Land surface model spin-up behavior in the North American Land Data Assimilation System (NLDAS)

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[1] The process of a model adjusting to its forcing (model spin-up) can severely bias land surface simulations, and result in questionable land surface model (LSM) output during the spin-up process. To gain a better understanding of how spin-up processes affect complex spatial and temporal land surface modeling situations in general, and the Retrospective North American Land Data Assimilation System (NLDAS) simulations in particular, a two-phase study was conducted. The first phase examined results from Control, Wet, and Dry 11 year-long Mosaic simulations, while the second phase attempted to explain spin-up behavior in NLDAS Retrospective simulations from the Mosaic, Noah, VIC and Sacramento LSMs based in part on the results from phase 1. Total column and root zone soil moisture spin up slowly, while evaporation and deep soil temperature spin up more quickly. Mosaic soil moisture initialization with NCEP/DOE Global Reanalysis 2 (NCEP/DOE R-2) data (Control run) leads to a faster spin-up time than saturated (Wet run) or dry (Dry run) initialization, with the Control run reaching equilibrium 1 to 2 years sooner than the Wet run and 3 to 4 years more quickly than the Dry run. Overall, practical drift of land surface stores and output ceased in the Control run within approximately 1 year, and fine-scale equilibrium was reached within 5.5 years. Spin-up times exhibited large spatial variability, and although no single causal factor could be determined, they were correlated most strongly with precipitation and temperature forcing. In general, NLDAS models reach a state of rough equilibrium within the first 1 to 2 years of the 3-year Retrospective simulation. The Sacramento LSM has the shortest spin-up phase, followed by the Mosaic, VIC, and Noah LSMs. Initial NCEP/DOE R-2 conditions were too dry in general for the VIC and Noah LSMs, and too moist for the Mosaic and Sacramento LSMs. These results indicate that in most cases, the 1-year spin-up time used in the Retrospective NLDAS simulations eliminated spin-up problems from the subsequent period that was used for analysis. *INDEX TERMS:* 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 1866 Hydrology: Soil moisture; 1829 Hydrology: Groundwater hydrology; *KEYWORDS:* LDAS, LSM, spin-up

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1. Introduction

[2] Land surface processes play an important role in the Earth system, governing exchanges of heat, moisture and momentum between the surface and atmosphere. Soil moisture, albedo, surface temperature, snow pack and runoff anomalies at various spatial and temporal scales greatly impact agriculture, large-scale water resource water management, and global weather patterns [*Shukla and Mintz*, 1982; *Dirmeyer and Shukla*, 1993; *Hall*, 1988]. Land

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surface models (LSMs) are valuable tools in the exploration of these impacts, and form the basis of the North American Land Data Assimilation System (NLDAS) project (K. E. Mitchell et al., The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system, submitted to *Journal of Geophysical Research,* 2003, hereinafter referred to as Mitchell et al., submitted manuscript, 2003). NLDAS project goals include the accurate offline initialization of NWP models with NLDAS land surface fields, and the intercomparison and improvement of the Mosaic [*Koster and Suarez*, 1992, 1996], Noah [*Mitchell et al.*, 2000], VIC [*Liang et al.*, 1996] and Sacramento [*Burnash et al.*, 1973] LSMs. Since realistic land surface states are vital to reach these goals, model spin-up processes must be understood and properly accounted for.

[3] LSMs are transitive in nature, and are each characterized by a unique land surface climatology. Even given identical meteorological forcing, vegetation parameters and soil characteristics, model climatologies can differ greatly from LSM to LSM owing to the complex interactions between model parameterizations [*Koster and Milly*, 1996]. This climatology represents a preferred model state which lies within the bounds determined both by external forcing and internal model physics. When a land surface model is initialized with land surface conditions which depart from this preferred state, the model will undergo a period of spin-up during which its internal stores of energy and water adjust from the initial conditions, to an equilibrium state [*Yang et al.*, 1995] in which they reflect only the integration of model forcing and the internal governing of model physics. A conceptual way to depict the spin-up process is to envision two land surface simulations; one initialized completely dry, and another initialized completely saturated. As the simulations progress, the soil moisture states of each run will gradually converge upon a common solution. During this period of adjustment, the temporal evolution of land surface states may trend in a direction opposite that of observations. As it may strongly reflect the anomalies introduced by the initialization, output during the spin-up period can be unusable and may exhibit a large amount of drift. Upon completion of the spin-up process, a physically realistic state of equilibrium should exist in the model, between external forcing and the simulated land surface fluxes, and the simulation should better reflect observations and respond realistically to atmospheric forcing.

[4] Unfortunately, many projects have allowed for little if any spin-up time, and have made use of LSM output for monsoon [*Gochis et al.*, 2002], seasonal prediction [*Fennessy and Shukla*, 2000], and model intercomparison [*Tackle et al.*, 1999] studies within one month or less of LSM initialization. Without proper spin-up, land surface simulations can be negatively impacted, as *Maurer and Lettenmaier* [2003] have shown that better initialization of soil moisture states leads to better long-lead streamflow forecasts, *Koster and Suarez* [2001] found that soil moisture is an important source of forecast skill for the predictability of precipitation, and *Zhang and Frederiksen* [2003] have shown that the initial soil moisture conditions supplied to an NWP model affect both temperature and precipitation forecasts. Previous spin-up studies have examined this issue across a wide range of LSMs, but often in limited single-vegetation, single-soil type situations [*Schlosser et al.*, 2000; *Yang et al.*, 1995] over 1 grid box. Other studies have explored spin-up processes over regional areas [*Robock et al.*, 1998], but have been limited in the land surface variables studied, or in the types of initialization situations examined. Therefore, the goals of this paper are to: a) characterize the range and causes of spin-up behavior in large scale, complex LSM modeling situations to provide information that will lead to more informed and more accurate land surface simulations, and b) analyze the extent to which NLDAS model results are impacted by spin-up processes, and so provide beneficial information to users of NLDAS products as well as similar projects. To reach these goals, we present the results of a two-part analysis study. The first phase examines a set of 11 year-long recursive Mosaic LSM runs, while the second phase centers on the analysis of the retrospective set of NLDAS model simulations (Mitchell et al., submitted manuscript, 2003).

2. Recursive Experiment Design

[5] The Mosaic LSM was used to conduct each of the recursive simulations. Developed at NASA GSFC by *Koster and Suarez* [1992, 1996], the Mosaic LSM calculates water and energy land surface fluxes in response to externally supplied meteorological forcing. The LSM features a complete snow budget and partitions precipitation into rain and snow based on the externally supplied two-meter temperature using a cutoff of 273K. It allows for direct vegetation control over the surface and energy water balances, with environmental stresses such as high temperatures or dry soils acting to increase canopy resistance and thus decrease transpiration. Accounting for subgrid-scale heterogeneity, Mosaic divides each model grid box up into several ‘tiles’ based on observed vegetation type. Each tile features its own energy balance calculations as well as prognostic temperature and soil moisture values. Gridded output is computed by taking a weighted average of tile output variables. As configured for this research, the model divides each grid cell into a maximum of ten tiles, utilizes a uniform soil type over all tiles within each grid box, and features three soil layers fixed at thicknesses of 10, 30, and 160 cm. The first and second soil layers comprise the root zone, while the third layer acts as a “recharge” reservoir for long-term moisture storage. Mosaic allows for overland and ground water drainage, and features parallel calculations of bare soil evaporation, transpiration and interception loss. The Mosaic LSM shares some formulations with the SiB model [*Sellers et al.*, 1986] upon which it is based, with the largest similarity occurring in the formulation of canopy resistance.

[6] The set of 11 year-long recursive runs conducted with the Mosaic LSM runs serves to establish bounds of typical and extreme LSM spin-up times and consists of simulations initialized with a) saturated conditions (Wet run), b) 0% soil moisture conditions (Dry run), and c) NCEP/DOE Global Reanalysis 2 (NCEP/DOE R-2) [*Kanamitsu et al.*, 2002] conditions (Control run). In order to obtain initial conditions for the Control run, NCEP/DOE R-2 plant available soil wetness values were spatially interpolated to the 1/8th

