	POR
NE	6	75	0.02	1.48	2.0	0.42	3	19	0.02	1.48	2.0	0.42
CE	1	61	0.02	1.48	2.0	0.42	6	17	0.02	1.48	2.0	0.42
AN	9	58	0.02	0.47	1.0	0.44	11	31	0.02	0.17	0.3	0.44

Table 2. Total Annual Precipitation, Mean Annual Temperature and Mean Annual Net Radiation in the NE, CE and AN Regions for the Period Used in the Simulations

	Total Annual Precipitation, mm	Mean Annual Temperature, K	Mean Annual Net Radiation, W m^{-2}
NE	413	300	147
CE	1374	298	162
AN	178	275	117

using the two different soil moisture initiation fields and the final soil moisture states after spin-up for each of the three regions (NE, CE and AN) shown in Figure 2.

5. Results

5.1. Percentage Change

[12] Over the majority of South America for all the spin-up simulations the time taken to reach equilibrium is less than 18 months (Figure 3). Figure 3 shows the number of months before the spin-up experiment reaches the *PC* thresholds of 1% (Figure 3a), 0.1% (Figure 3b) and 0.01% (Figure 3c) in the CTR run. In South America, the regions with most delay in spin-up are those where ice, snow and frozen soil are present for long periods of the year, for example over the Andes mountains. Another contributing factor to the delay in the spin-up time is low precipitation. Regions with low precipitation, such north-eastern Brazil and the Atacama desert to the north of Chile, have a longer spin-up time. In addition, other areas in central Brazil, eastern Amazonia, southern Argentina, coastal Ecuador and Colombia show up to 24 months delay in the spin-up. (Note that Figure 3 shows the spin-up times only for the CTR experiment because, although the actual number of months required to reach a specified threshold differ between the CTR, WET, and DRY experiments in the areas where the model spin-up takes 24 or more months are essentially the same.)

[13] In a similar study conducted over North America using the Mosaic LSM, *Cosgrove et al.* [2003] found longer spin-up times. For the period studied by *Cosgrove et al.* [2003], the total annual precipitation over the North American continent rarely exceeded 1000 mm, but the annual precipitation in South America generally exceeds 1000 mm (except for in northeastern Brazil and the Andes mountains and for latitudes south of 33°S) and even reaches 5000 mm in some tropical regions. There is also little variation in temperature through the year in South America: Temperatures range from 290 K to 300 K, on average. The initial soil moisture states in their CTR run were closer to the final spin-up states than their WET and DRY runs and consequently reached equilibrium more quickly but nonetheless took 5 years to spin up to a 0.01% PC (their WET run took 12–24 months and DRY run 30–50 months longer than this). In this current study, the WET run reached the equilibrium most quickly because, as we show later, the preferred (i.e., equilibrium) states for SSiB after spin-up are moister and nearer to the WET initiation than to the generally fairly dry CTR initiation. Differences in vegetation may also influence spin-up time and are different in North and South America. The predominant vegetation covers in South America are tropical rain forest, broadleaf and needleleaf trees, broadleaf trees, with ground cover, croplands, and broadleaf trees with shrub. Predominant covers in North America are evergreen needleleaf forest, cropland, mixed cover, open shrub and wooded grassland. It is possible that the more abundant vegetation associated with the higher precipitation regime increases the speed with which the LSM adjusts soil moisture in South America.

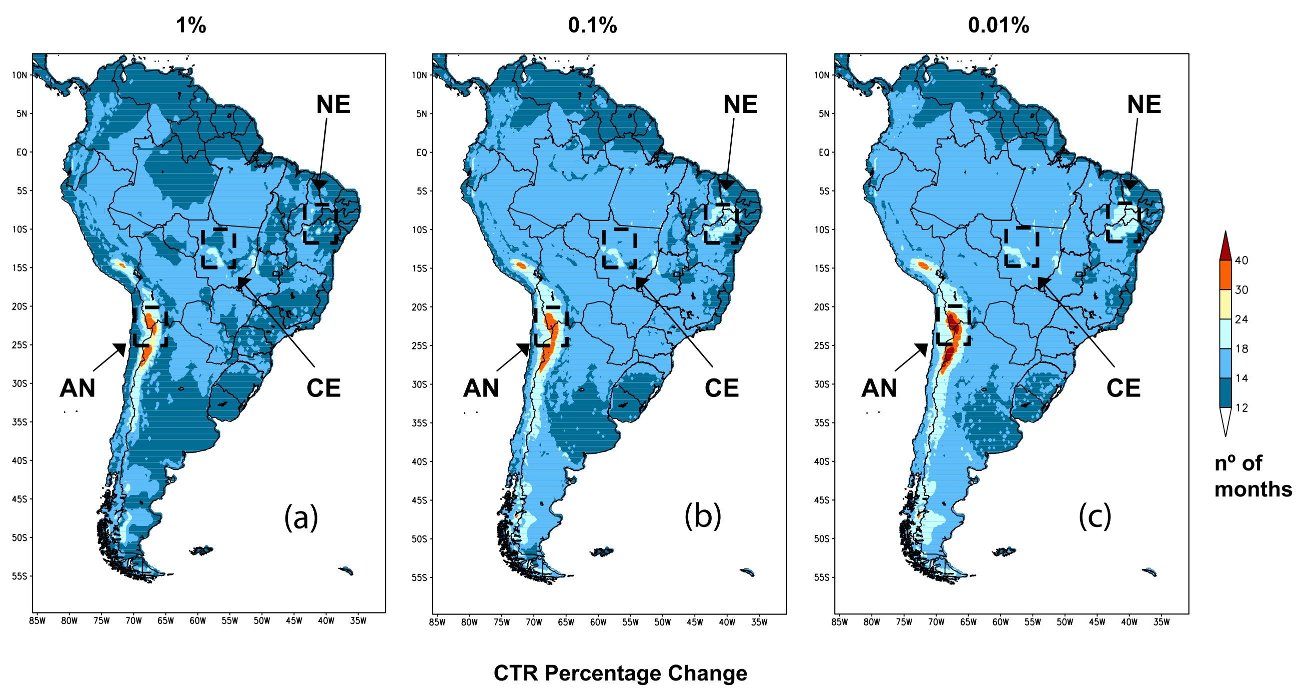

Figure 3. Number of months necessary to reach PC thresholds of (a) 1%, (b) 0.1% and (c) 0.01% for the CTR simulation. The regions of interest (NE, CE and AN) are shown as dashed black boxes.