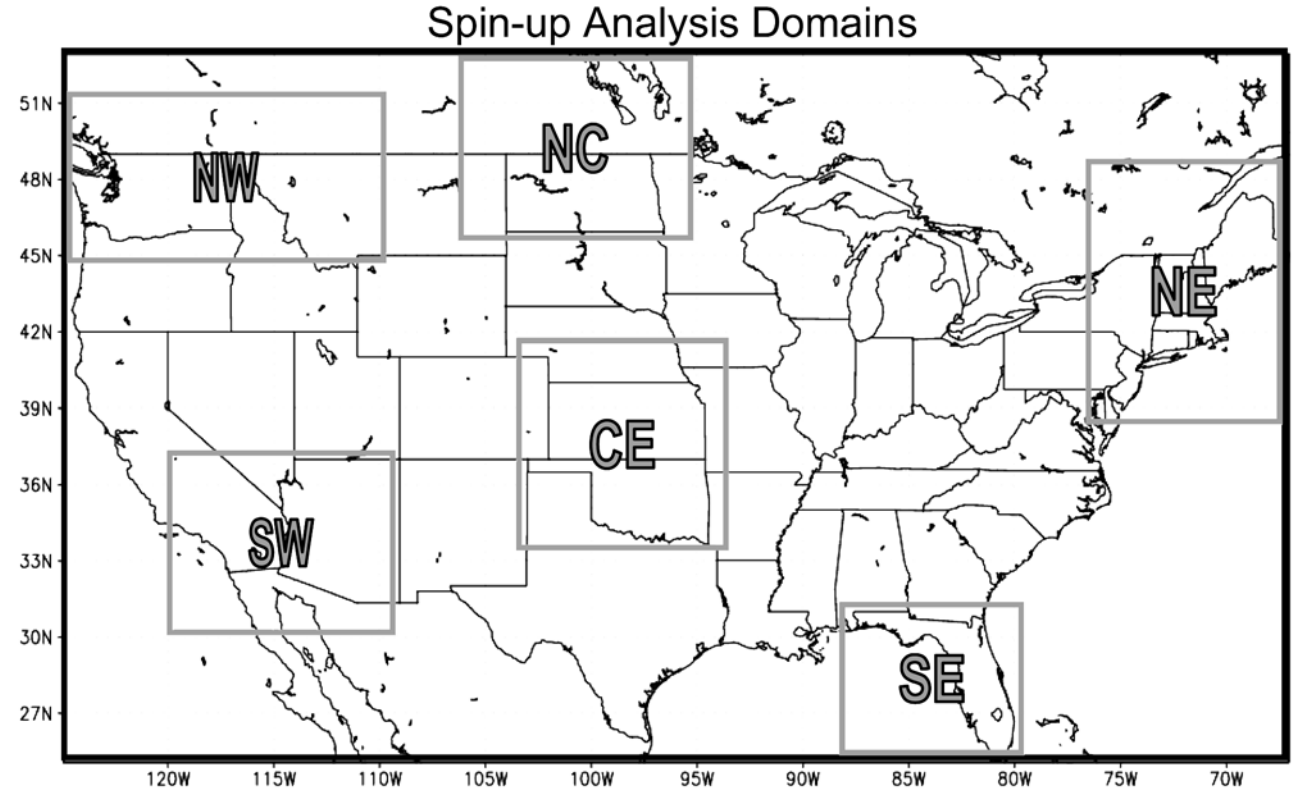


Figure 1. Small grey rectangles denote six subregions analyzed in recursive spin-up experiments. Large black rectangle denotes 1/8th degree NLDAS domain used in Retrospective simulation.

degree NLDAS grid and then converted into total wetness values for use with Mosaic. Plant available wetness provides a measure of the moisture above the wilting point available to vegetation, while total column wetness represents the total amount of water in the soil column. Because of computational limits, each of the three simulations was conducted over NLDAS subregions covering North America (Figure 1). These windows, hereafter referred to as the NE, NC, NW, SE, CE and SW regions, were chosen to encompass a wide variety of climate, soil and vegetation regimes (Table 1). Each experiment used identical soil data, vegetation parameters, NLDAS meteorological forcing data [*Cosgrove et al.*, 2003], and initial NCEP/DOE R-2 deep soil temperatures (Mitchell et al., submitted manuscript, 2003). To facilitate the detection of spin-up trends, forcing from 1st October 1996 to 30th September 1997 was repeated in a yearly cycle for 11 years. With forcing at 23Z 30th September 1997 linked to forcing at 00Z 1st October 1996 to form a 1 year forcing loop, the possibility exists for a large "jump" in meteorological conditions as the model begins a new year of simulation. Such a perturbation, if serious enough, could negatively impact the spin-up process. However, differences in meteorological conditions at this juncture point were found to be within the range of synoptic variability. Thus, use of this yearly recursive forcing eliminates interannual climate variability and links any model change from year to year directly to spin-up processes.

[7] It can be assumed that these spin-up processes will lead the model into an equilibrium state that is representative for the climatology of the one-year forcing in each grid cell. This bears certain risks. In particular, for some areas the meteorological forcing and vegetation parameter data in the chosen time period might show anomalies compared to climatology. Therefore, the equilibrium model state will be different from an average model state derived from a long-term data set that represents the climatology of that grid cell. Nevertheless, we think that this numerical experiment still gives us valuable answers about the time scales involved in the initialization of land surface schemes.

3. Recursive Experiment Analysis

[8] Both area averaged and spatially distributed results from the Mosaic LSM 11 year-long Dry, Wet and Control simulations were used to determine the temporal and spatial characteristics and underlying causes of spin-up behavior. The examination of spatially distributed data can reveal important information about the variation of the spin-up process over each region, while area averaged data is well-suited for the application of statistical analysis procedures and for the creation of regional summaries.

[9] There are many accepted ways to define model equilibration or spin-up. In the strictest sense of the word, an equilibrated model will exhibit no artificial drift in model stores or in prognostic variables. In recursive model studies, time series predictions of variables such as soil moisture and evaporation will be identical from year to year. In practice, numerical roundoff and the complexity and CPU intensiveness of modern LSMs make such a strict result difficult if

Table 1. Soil, Vegetation, and Climate Statistics for Six Study Regions[a]

Region	Top Three Vegetation Classes	Top Three Soil Classes	Total Annual Precipitation, mm	Average Annual Temperature, K	Average Annual Solar Radiation, W/m^2
NW	EN,G,C	L,SiL,SL	959.66	277.10	169.87
NC	C,G,W	L,CL,SL	504.54	275.76	172.35
NE	MC,W,DB	SL,SiL,L	1055.31	277.60	167.18
SW	OS,WG,CS	SL,L,SCL	264.83	288.09	233.66
CE	C,G,WG	SiL,L,SiCL	753.85	285.44	196.25
SE	WG,W,EN	S,LS,C	1309.26	294.30	209.76

[a]The table includes the three most common vegetation and soil classes listed in order in each region, where EN is evergreen needleleaf forest, G is grassland, C is cropland, W is woodland, MC is mixed cover, DB is deciduous broadleaf forest, OS is open shrubland, WG is wooded grassland, CS is closed shrubland, L is loam, SiL is silty loam, SL is sandy loam, CL is clay loam, SCL is sandy clay loam, SiCL is silty clay loam, S is sand, LS is loamy sand, and C is clay.

not impossible to obtain over a large domain. As such, the land surface modeling community has identified other measures of spin-up time. In particular, in the Project for Intercomparison of Land Surface Parameterization Schemes (PILPS) experiment [*Henderson-Sellers et al.*, 1993], the GISS group judged their model to be equilibrated if the monthly means were within 0.01% of each other from year to year, while the SSiB modeling group used a 0.1% threshold [*Yang et al.*, 1995]. Other modeling groups have used the e-folding time [*Delworth and Manabe*, 1988] or the halving time [*Simmonds and Lynch*, 1992] to compare spin-up times.

[10] Based in part on these examples, we make use of several statistical tools to measure and characterize spin-up time. These tools include the percent cutoff-based (PC) time, the e-folding time, and anomaly values. The PC time is a measure of how long it takes for yearly changes in monthly averaged model output to decrease to a certain threshold. Threshold values of 10%, 5%, 1%, 0.5%, 0.1%, 0.05%, 0.01%, 0.005% and 0.001% were chosen, and were applied to both area averaged and spatially distributed data. Emphasis was given to the PC times obtained using the 1% and 0.01% thresholds. The first value represents a level at which the LSM ceases to exhibit model output changes on a ‘‘practical’’ scale, having reached practical equilibrium, and represents the margin of error in many observation systems. The second cutoff level represents fine scale model equilibrium, and satisfies both the GISS and SSiB requirements in the PILPS experiment. Although this statistic was computed for all regions of the Wet, Dry and Control runs at the 1% and 0.01% threshold levels (see Table 2), discussion in this article is limited to those cases which provide significant insight into the spin-up process.

[11] As with the PC time, the e-folding time provides valuable insight into the temporal characteristics of the LSM spin-up process. In the case of this particular study, the e-folding times of the autocorrelation functions of soil moisture anomalies were computed. This was accomplished by first drawing on the principles of the bucket model [*Delworth and Manabe*, 1988] and the antecedent precipitation index (API) to fit an exponential function to the autocorrelation function of monthly soil moisture anomalies. This ‘‘best fit’’ exponential function was computed using the least squares method and was used as the basis to calculate the e-folding time. This process was repeated over each of the six regions in the Control, Wet and Dry simulations. Low e-folding times would indicate that model anomalies were short-lived, and thus that the model would be able to recover relatively quickly from an incompatible initialization of its soil moisture states. High e-folding values would indicate that anomalies were slow to dissipate, and so emphasize that it is vital to initialize the model's soil moisture states with realistic values close to the model's natural range.

[12] The e-folding time is valuable as a means of cross-study comparison, but must be used with caution. Unlike the PC time, an accurate e-folding calculation depends on the model having reached equilibrium. Because the Wet and Dry runs did not reach equilibrium in many cases, the last year of the Control simulation served as the ‘‘average’’ year from which all Wet, Dry and Control run anomaly values were calculated. In addition, although it serves as a useful indicator of how long it takes for 63% of an anomaly to dissipate, the e-folding time gives no information as to the magnitude of the anomaly. A large e-folding time indicates that it takes many years for a model to shed most of its initial anomalies—yet, for example, if the anomaly in soil temperature is only 0.1 K, it may be reasonable to deem the model as ‘‘spun-up’’ even before the e-folding time is reached. Large e-folding times with small anomalies point to the fact that in nature, the timing of most anomalies can only be approximated with an exponential function. Because of these issues, it is important to assess on a situation by situation basis which gauge of spin-up is more desirable and appropriate: one that quantifies the time lag needed for the correlation between model anomalies to decrease by 63% (e-folding time), or one that quantifies the time needed for yearly model change to be reduced to an acceptable level determined by the user (PC time).

[13] Complementing the PC and e-folding times described above, anomaly and Spearman rank correlation calculations were also performed to examine Mosaic spin-up behavior. Ideally, anomalies should be calculated based on a fully equilibrated model. As a reasonable approximation of this, the last year of the Wet, Dry and Control Mosaic simulations was used, and anomaly calculations for model output were performed. These values are useful in determining the ‘‘compatibility’’ of the model initialization, i.e., how far from equilibrium the model was initialized.

[14] The correlation of model spin-up time with yearly averaged precipitation, temperature, shortwave radiation and all Mosaic soil and vegetation parameters was also examined. This analysis was performed in parallel with visual inspection of input data sets and model output data,

Table 2. Displays the Number of Months Required for Area and Monthly Averaged Total Column Soil Moisture (SOILMTC), Root Zone Soil Moisture (SOILMRZ), Deep Soil Temperature (TSOIL), and Evaporation (EVP) Variables to Reach the 5%, 1% and 0.01% PC Threshold Levels in the Dry, Wet and Control (ctl) Simulations Over the Six Subregions[a]

	PC Level	dry.ne	ctl.ne	wet.ne	dry.se	ctl.se	wet.se	dry.ce	ctl.ce	wet.ce	dry.sw	ctl.sw	wet.sw	dry.nw	ctl.nw	wet.nw	dry.nc	ctl.nc	wet.nc	dry.all	ctl.all	wet.all
SOILMTC	5	25	7	8	14	9	8	25	4	13	48	0	14	33	9	15	36	0	22	32.34	4.38	14.32
	1	44	18	22	22	12	14	46	13	25	94	1	37	47	12	27	55	0	34	54.67	9.05	28.26
	0.01	109	75	85	48	38	41	–	44	79	–	–	–	–	47	84	105	55	81	>112	>65	>87
SOILMRZ	5	23	1	10	14	8	7	21	0	12	29	1	11	22	10	13	33	6	22	25.00	4.07	13.49
	1	37	21	21	20	14	14	35	13	23	59	12	34	37	11	25	47	7	35	41.56	12.64	26.94
	0.01	108	83	84	50	38	40	113	49	66	–	–	–	–	47	84	101	49	83	>110	>66	>84
TSOIL	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00
	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00	0.00	0.00
	0.01	24	12	24	18	12	12	36	11	25	44	12	23	47	12	25	48	12	36	39.35	11.80	26.16
EVP	5	22	0	1	14	7	7	30	0	13	37	2	21	35	11	23	35	4	25	31.24	3.85	16.60
	1	24	12	22	19	12	12	37	13	25	69	12	34	47	23	35	57	9	37	45.51	14.06	30.06
	0.01	83	71	71	43	32	36	116	100	66	–	114	–	108	59	73	100	49	83	>103	75.37	>80

[a]Dashes indicate that a region did not reach equilibrium over the course of the simulation.

and was used to determine the factors which impacted the Mosaic spin-up time.

[15] Rather than apply these measures of spin-up to all output from the Mosaic LSM, a representative subset of variables was selected for analysis. These variables include three model state measures (total column soil moisture over Mosaic's 2 m soil column, root zone soil moisture over Mosaic's 40 cm active root zone, and deep soil temperature), and one model diagnostic variable (evaporation). Model spin-up is ultimately a manifestation of LSM model states drifting toward their preferred, equilibrated state and would be reflected in these four variables. Spin-up-related changes in any of these variables would have significant impacts on land-atmosphere interaction, and so each quantity serves as an important focus of the model spin-up studies.

4. Recursive Results and Discussion

4.1. Total Column Soil Moisture Results

[16] By computing the absolute and percent difference in total column soil moisture between the first hour of year 1 and the first hour of year 11 of the recursive simulations, the amount of change between initial and final land surface states can be determined and the ''compatibility'' of the Mosaic soil moisture initializations described in Section 1 with Mosaic's ultimate preferred soil moisture states can be illustrated. As seen in Figure 2, the Control run initialization procedure yields initial total column soil moisture values which range (with respect to Mosaic's ultimate preferred state) from 73% too dry to 180% too wet at the start of the run, but which are, in general, on the wet side. Over half of the area of the NC, NW, NE, SW and CE regions is initialized with soil moisture values within 20% of Mosaic's equilibrium value, but much of the SE region is poorly initialized with values from 40% to 110% too high. Initialization values in the Wet run are significantly moister than those in the Control run, and range from 0.26% to 528% too wet over the study domain.

[17] As seen in Table 2, the NC and SW regions have the lowest 1% PC times in the Control run and reach practical equilibrium 8 months faster than does the study area as a whole, which takes 9 months. On average, dry initialization adds 45 months to the practical equilibration process, while saturated initialization adds 19 months. The negative impacts of wet and dry initialization are felt even more strongly at the 0.01% PC level. Here, Wet run initialization adds 22 months and Dry run initialization adds 47 months to the spin-up process. The NE and SE regions are generally the least affected by wet and dry initialization, while the NW and CE regions are the most affected (Table 2 and Figure 3). In fact, dry initialization prevents these two regions from reaching fine scale equilibrium within the 11 years of the recursive simulation.

[18] Figure 4 shows the autocorrelation of total soil moisture anomalies with the fitted exponential function for the NE region. In general the exponential function provides a reasonable fit to the autocorrelation function. Figure 5 summarizes these results for root zone and total soil moisture for all six regions. In contrast to the PC times, the e-folding times of the Control run area averaged total column soil moisture anomalies are generally larger than those seen in

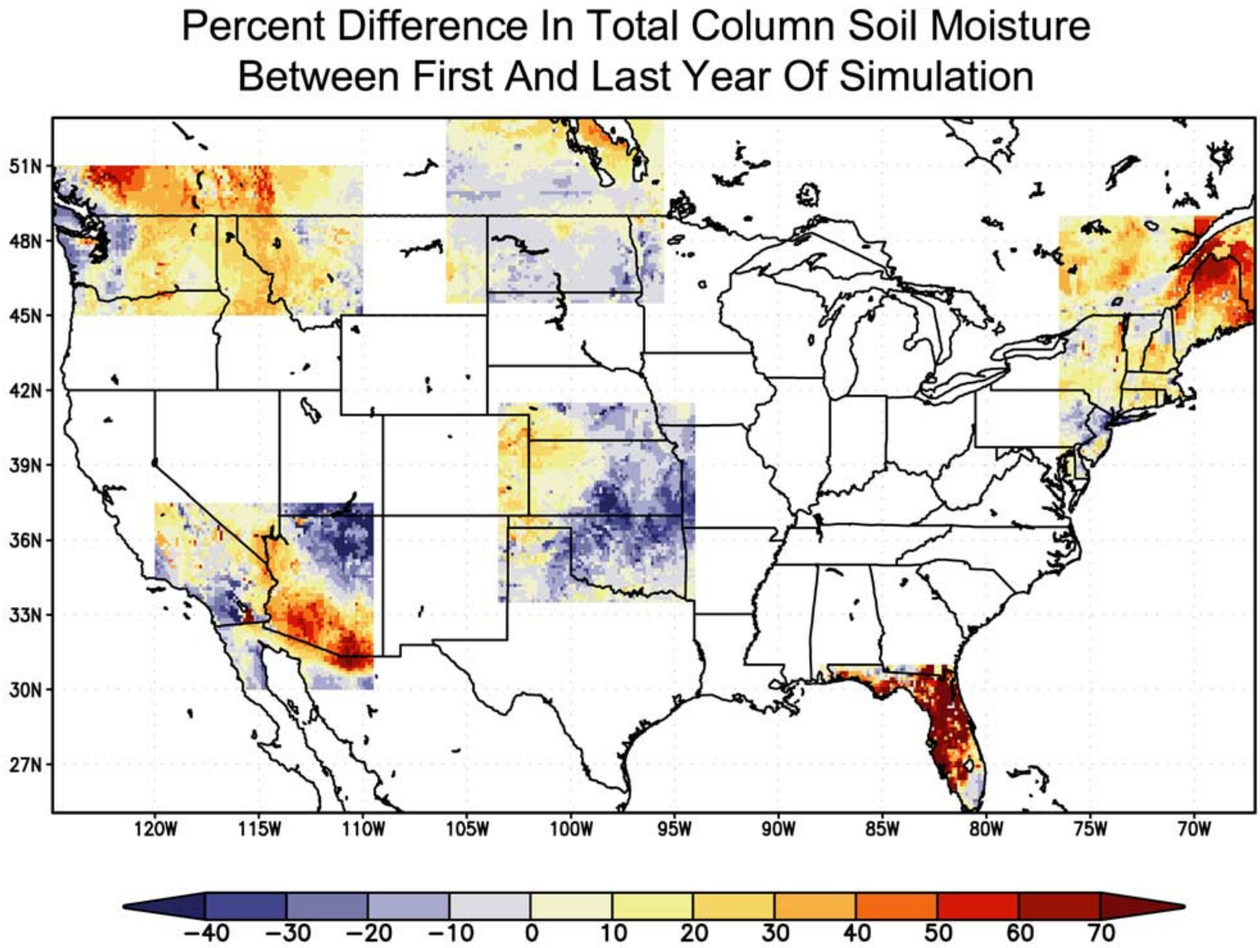


Figure 2. Percent difference between initial and final Mosaic total column soil moisture values in the Control run, computed as ((Year1 – Year11)*100/Year11). Positive values indicate an overly wet initialization while negative numbers indicate an overly dry initialization.