Table 3. Average Number of Months Necessary for the Total Column Soil Moisture to Reach 1%, 0.1% and 0.01% PC Within the Regions NE, CE and AN

	1% PC			0.1% PC			0.01% PC		
	CTR	WET	DRY	CTR	WET	DRY	CTR	WET	DRY
NE	15	14	15	17	17	17	18	18	18
CE	16	14	16	16	14	16	16	14	16
AN	20	17	22	23	20	25	25	22	27

[14] The average number of months necessary to reach a given PC threshold (1%, 0.1% or 0.01%) for the three regions in all simulations is shown in Table 3. Table 4 shows the maximum time in months to reach a given PC threshold. Note that the values in Table 4 are not area averages, rather they represent a single (40 km $\times$ 40 km) cell. It is interesting that although the average time taken to reach equilibrium in the NE region increases as the threshold decreases (from 1% to 0.1% to 0.01%), the time to threshold is very similar for each initial state (i.e., WET, CTR, or DRY). In the CE region, the time required for the model to reach equilibrium range between 14 and 16 months for all PC thresholds and is therefore, on average, 3 months less than in the NE. This may be explained by the higher total annual precipitation (three times larger) in the CE region. The average time necessary for the model to reach equilibrium in the AN region is up to 11 months more (see, for example the value for a PC of 0.01% in the DRY simulation) than in the NE and CE regions. This is likely a result of a combination of low precipitation, the presence of frozen soil during significant proportions of the year, and low net radiation as result of the high albedo due to partial snow and ice cover. With the DRY initialization, parts of the AN region take up to 42 months to reach the 1% PC threshold, 46 months to reach the 0.1% PC threshold, and 51 months to reach the 0.01% PC threshold. On average there is a greater difference in spin-up times between the WET and DRY initializations in this region. Perhaps this is because of the way SSiB partitions infiltration and runoff in the presence of frozen soil, which may lead to a rapid runoff of excess water when snowmelts or it rains. This runoff is caused by the decrease in soil conductivity when the soil is frozen, which results in less surface water infiltration. When the soil is already saturated (as in the WET initialization), the model needs to discard the excess moisture quickly and the equilibrium state is thus less dependent on the external inputs (snowmelt and precipitation).

5.2. Comparison With NCEP/DOE Reanalysis-2 and CPTEC Soil Moisture Fields

[15] The monthly average NCEP/DOE-R2 soil moisture for March used as the initial state for the CTR simulation was compared with the soil moisture field derived from SSiB for March in the last year of the simulation. Figure 4 shows the percentage difference between the NCEP/DOE-R2 and preferred (ultimate) SSiB states. Positive values (green) mean the NCEP/DOE-R2 is larger and negative values mean the SSiB states are larger. Over the majority of South America, the SSiB total column soil moisture final state is wetter than the NCEP/DOE-R2 initial field (Figure 4a). The percentage difference is highest in semiarid northeastern Brazil, central Argentina, and the north of Venezuela. The remaining areas show differences between 10% and 80%, except the north of Chile, northwestern Argentina, and southwestern Bolivia, including the central Andes and the desert of Atacama. In the root zone (Figure 4b) the areas where the final spin-up states are wetter than the NCEP/DOE-R2 soil moisture are similar to those for total column, except in the region from central Argentina to south of Amazonia where the percentage differences are noticeably smaller. A more detailed analysis of the differences between the initial and final states of simulations for the NE, CE and AN regions is given later.

[16] Figure 5 shows the percentage difference in the soil moisture between the SSiB final states and the climatological fields used for initialization at CPTEC. The total column spin-up states are more than 120% larger than CPTEC initial states over an area that covers northeast Brazil and extends toward central South America. Most of Argentina (except eastern areas close to Uruguay and southern Brazil), southern Bolivia, and western Peru along the west side of Andes also have spin-up soil moisture states which are more than 120% larger than the CPTEC fields.

[17] In general, positive differences occur over most of the continent, except eastern Argentina; southern Uruguay (a region of winter wheat in the La Plata basin); southern Chile; and northern parts of the Amazon tropical forest. The differences in the root zone soil moisture (Figure 5b) are very similar to the total column differences (Figure 5a) although in northern latitudes the percentage differences are smaller, between -10% and 10%, compared with the 40% of the total column soil moisture.

5.3. Differences Between First (Reanalysis) and Last (Spin-Up) Years of Simulation

[18] A more detailed comparison between the NCEP/DOE-R2 reanalysis soil moisture fields and the preferred SSiB final states was carried out for the NE, CE, and AN regions. Figures 6a and 6b respectively show the NE region monthly average total column soil moisture and root zone soil moisture for the first year (dashed line) and last year (solid line) of the simulation. Figure 6c shows the total monthly precipitation (bar plot), surface temperature for the first (red line with stars) and last years (red line with circles) and also the total evapotranspiration for the first (black line with stars) and last years (black line with circles). Figures 7 and 8 show the same variables for the CE and AN regions respectively.