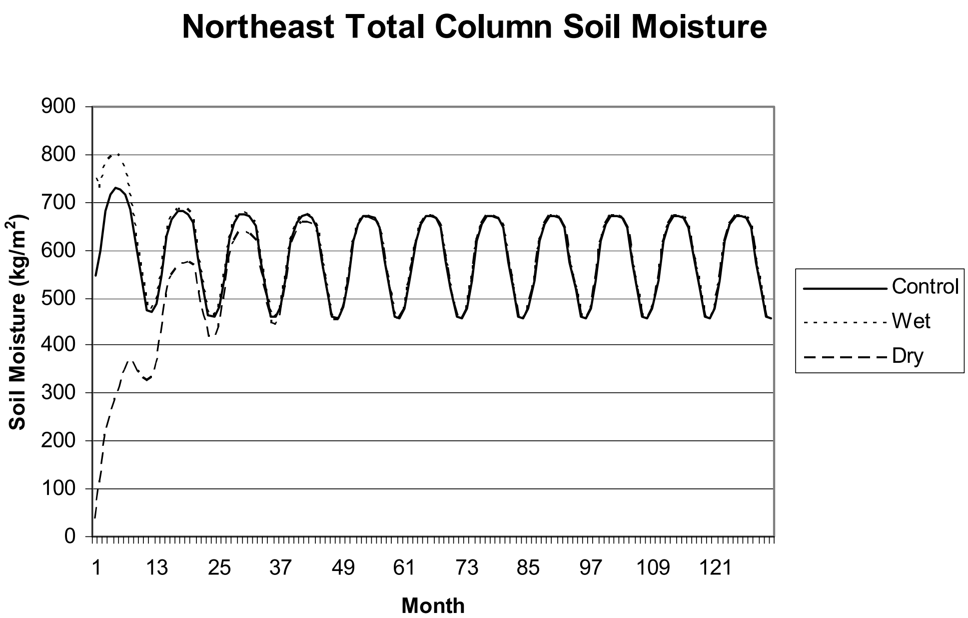


Figure 3. Time series plot of NE total column soil moisture (kg/m^2) over the 11 year simulation. This region is among the least affected by Wet and Dry initializations, and this figure illustrates the relative quickness with which Wet and Dry runs converge with the Control simulation.

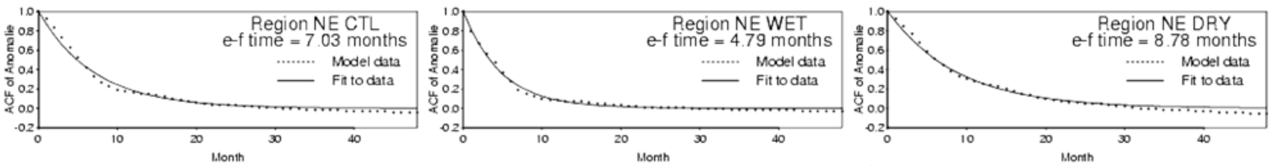


Figure 4. Autocorrelation function of Mosaic total column soil moisture anomalies in the Control, Wet and Dry simulations for the NE region. Each plot also contains the corresponding fit with an exponential function and the e-folding time.

the Wet simulation, and range between 0.5 and 2.1 years. These e-folding times grow even larger when dry initialization is used. The sole exception to this occurs in the SW region, where the Dry run features an e-folding time less than that of the Control run. A time series plot (Figure 6) of Dry run SW total column soil moisture illustrates the juxtaposition of a relatively short e-folding time with a relatively large PC time (in comparison to the Control run). Dry run soil moisture in this region converges most of the way toward equilibrium within the first year, however, even after 10 years when the simulation has reached the 0.1% PC level, soil moisture values are still significantly less than those in the Control or Wet simulations. This situation serves to highlight the caution regarding e-folding times given in Section 3—that lower e-folding times do not necessarily translate into a more favorable spin-up process. It shows that the dissipation of soil moisture anomalies does not necessarily behave like an exponential function and we therefore must look at the time scales and the amplitude of the anomaly at the same time.

[19] Previous research by *Entin et al.* [2000] used soil moisture observations over China, Mongolia, Illinois and Iowa to determine that e-folding times in the 0 to 1m soil layer range from 1.3 to 2.4 months, and that e-folding times in the 1 to 2 m soil layer range from 5 to 7 months. With the exception of the NC and SW regions, e-folding times of anomalies in Mosaic's 0 to 2 m soil column in the Control and Wet simulations are less than 7 months, and so agree with the observation-based 1 to 2 m times. The Dry simulation, by contrast, features e-folding times that are several months greater than those of either the 0 to 1 m or 1 to 2 m observation-based times. These results imply that dry soil moisture anomalies and anomalies in arid regions may persist for an excessive length of time in the Mosaic model, emphasizing the fact that care must be taken in properly initializing LSM soil moisture levels.

[20] The three soil moisture initialization procedures used in the recursive simulations lead to differences in area averaged total column soil moisture anomalies which persist over the entire course of the runs. Table 3 shows that in the Control run, initial area-averaged anomalies in the six regions ranged from a high of 73 mm (a difference of 22% from the year 11 value) in the SE region, to a low of −0.72 mm (−0.17%) in the NC region, and decrease to under ±0.08% over all regions by the end of the simulation. By contrast, initial anomalies in the Wet run ranged from 48% to 102% and were still at the level of ±0.2% by the end of the simulation. The Dry run was even more affected, with initial anomalies of −99% to −79%, and final anomalies as high as −4.6%. However, similarities do exist between the

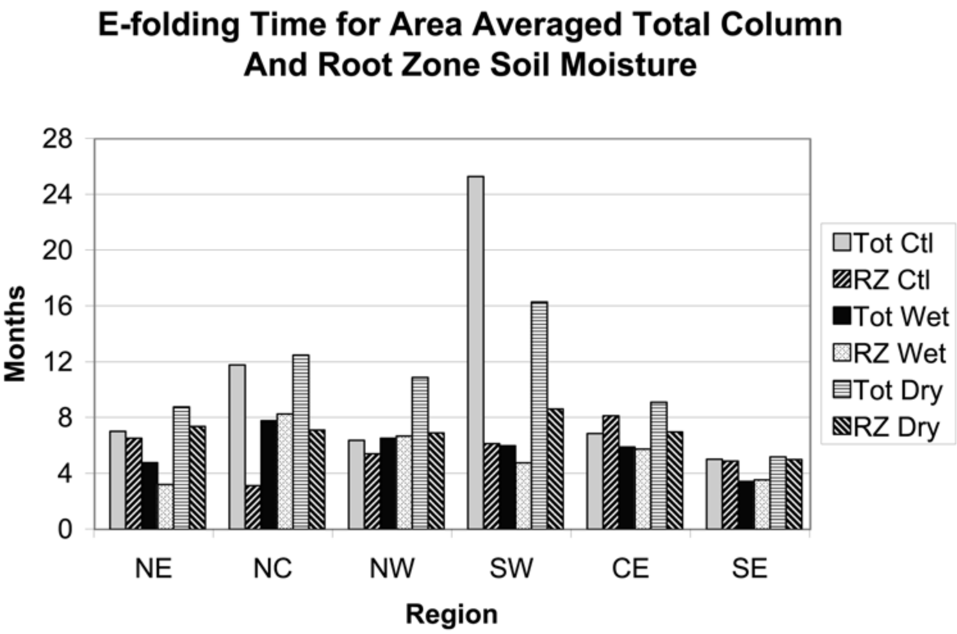


Figure 5. E-folding times in months of Mosaic total column soil moisture (Tot) and Mosaic root zone (RZ) soil moisture anomalies in the Control, Wet and Dry simulations.

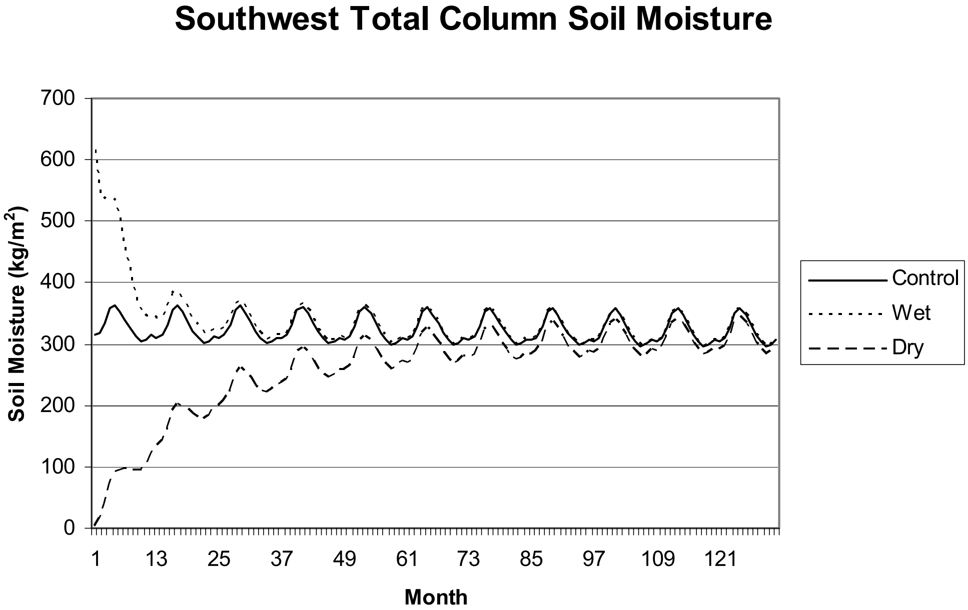


Figure 6. Time series plot of SW total column soil moisture (kg/m^2) over the 11 year simulation. This region has a lower e-folding time in the Dry run than in the Control run, yet fails to converge with the Control time series over the course of the simulation.

Control, Wet and Dry simulations, as the SE region consistently exhibited the smallest final anomaly values, and the SW region consistently exhibited the largest final anomaly values.

4.2. Root Zone Soil Moisture Results

[21] Plant roots extend down through the top 40 cm of Mosaic's soil column, and it is from this layer that evapotranspiration processes can draw moisture. Analysis of the PC times in Table 2 shows that in the Control and Dry runs, area averaged root zone soil moisture spins up in about the same amount of time as total column soil moisture. This similarity disappears in the Wet run, where root zone soil moisture reaches practical equilibrium 1 month more quickly than does total column soil moisture, and fine scale equilibrium 3 months more quickly. On average, it takes 9 months for practical drift to dissipate in the Control run, and at least 66 months to reach fine scale equilibrium. These times are greatly lengthened by the suboptimal initialization in the Wet and Dry runs. Wet initialization adds 14 months to practical equilibration and 18 months to fine scale equilibration, while dry initialization delays these two events by 30 months and 45 months respectively. The SW region does not reach the 0.01% PC threshold in any of the three simulations, and dry initialization prevents this threshold from being reached in the NW region as well.

[22] As seen in Figure 5, e-folding times of Control run root zone soil moisture anomalies were generally less than those of total column soil moisture anomalies, and ranged from 3 to 8 months. These times tended to decrease with saturated initialization and lengthen with dry initialization. Values are similar to those computed by *Entin et al.* [2000] for the 1 to 2 m column, but are longer than those for the 0 to 1 m column. As Mosaic's root zone extends from 0 to 40 cm, this result implies that, compared to observations, the soil physics of Mosaic's root zone gives rise to overly persistent anomalies. Values of these anomalies in all three simulations are similar (on a percent basis) to those seen in the analysis of total column soil moisture (Table 3).

[23] Out of all of the regions, NE features what is perhaps the most interesting area averaged Control run root zone soil

Table 3. Monthly Averaged Control Run Anomalies at the 0, 1 and 5 Year Marks[a]

	Year	ctl.ne	ctl.se	ctl.ce	ctl.sw	ctl.nw	ctl.nc
TC Soil Mst (mm,%)	0	66.3, 13.9	72.6, 21.7	−33.4, −7.9	9.2, 3	47.1, 11.3	−.72, −.17
	1	12.0, 2.6	8.1, 2.8	−8.1, −1.9	7.6, 2.5	6.9, 1.7	−3.1, −.75
	5	.29, .06	.002, .0007	.027, .006	2.4, .79	.016, .004	−.039, −.009
RZ Soil Mst (mm,%)	0	10.8, 11.1	8.9, 16.2	−2.3, −3.3	3.8, 7.7	14.6, 18.8	9.8, 14.2
	1	2.1, 2.6	1.1, 2.6	−1.7, −2.3	1.1, 2.2	.72, 1.1	−.44, −.64
	5	.056, .067	.0003, .0008	−.005, −.007	.13, .26	.002, .002	−.007, −.01
Soil Temp (K)	0	.61	−.57	.58	−2.0	−1.1	−.14
	1	−.03	−.075	.024	−.18	−.15	.046
	5	−.00018	0	−.000031	−.002	−.000092	.0002
Evaporation (mm)	0	2.8	.901	−.65	5.95	9.3	8.75
	1	1.73	2.28	−1.75	.76	2.1	−.22
	5	.009	.00035	−.002	.063	−.001	−.005

[a]Anomalies are given in the following formats: Total column soil moisture (mm, %), root zone soil moisture (mm, %), deep soil temperature (K), evaporation (mm).

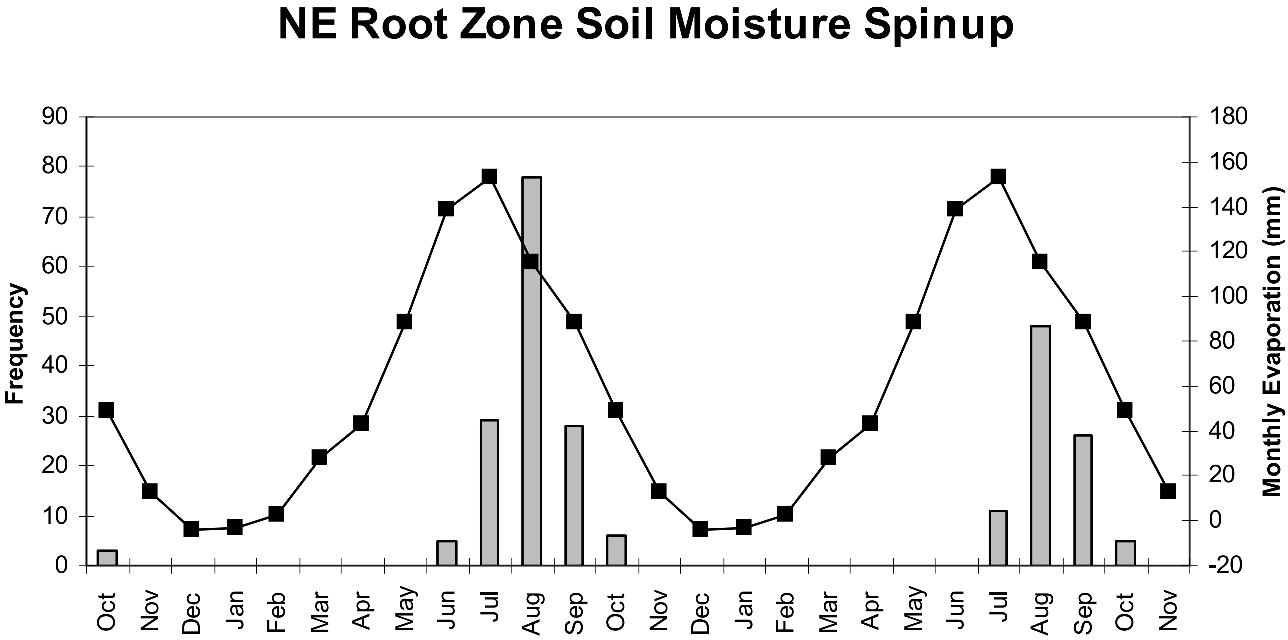


Figure 7. Number of 1/8th degree grid boxes over the NE region which reach fine scale equilibrium from October of year 8 through November of year 10 of the Control run (grey), and total monthly evaporation over that same time period and region (black).

moisture spin-up pattern. As described above, PC times measure the number of months needed for the rate of yearly change in a LSM variable to decrease below a certain threshold. It might be expected that the rate of change would decrease smoothly over time as the model converges toward equilibrium. However, as seen in Figure 7, this is not always the case. In this region over all 11 years of the simulation, most grid boxes cross the 0.01% threshold in late summer or early fall, with few or none reaching the threshold in winter, spring or early summer. This can be explained by combining a study of evaporation time series data with information about the temporal trend of root zone soil moisture over the NE. Here, the initial conditions supplied in the Control run are too moist, leading to a continual drying trend as the 11 year simulation progresses. At the same time, the region goes through a seasonal cycle of evaporation, with evaporation values peaking in the spring and early summer when plant activity, available moisture, solar radiation and temperature values are high. This warm season evaporation acts to enhance the natural drying trend that is present over the NE, leading to the highest levels of model drift of the year. With lower amounts of yearly drift to either side of the spring and early summer, a grid box which first passes below the 0.01% PC threshold in the wintertime will experience enhanced drying in the spring/summer and pass back over this PC threshold, only to reach the 0.01% threshold again after the summer ends and the enhanced drying ceases. This leads to the clustering of PC times from July to October seen in Figure 7. Though much less prevalent, scattered examples of this behavior can be seen in the other five regions as well.

[24] Although area averaged data are useful for making general statements and are well suited for the application of statistical analysis, the examination of spatially distributed data can reveal important information about the spatial character of the spin-up process. Such an examination of Figure 8 shows that the vast majority of gridpoints in the Control run reach the 1% PC threshold in less than 24 months, with many reaching the cutoff in less than 12 months. That being said, it is also true that some grid-points over northeastern Canada, southwestern Arizona and the western portion of the CE region fail to drop below the 1% yearly drift mark until after 72 months. The spatial variability of spin-up times increases when a 0.01% cutoff is used in PC time calculations (Figures 8 and 9). Significant spatial spin-up gradients exist in the NW, NC and NE regions, where PC times vary by up to 10 years. By contrast, the SE region features no systematic gradient, and generally low, evenly dispersed PC times. The SW region features, by far, the longest 0.01% PC threshold spin-up times, with the vast majority of the area having PC times of greater than 10 years. Many of these patterns are reflected in both the Wet and Dry simulations, and CE and NW examples can be seen in Figures 8 and 9.

[25] In an attempt to uncover the primary influences on Control run root zone soil moisture PC times, 0.01% PC times over each of the six regions were correlated with annually averaged two meter air temperature and solar radiation, with yearly accumulated precipitation, and the compatibility of the initialization. Correlations were also computed between PC times and over 40 Mosaic soil and vegetation parameters including: canopy height, rooting depth, cross sectional root area, moisture stress vegetation parameters, vegetation wilting point, temperature stress vegetation parameters, temperature-based transpiration control values, resistance parameters controlling moisture transport within vegetation and the root system, leaf angle parameter, stomatal resistance parameters, vapor pressure deficit stress parameter, snow-albedo parameter, b soil parameter, saturated soil moisture potential, soil hydraulic