[19] In the NE region, the soil moisture adjusts to its final state rapidly. After the first 3 months of simulation there is little difference between the first and last year of the simulation. In the first two months the precipitation is slightly greater than the evapotranspiration, creating a

Table 4. Maximum Number of Months Necessary for the Total Column Soil Moisture to Reach 1%, 0.1% and 0.01% PC Within the NE, CE and AN Regions

	1% PC			0.1% PC			0.01% PC		
	CTR	WET	DRY	CTR	WET	DRY	CTR	WET	DRY
NE	24	24	24	24	24	24	24	24	24
CE	19	19	20	19	19	20	20	19	21
AN	35	22	42	41	24	46	46	32	51

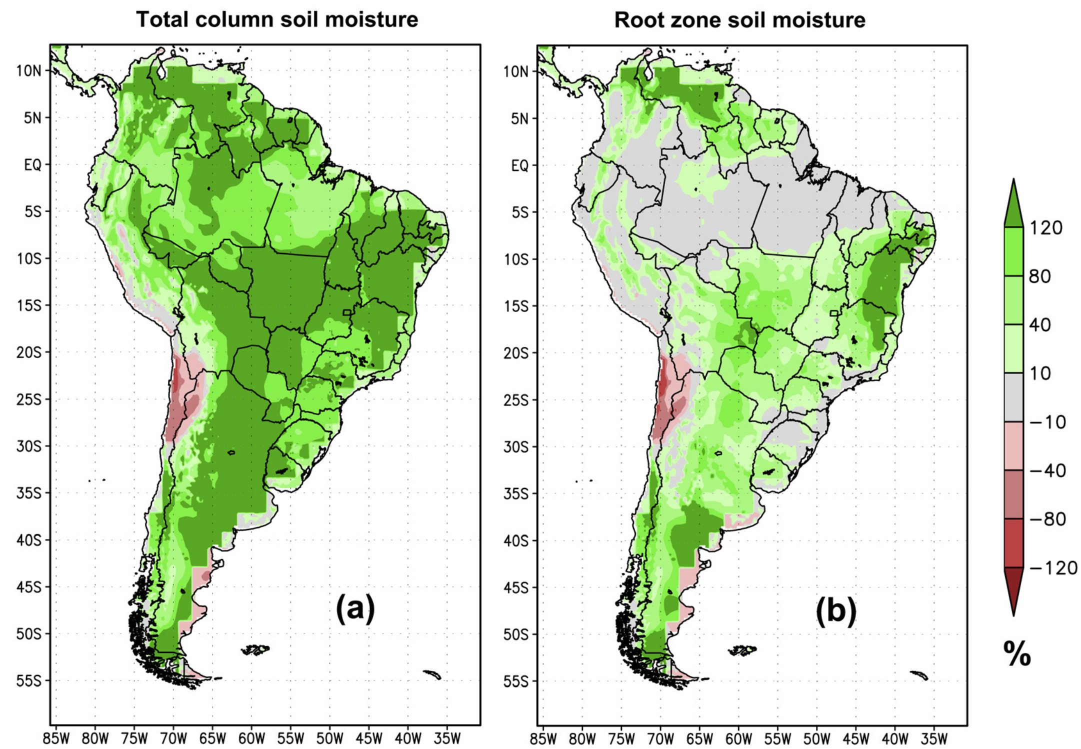

Figure 4. (a) Total column and (b) root zone soil moisture percent differences between last (SSiB preferable states) and first (NCEP/DOE R-2) months in the CTR simulation. Positive values mean final states higher than NCEP/DOE R-2.

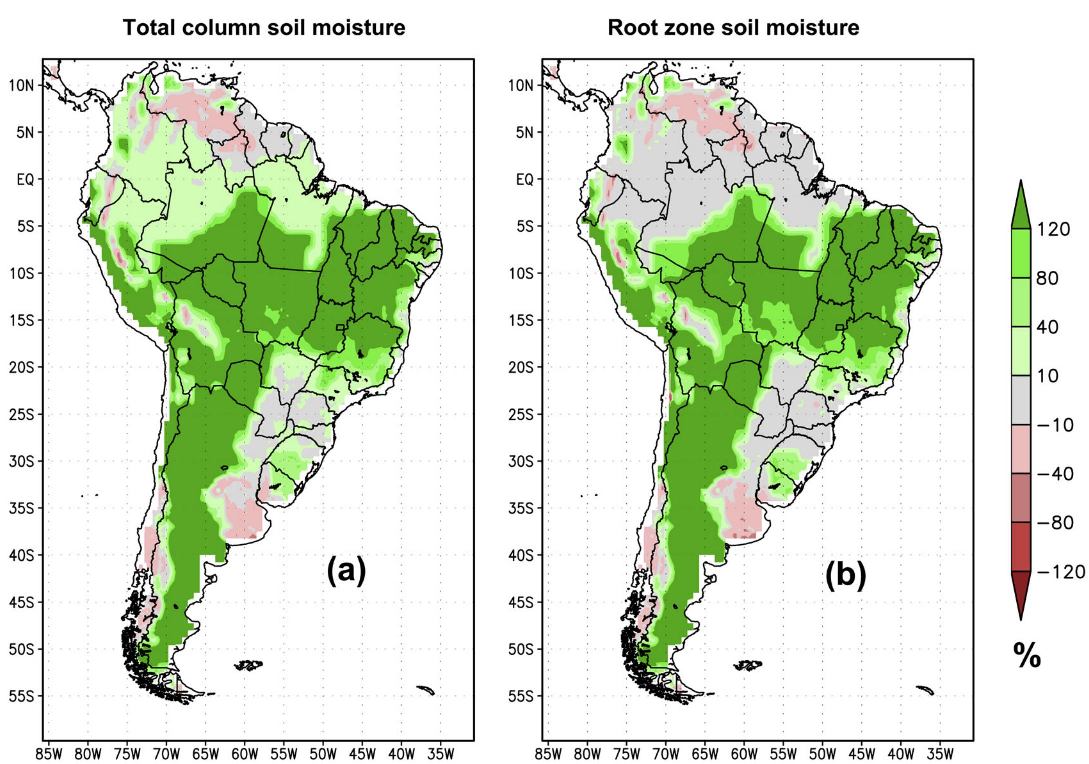

Figure 5. (a) Total column and (b) root zone soil moisture percent differences between last (SSiB preferable states) and CPTEC initial states. Positive values mean final states higher than CPTEC.