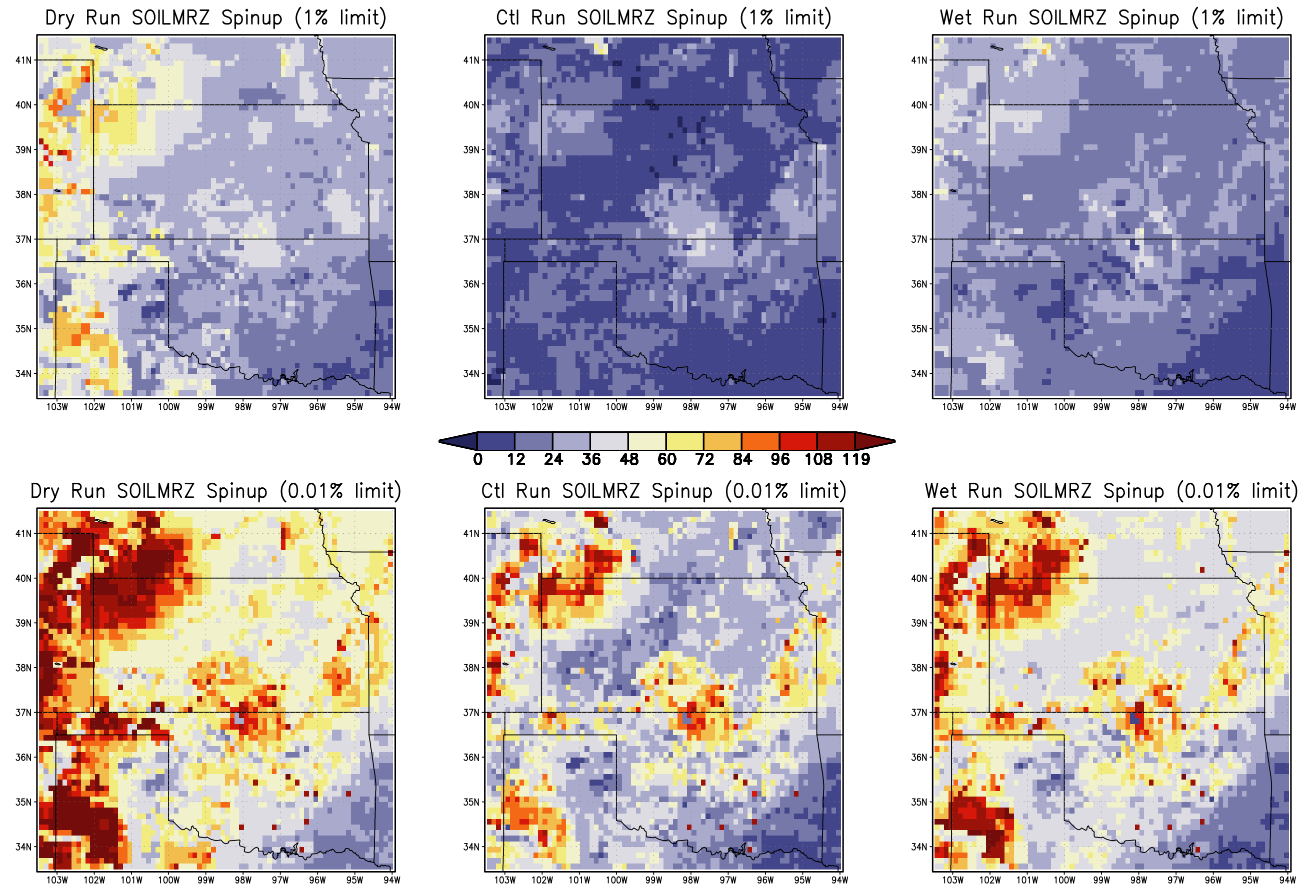


Figure 8. Spatially distributed PC times showing the number of months needed for CE root zone soil moisture to reach practical (1% PC time) and fine scale (0.01% PC time) equilibrium in the Dry, Wet and Control Simulations. Darkest blue shade indicates regions that reach PC thresholds immediately at start of simulation, while darkest red shade indicates regions that do not reach PC thresholds throughout entire simulation.

conductivity, soil moisture holding capacity, end-of-simulation soil moisture values, soil porosity, and soil layer thickness values. The resulting correlation coefficients (significant at the 0.01 level) of the two variables in each region most strongly correlated with 0.01% PC times are listed in Table 4. Of these variables, total yearly precipitation and average yearly 2-meter temperature are the ones most commonly well-correlated with root zone soil moisture spin-up times. In almost all cases, lower temperature and lower precipitation values are associated with higher PC times (i.e., longer spin-up time). The one exception is in the NC region where higher precipitation values are associated with longer spin-up times. In some regions of the country, high soil moisture potential and wilting point values, as well as low rooting depth, soil pore size index, soil moisture holding capacity, canopy height and stomatal parameters also appear to be well-correlated with higher PC times. The compatibility of initialization did not always correlate well with spin-up time, as seen in the SE region which posted some of the lowest PC times yet featured initial root zone soil moisture values more than 40% different from equilibrated values.

[26] Spatial heterogeneities in soil, vegetation and climate have the potential to impact area-averaged PC times as illustrated by the correlations mentioned above. To explore this issue, a spatial analysis was performed in each of the six regions for the two climate, soil or vegetation factors (Table 4) which were found to correlate most strongly with 0.01% PC times. Most grid boxes within the SW region feature PC times close to that of the regional average. However, small areas of low spin-up values exist within the region, which act to lower the overall average. These areas, along the California coast and in northern Mexico, coincide with areas of higher annual precipitation. The NE and NW regions, by contrast, feature localized areas of very high PC times which act to raise the regional average above that of the majority of grid boxes. These large spin-up values are related to the temperatures and precipitation patterns which characterize each region. In the NW region, large coastal precipitation amounts lead to low PC times, while cold temperatures along the Canadian border lead to relatively high PC times. Similarly, the cold temperatures and low precipitation amounts of southern Canada lead to large PC times in the NE region. However, these relationships vary both between and within regions, and it is often not possible to determine a direct connection between any single climate, soil or vegetation characteristic and spin-up times. This is especially true in the SE, NC and CE regions

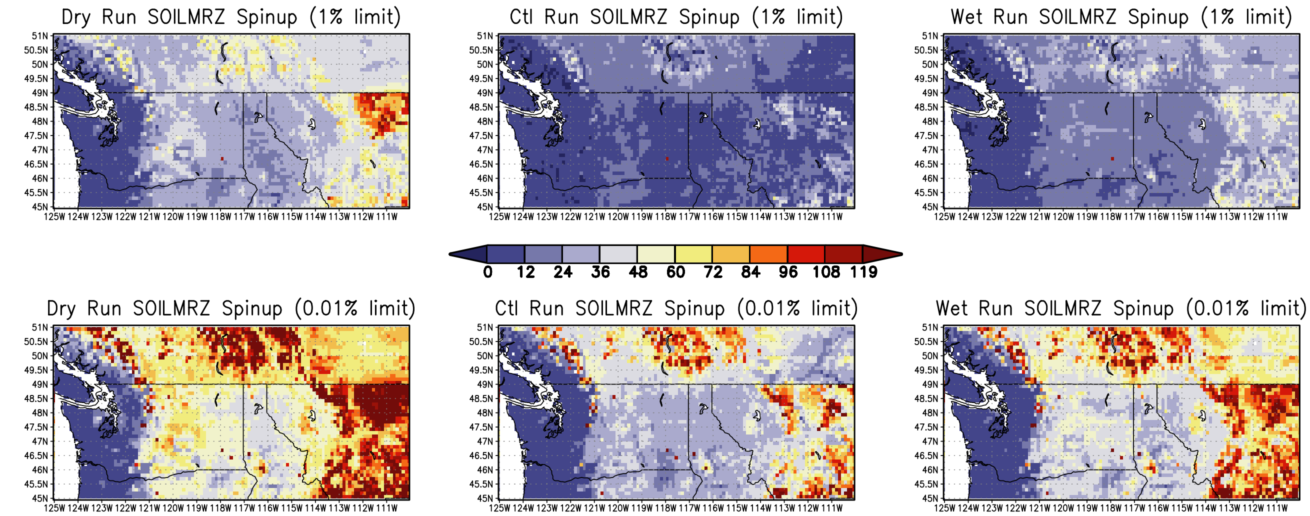


Figure 9. Spatially distributed PC times showing the number of months needed for NW root zone soil moisture to reach practical (1% PC time) and fine scale (0.01% PC time) equilibrium in the Dry, Wet and Control Simulations. Darkest blue shade indicates regions that reach PC threshold immediately at start of simulation, while darkest red shade indicates regions that do not reach PC thresholds throughout entire simulation.

where relatively weak correlations illuminate the fact that the spatial distribution of such parameters does not resemble the distribution of spin-up values. From these examples it can be concluded that although the spatial heterogeneity of single climate and land surface parameters can, at times, serve as the dominant influence on spin-up times, these times are most often affected by the complex interaction of the spatial distribution of the entire range of LSM parameters, making it extremely difficult to isolate a single dominant influence.

4.3. Deep Soil Temperature

[27] The NCEP/DOE R-2 soil temperature data used to initialize the Control, Wet and Dry runs produce a good Mosaic initialization, and from the start, all three runs exhibit less than 1% yearly drift (Table 2). While deep soil temperature spins up much more quickly in all three runs than does root zone or total column soil moisture, saturated and dry initializations still negatively impact 0.01% PC times. Deep soil temperatures in the Control run reach fine scale equilibrium within 1 year, but are delayed by 12 months in the Wet simulation and by 30 months in the Dry simulation. Control run anomalies were relatively small, with an initial maximum of 2.0 K in the SW region, and values in all regions below ±0.18 K by the end of the first year (Table 3). Initialization with saturated conditions led to increased negative anomalies, while dry initialization led to increased positive anomalies.

[28] Unfortunately, it proved to be impractical to compute e-folding times for this variable. Unlike soil moisture, deep soil temperature did not always constantly converge toward an equilibrium value. As seen in Figure 10, this variable would sometimes converge toward equilibrium at the start of the simulation, only to exhibit periods of divergence and convergence later in the run—a behavior ill-suited to e-folding analysis. This lack of constant convergence can be explained through the interplay between deep soil temperature and total column soil moisture. Figure 10 shows that over the NC region, the soil column was initialized with overly low soil moisture and temperature values. These dry conditions lead to a skewing of the partition of energy away from latent heat and toward sensible heat, which in turn leads to overly high surface soil temperatures. This effect is transmitted to the deeper soil layers and changes the initially cold deep soil temperature to excessively warm deep soil temperatures. As the total column soil moisture anomalies dissipate, the partitioning of energy between sensible and latent heat fluxes returns to normal and deep soil temperature anomaly values converge to 0. Similar relationships were observed in the other five regions of the experiment.

4.4. Evaporation

[29] Evaporation is influenced more by total column and root zone soil moisture than was deep soil temperature. As such, it displays a spin-up behavior which bears some similarity to that of soil moisture (Table 2). Although evaporation spin-up occurs more quickly than soil moisture

Table 4. Results of Correlation Analysis of 0.01% PC Control Run Data With Forcing Data and Model Parameters[a]

Region	Variable	Correlation
NW	Temperature	−0.60
	Precipitation	−0.38
NE	Temperature	−0.71
	Precipitation	−0.65
NC	Soil Moisture Potential	0.28
	Precipitation	0.25
SE	Precipitation	−0.44
	Moisture Holding Capacity	−0.33
CE	Precipitation	−0.30
	Stomatal Parameters	−0.27
SW	Precipitation	−0.59
	Wilting Point	0.37

[a]The two variables most highly correlated with PC times are listed.

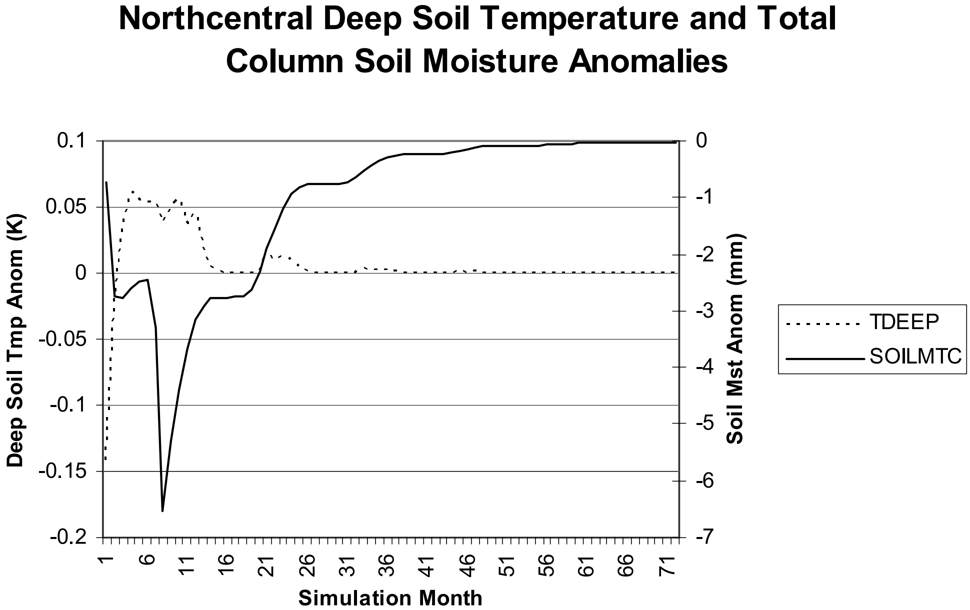


Figure 10. NC deep soil temperature anomalies (K) and total column soil moisture anomalies (mm) in the Control run. Deep soil temperature anomaly values converge toward 0 only to diverge and then converge again, showing the interplay between soil moisture and soil temperature.

spin-up in the NE, SE, and SW regions, the same is not always the case in the other three regions. Taking the study area as a whole, Control run evaporation takes 2 to 5 months longer than soil moisture to reach the 1% PC levels, but then overtakes soil moisture and reaches the 0.1% level in 9 month's less time. Results are mixed at the 0.01% level, with evaporation sometimes taking an additional 56 months, but sometimes reaching fine scale equilibrium in cases where soil moisture does not. Initialization with saturated conditions doubles the time needed for the study region as a whole to reach practical equilibrium, and adds 5 months to the time needed to reach fine scale equilibrium. Spin-up times are also increased in the Dry run, with practical and fine scale equilibrium taking 30 months longer to reach than in the Control run. Both suboptimal initializations affect the SE region the least, and both prevent the SW region from reaching fine scale equilibrium over the 11 year run. Table 3 shows that Control run anomalies decrease quickly over the course of the simulation, beginning with a maximum of 9.3 mm, and decreasing to under ±0.063 mm by the end of year 5. Anomalies in the Wet and Dry runs are much larger, and by year 5 the Wet run features positive values under 0.13 mm, and the Dry run features negative values under −0.87 mm. As was the case with deep soil temperature, the behavior of the evaporation variable precluded the calculation and analysis of e-folding times.

4.5. Summary

[30] Initialization of Mosaic with NCEP/DOE R-2 data was accomplished with varying degrees of success. While the deep soil temperature field was initialized very well and featured the lowest PC times, root zone and deep soil moisture fields were initialized with soil moisture values that were too high and featured large PC times. Evaporation took more time to spin up to practical levels of equilibrium than did root zone and total column soil moisture, but it required less time to reach more fine scale levels of equilibrium. Root zone soil moisture took about the same amount of time to spin up as did total column soil moisture in the Control and Wet runs, but reached equilibrium more quickly than total column soil moisture in the Dry run. On average, practical drift of soil moisture values stopped in the Control run within 1 year, and the study region as a whole took 5.5 years to reach fine scale equilibrium. Saturated initial conditions added 12 to 24 months to these numbers, while dry initial conditions incurred a spin-up penalty of 30 to 50 months. These penalties are tied to the basic nature of the spin-up process. This process proceeds until the LSM has recovered from the initial anomalies introduced by the soil moisture and soil temperature initialization and has reached the preferred model climatology. In the case of a wet initialization, this process progresses steadily as the soil column loses excess water through evaporation and baseflow runoff. In the case of a dry initialization, this spin-up process proceeds as the soil column moistens, and thus can only occur during rainfall, dewfall, and snowfall events. With this reliance on potentially scarce precipitation events, spin-up from a dry initialization can be expected to take longer than spin-up from a wet initialization—especially in geographic areas or over spans of time where precipitation amounts are small.

[31] Spatial analysis of this data shows that precipitation and temperature were closely associated with root zone soil moisture spin-up times, and that variation of PC times within regions was often greater than variation of PC times between simulations. In all simulations, the SE region was the quickest to spin-up, while the SW was the slowest and never reached the 0.01% level. Spin-up behavior of all variables was not always temporally uniform, and sometimes exhibited a strong seasonal component, especially in the NE region. Most total column and root zone e-folding times ranged between 3.5 to 8 months, agreeing with the

1 to 2 m observation-based e-folding times of *Entin et al.* [2000], but exceeding the 0 to 1 m e-folding times. This implies that anomalies may persist for an excessive length of time in the Mosaic LSM, and emphasizes the need for a compatible, accurate initialization of LSM soil moisture stores.

5. NLDAS Retrospective Simulations

[32] Information gleaned from the Wet, Dry and Control runs was used to understand the spin-up trends present in the NLDAS Retrospective simulations. These simulations, conducted with the Mosaic, Noah, VIC and Sacramento LSMs, are a central pillar of NLDAS research (Mitchell et al., submitted manuscript, 2003). The four NLDAS LSMs feature identical hourly forcing data, soil type data, vegetation class data, terrain height fields and the 1/8th degree central North American modeling grid seen in Figure 1. Each was initialized with the same NCEP/DOE R-2 plant available soil wetness and soil temperature data as were used to initialize the Control run described above, and feature the same first year of forcing as was used in the recursive simulations. These similarities facilitate comparisons between the two sets of experiments. The NLDAS Retrospective simulations cover the October 1st 1996 to September 30th 1999 time period, and feature hourly output of a common set of variables.

[33] Given the nonrecursive nature and relatively short 3-year length of the NLDAS Retrospective simulations, many of the statistical tools used to analyze the recursive 11 year simulation described in Section 4 cannot be used to analyze the spin-up behavior of the Mosaic, Noah, Sacramento and VIC models. Further complicating the analysis is the fact that LSMs are characterized by unique model parameterizations, model structures, soil parameters, and vegetation characteristics. In particular, soil layer structure, soil parameter values and soil moisture governing equations often differ between LSMs, leading to differing absolute quantities of soil moisture. In some models, these qualities give rise to simulations which can feature greatly differing energy and water balances [*Koster and Milly*, 1996]. However, many models, although featuring greatly differing absolute stores and dynamic ranges of land surface quantities, have similar normalized responses to forcing and feature similar patterns of land surface state anomalies [*Robock et al.*, 1998; *Entin et al.*, 1999]. Thus, much of the value of LSM output may lie not in direct use of raw output, but in the interpretation of changes in LSM land surface states such as soil moisture, soil temperature and snowpack. In fact, time series plots of LSM output anomalies offer valuable insight into spin-up behavior and can define the start and finish of a rough equilibration process. In particular, if models which had opposite anomalies early in the run converge to a common set of anomalies, it can be assumed that a degree of equilibrium has been reached. As a long term climatology was not available upon which to base the anomalies, the last two years of the three year simulations were used. The first year was not included, as it was assumed that any model spin-up that took place would be most severe in this first year and so would bias the anomaly results.