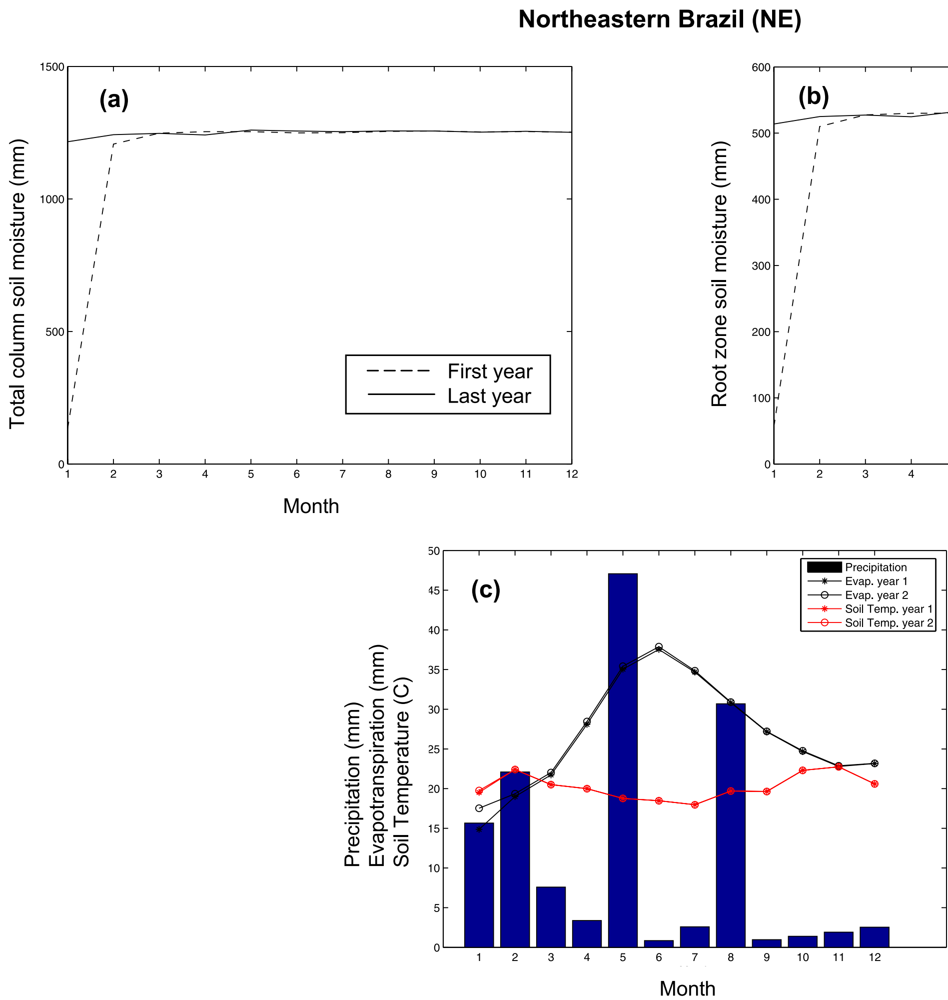

Figure 6. Monthly mean in the first (dashed) and last (solid) years of spin-up for the (a) total column soil moisture and (b) root zone soil moisture for region NE. (c) Atmospheric forcing precipitation (in mm) and the soil temperature (in C; in red) and the evapotranspiration (in mm; in blue) for the first (line with stars) and final (line with circles) years of simulation.

positive input into the system (although runoff is not shown, there is still has a net positive input) which helps resolve the initial water deficit. There is little change in either the evapotranspiration or the surface temperature between the first and last year of the simulation. In fact, the monthly average soil temperature does not change significantly from the first to the last year, keeping its value relatively constant throughout the year (20°C ± 3°C). Although evapotranspiration is higher than precipitation most of the year, there is no evidence of a decrease in the total column soil moisture during the 11 years of simulation. This is discussed further later. In the CE region, the total column soil moisture (Figure 7a) takes longer, between 5 to 6 months, to reach average final states values. This is despite the monthly net water input being much larger in the first months of simulation than in the NE region. This delay may be related to differences in the vegetation characteristics. The CE region is 75% covered by tropical forest and the NE region 61% by broadleaf trees with bare soil. The evapotranspiration in the CE region is almost entirely due to the extraction of the water from the root zone by the plants (i.e., transpiration). Although the timescale might allow soil evaporation, in a tropical forest the extraction of water by plants is more efficient as shown by *Shuttleworth et al.* [1984] and more recently by *Da Rocha et al.* [2004]. This is in contrast to the NE region where a significant portion of the total evapotranspiration is from bare soil. The use of the soil moisture to support transpiration could delay the adjustment of soil water deficit a few months as shown in Figure 7a, although the root zone soil moisture in the CE region does not experience the same delay when compared to the root zone in the NE region. This also could be a result of continuous extraction from the root zone of excess water that, in NE, would move downward to the drainage layer. The CE region is a transition zone (albeit 75% of the vegetation cover is tropical forest) which receives less total annual precipitation than other areas with similar vegetation (see Figure 1c). More abundant precipitation likely feeds both evapotranspiration and soil deficit demands in the first year of simulation with the same vegetation characteristics (temperature does not change substantially in the tropical area, see Figure 1b).

[20] In contrast to the other two regions, the AN region shows a difference in soil moisture at the end of the first

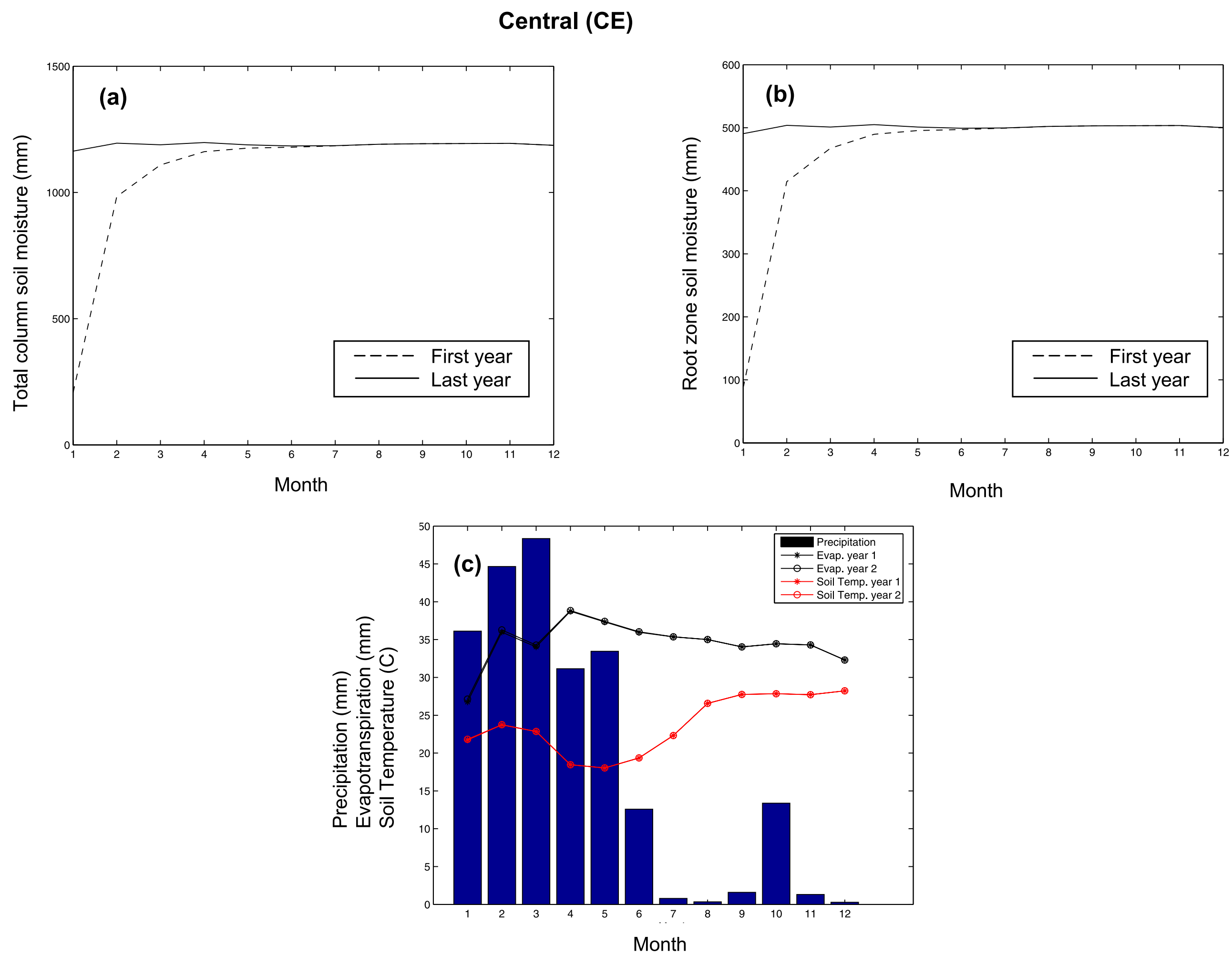

Figure 7. Monthly mean in the first (dashed) and last (solid) years of spin-up for the (a) total column soil moisture and (b) root zone soil moisture for region CE. (c) Atmospheric forcing precipitation (in mm) and the soil temperature (in C; in red) and the evapotranspiration (in mm; in blue) for the first (line with stars) and final (line with circles) years of simulation.

year of the simulation (Figures 8a and 8b). The total column and root zone soil moisture experience a rapid increase between the first and second months and then continue to increase steadily for the remainder of the first year. The evapotranspiration is constant through the year and is slightly larger in the last year. The monthly average soil temperature remains below freezing from the second to the eleventh months in the first year, and in all months except December in the last year of simulation. The implications of long periods of frozen soil are that the precipitation is almost entirely partitioned into snow accumulation and runoff (not shown). If ice is present, the infiltration decreases and the snowpack last longer because frozen soil prevents melting from below. The AN region (Figure 2 and Table 1) is predominantly covered by shrubs with bare soil (type 9), with a shallow root depth of 47 cm and with a 1 m for drainage layer, and is 31% bare soil (type 11), with root and subsurface zones of 17 cm and 30 cm, respectively. The coverage characteristics and the low total annual precipitation of 178 mm (see Table 2) associated with the (almost permanent) frozen soil complicate the interaction between the soil and the atmosphere and slow the process of soil moisture adjustment.

5.4. Differences in Heat Fluxes Between the First and Last Year of Spin-Up

[21] The mean diurnal cycles of the latent, sensible and ground heat fluxes are shown in Figures 9 (NE), Figure 10 (CE) and Figure 11 (AN) for the first and last years of the simulation. Values shown are 3-hourly averages. In the NE region (Figure 9), the sensible heat flux is larger than the latent heat flux as is expected for semiarid environment. In the final year the latent heat flux is, on average, 17.5 W m^{-2} greater than in the initial year (Figure 9a), with a maximum difference between the two of 60 W m^{-2} around 0900 local time (LT). The sensible heat decreases by, on average, 13.2 W m^{-2} (Figure 9b) and there was little change in the ground heat flux (Figure 9c). This decrease in the Bowen ratio is likely a result of the increase in the available soil moisture in all soil layers.

[22] In the CE region, which is mainly a tropical region, most of the available energy is released as the latent heat flux. However, as for the NE region, there is an increase in

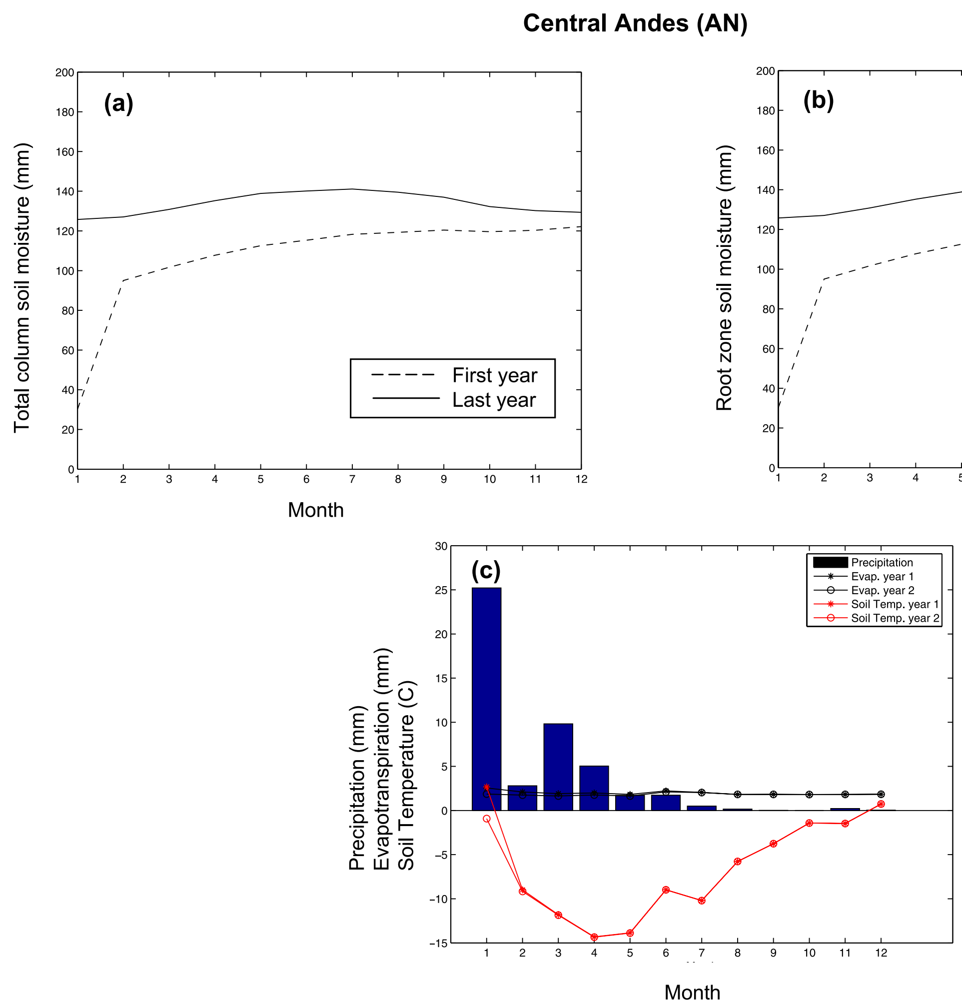

Figure 8. Monthly mean in the first (dashed) and last (solid) years of spin-up for the (a) total column soil moisture and (b) root zone soil moisture for region AN. (c) Atmospheric forcing precipitation (in mm) and the soil temperature (in C; in red) and the evapotranspiration (in mm; in blue) for the first (line with stars) and final (line with circles) years of simulation.

the amount of water in the soil in the last year compared with the first year, and a decrease in the Bowen ratio (Figures 10a and 10b). The mean difference in the diurnal cycle of the latent heat is 24.0 W m^{-2} with a maximum difference of 75 W m^{-2} at 1200 LT. The sensible heat decreased overall by 17 W m^{-2}, with a maximum difference of around 70 W m^{-2} at 1200 LT. Again there was minimal change in the ground heat flux.

[23] In the AN region, frozen soil, ice, and snow is expected for most of the year (Figure 8c). This leads to a reduced albedo. The ground heat flux (Figure 11c) is large, with a maximum of around 150 W m^{-2} (at 0900 LT) and minimum of around −100 W m^{-2} (at 1800 LT). The combined latent and sensible heat fluxes are much lower than in the other two regions. In general there was little change in the diurnal energy balance between the first and last years of the simulation.

6. Summary and Conclusions

[24] The present study investigated aspects of the spin-up for the SSiB model applied over South America. Specifically, it explored the time it takes for this model to adjust soil moisture in response to atmospheric forcing, and the differences in modeled moisture states (and related surface fluxes) between values defined from the NCEP/DOE Global Reanalysis 2 (NCEP/DOE R-2 [*Kanamitsu et al.*, 2002]) data set and the equivalent states calculated by SSiB as equilibrium states with recursive application of meteorological forcing data for South America. The preferred SSiB soil moisture states are also compared with those used at CPTEC for climate and weather forecast models.

[25] A spatial analysis was made of the time required for modeled states to approach within specified percentages of their long-term equilibrium values. This revealed a marked dependency of spin-up time on precipitation regime. Over some regions with low precipitation but relatively large evapotranspiration, such as the semiarid northeastern Brazil (NE), or with little precipitation and long periods with frozen soil and low near surface air temperatures, such as the Central Andes (AN–north of Chile, northwest Argentina and southwest Bolivia), or in transition zones, such as the southern limits of the Amazon tropical forest in the Brazilian state of Mato Grosso (CE), the model can take

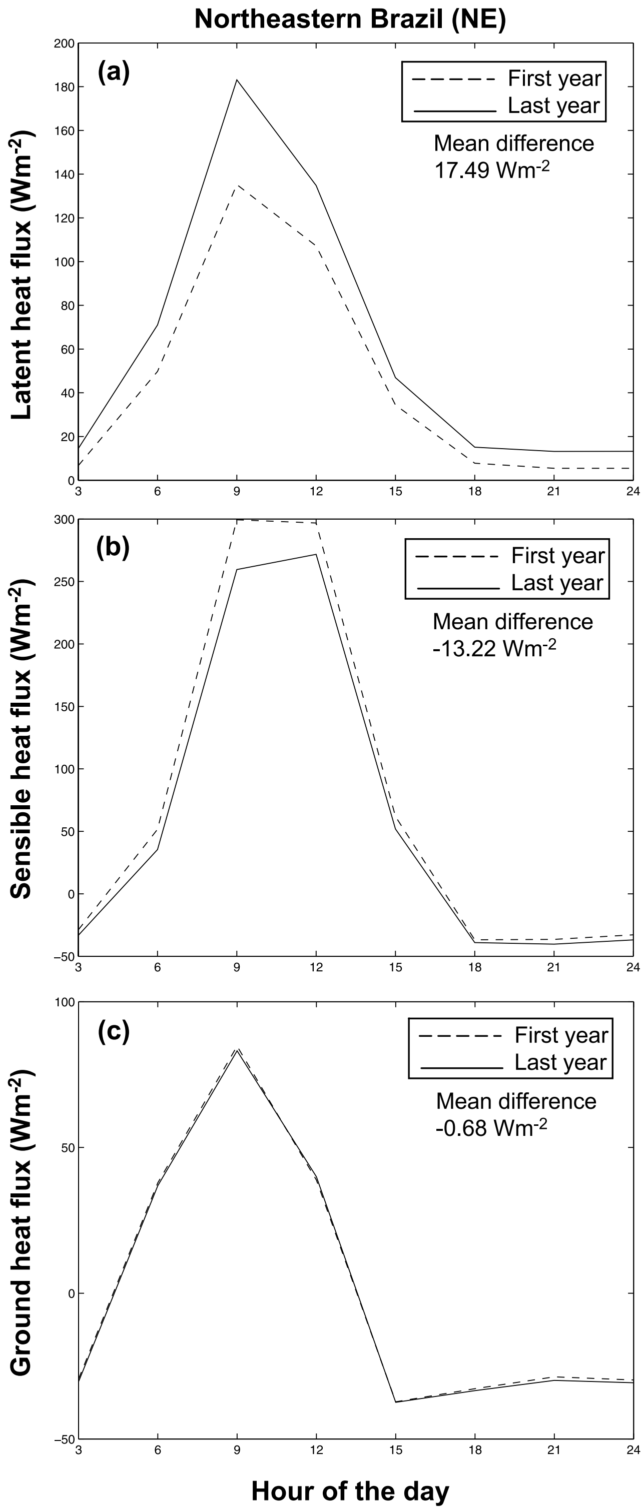

Figure 9. Mean annual diurnal cycle of (a) latent, (b) sensible and (c) ground heat flux in W m^{-2} for the first (dashed line) and last (solid line) years of simulation for region NE. The diurnal cycle has a 3-hourly average interval.

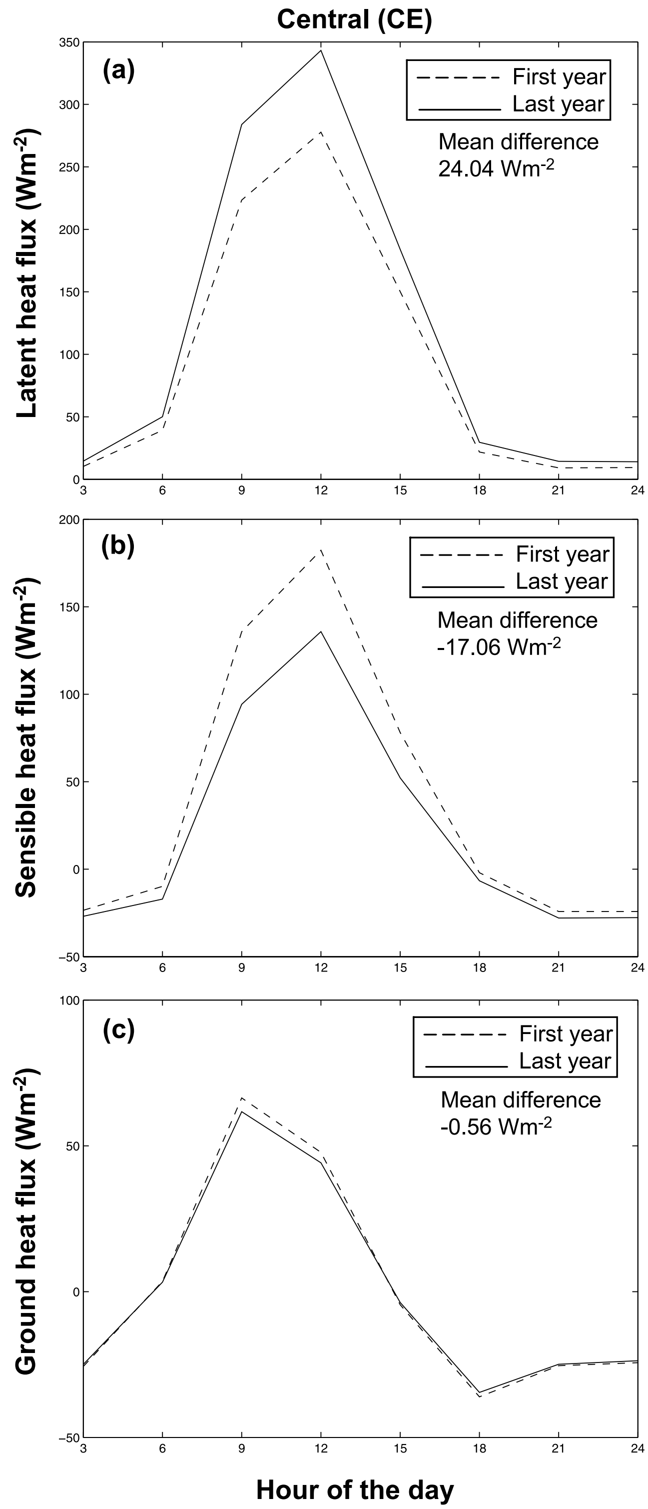

Figure 10. Mean annual diurnal cycle of (a) latent, (b) sensible and (c) ground heat flux in W m^{-2} for the first (dashed line) and last (solid line) years of simulation for region CE. The diurnal cycle has a 3-hourly average interval.

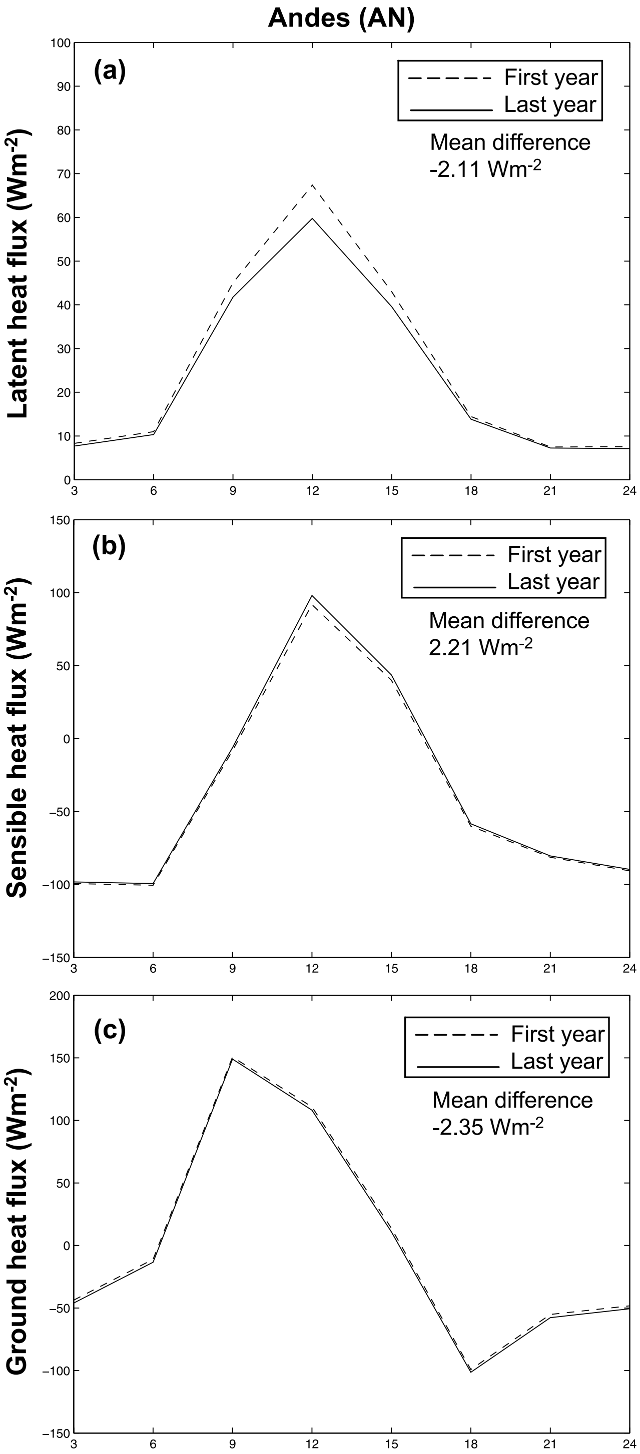

Figure 11. Mean annual diurnal cycle of (a) latent, (b) sensible and (c) ground heat flux in W m^{-2} for the first (dashed line) and last (solid line) years of simulation for region AN. The diurnal cycle has a 3-hourly average interval.

many months (even several years) to reach equilibrium. However, over regions where precipitation is abundant (e.g., the tropical Amazon forest) or well distributed through the year (southern and central South America and coastal areas), the model reached equilibrium for 0.01% PC in less than 18 months. In this present study, spin-up times are, in general, noticeably less than those found by *Cosgrove et al.* [2003] for the Mosaic model applied in North America. Arguably this is related to the more abundant precipitation and the more prevalent presence of denser associated vegetation cover.

[26] The final soil moisture states calculated by recursive application of forcing data with SSiB are, in general, moister than those derived from the NCEP/DOE R-2 reanalysis fields except in southeastern Argentina and central Andes (AN). The impact of using different specifications of initial states was also investigated for three regions (NE, CE and AN) in more detail. In the NE and CE regions, the preferred SSiB soil moisture states are moister than the NCEP/DOE-R2 and moister still than the climatological soil moisture states used at CPTEC for routine whether and climate simulations for South America. Consequently, there is an average increase in the latent heat flux and decrease in sensible heat flux, suggesting a potential impact on precipitation and perhaps atmospheric circulation. In the AN region, where the soil temperature is below freezing most of the year, the preferred SSiB states are drier than the NCEP/DOE-R2 soil moisture states, resulting in a decrease in the latent heat flux and an increase in the sensible heat flux. Note that, unlike NCEP/DOE-R2, the CPTEC soil moisture states in this region (AN) are drier than the preferred SSiB states. Although one of the main motivations for this study was to provide a better understanding of the spatial characteristics of spin-up of SSiB over South America, and insight has certainly resulted from this, a more broadly based study similar to that of *Rodell et al.* [2005] is needed, using other methodologies which, for example, take interannual variability into account.

[27] **Acknowledgments.** Primary support for this research came from NASA project NAG5-9796. Additional support for W. James Shuttleworth came from NASA–LBA Ecology Program (Group CD18) under grant NCC5-709 and by SAHRA (the NSF Center for Sustainability of semi-Arid Hydrology and Riparian Areas) under grant EAR- 9876800. The authors wish to thank the Hydrology Sciences Branch team (code 614.3) at NASA/GSFC for their full support on the set up of SALDAS and CPTEC for making their model data available and the NASA Postdoctoral Program.

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