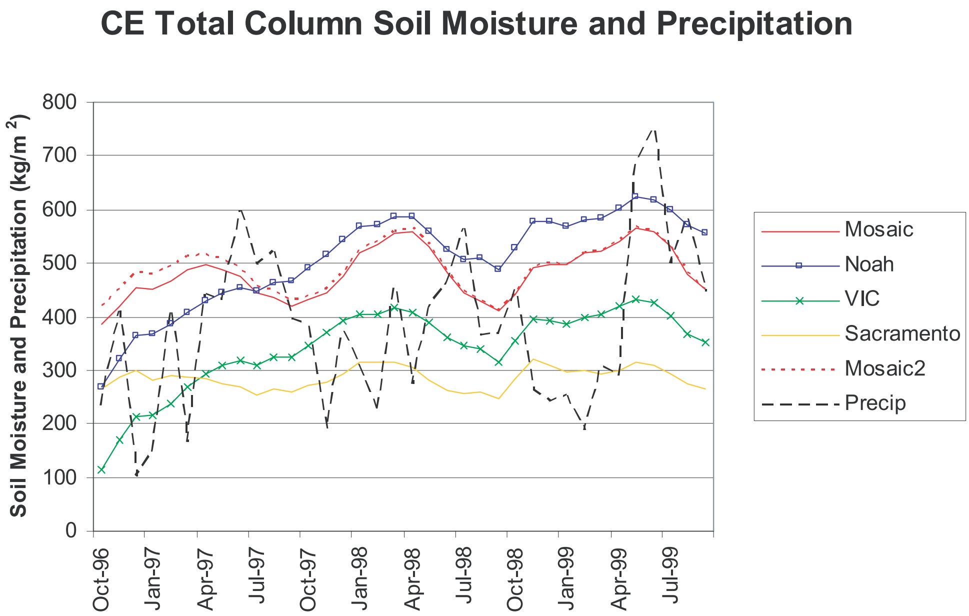
[34] In addition, Retrospective results were compared to an equilibrated Mosaic simulation (hereafter Mosaic2) over the same time period which started with year 11 of the recursive Control run and ran forward in time two more years to cover the full 1996 to 1999 Retrospective time period. This provided additional insights into the spin-up behavior and status of these simulations. In particular, any high degree of convergence between Mosaic and Mosaic2, or correlation between Mosaic2 and the Noah, Sacramento and VIC models would provide evidence that the LSMs had reached a measure of equilibrium.

5.1. Total Column Soil Moisture

[35] As seen in Table 5, the time required for LSMs to spin up can vary greatly, even when such LSMs are initialized with identical initial soil moisture data as occurred in the NLDAS project. Mosaic exhibits a small drying trend in all regions except CE as it converges with Mosaic2, and so NCEP/DOE R-2 initialization conditions appear to be too wet for this LSM. Mosaic converges to within 2% of Mosaic2 within 1 year in the CE, NC and NW regions and within 2 years in the SW, and NE regions. In the SE region, differences between Mosaic and Mosaic2 often exceed 2% throughout the 36 month simulation. By contrast, NCEP/DOE R-2 conditions prove to be too dry for the Noah and VIC models. This leads to moistening spin-up trends in Noah in the CE and NW regions that persist into the third year. Lesser trends are present in the SW, NC, SE and NE areas where rough spin-up appears to last 1 to 2 years. The moistening trends seen in VIC are generally smaller than those seen in Noah. These trends tend to dissipate in less than 1 year except in the SW and CE regions where spin-up trends are detected in years 1 and 2 (Figure 11, CE region). None of these long-lived trends occur in the Sacramento model, which features the least total column soil moisture spin-up of the four NLDAS models. Spin-up times for this LSM over the six regions are all less than 1 year. It can be seen that the initial ranking of NLDAS LSMs from driest to wettest was not a good predictor of the final ranking of these same models. While initially Mosaic was wettest, followed by the Sacramento, Noah and VIC LSMs, spin-up processes lead to a final ranking from driest to wettest of Noah, Mosaic, VIC and Sacramento. In addition, it should be noted that soil moisture levels varied greatly between NLDAS LSMs, emphasizing the fact that care must be taken when initializing one LSM with soil moisture values from a second LSM.

5.2. Root Zone Soil Moisture

[36] Over the NE, SE, NW and NC regions, root zone soil moisture appears to spin up 1 to 12 months more quickly than does total column soil moisture, a characteristic particularly evident in the Noah model. However, over the CE and SW regions, no spin-up time advantage was observed. Results indicate that the initial NCEP/DOE R-2 conditions were too dry for the VIC and Noah models. Noah displays moistening trends over all regions, while VIC is characterized by significant moistening tends in all but the SE region (Figure 12). These spin-up trends are generally more serious in the Noah model than in the VIC model, but in all regions except for SW become undetectable in both models after 1 year. As Mosaic2 results were available for comparison with the Mosaic run, it proved easier to detect trends in Mosaic data than in the three other LSMs. Trends were generally negative in nature, and Mosaic root zone soil moisture



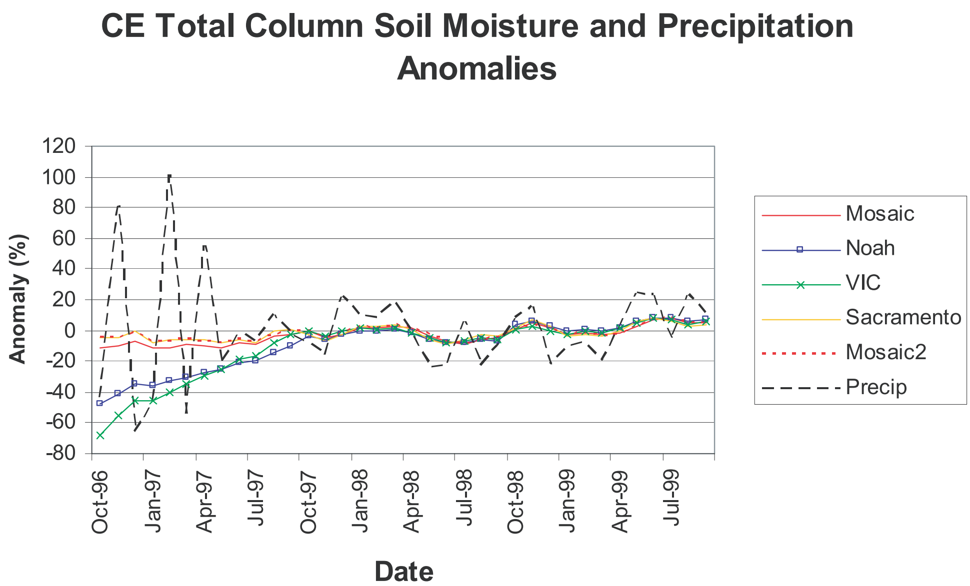


Figure 11. (top) Time series plot of NLDAS Retrospective total column soil moisture (kg/m^2) and precipitation (kg/m^2) over the CE region. Although models were initialized with identical plant available soil wetness (%) data, initial values on plot differ due to conversion from % to kg/m^2 units involving model-specific parameters. (bottom) Time series plot of anomalies (%) for the same region and time period based on the last two years of the Retrospective run.

converged within 2% of Mosaic2 after approximately 1 year. Exceptions to this include the CE region, where Mosaic experiences moistening, and the SE region where differences between the runs continue to be 1–2% over the course of the simulation. The Sacramento LSM does not have vegetation or a root zone per se, and so was not included in this comparison.

5.3. Deep Soil Temperature

[37] The Mosaic, Noah and VIC LSMs did not show a significant deep soil temperature spin-up trend over the six regions of study. Mosaic results agree with Mosaic2 results within 0.7% from the start of each simulation, showing a slight initial cooling trend in the NE and CE regions, and a slight initial warming trend in the SE, NW, NC and SW regions as results converge toward the Mosaic2 simulation.

5.4. Evaporation

[38] Some spin-up trends were detected in the evaporation variable over the three year Retrospective period, but they were minor compared to those seen in the soil moisture stores discussed above. The trend of evaporation anomalies

Table 5. Number of Months Required for NLDAS LSMs to Lose Detectable Rough Spin-Up Trends in Total Column Soil Moisture, Root Zone Soil Moisture, Evaporation and Deep Soil Temperature[a]

		NE	SE	CE	SW	NW	NC
Total Column	Mosaic	12 (14)	6 (16–36)	12 (11)	* (15)	12 (11)	* (0)
Soil Moisture	Noah	14–30	9	12–24	12–18	24–36	24
	VIC	9	6	12–24	12–18	12	12
	Sac.	9	6	*	3	12	*
Root Zone	Mosaic	12 (13)	6 (22–36)	6 (12)	9 (3)	11 (11)	6 (7)
Soil Moisture	Noah	12	6	12	12–18	12	12
	VIC	9	6	12	12–18	12	12
Evaporation	Noah, VIC, Sac.	4–6	*	*	4–6	4–6	4–6
	Mosaic	4–6 (1–11)	* (0–31)	* (0–12)	4–6 (2–35)	4–6 (1–23)	4–6 (7–31)
Deep Soil	Noah, VIC	*	*	*	*	*	*
Temperature	Mosaic	* (0)	* (0)	* (0)	* (0)	* (0)	* (0)

[a]Asterisks indicate that no trend could be detected. Number of months required for Mosaic to converge within 2% of Mosaic2 is given in parenthesis (Mosaic and Mosaic2 often experienced multiple periods of convergence and divergence, leading to the range of times given in this table).

significantly differed in the first four to six months of simulation in the SW, NW, NC and NE regions (Figure 13, SW region), potentially as a result of spin-up processes, but agreed in the SE and CE regions (Figure 14, CE region). In general, Mosaic took approximately 1 year to converge with the Mosaic2 simulation. In the months following convergence, periods of divergence often occurred, showing that evaporation can be significantly impacted by 1) how soil moisture responds differently among the four models to the surface forcing (especially precipitation), and 2) the different treatment among the models of the seasonal cycle of vegetation phenology. In addition, it is important to note that the models which exhibit the largest evaporation values are not those which exhibit the wettest soil moisture states. A comparison of Figures 11 and 14 shows that, in the CE region, the Noah model displays the largest values of total column soil moisture, while the Mosaic and Sacramento LSMs display the largest evaporation values.

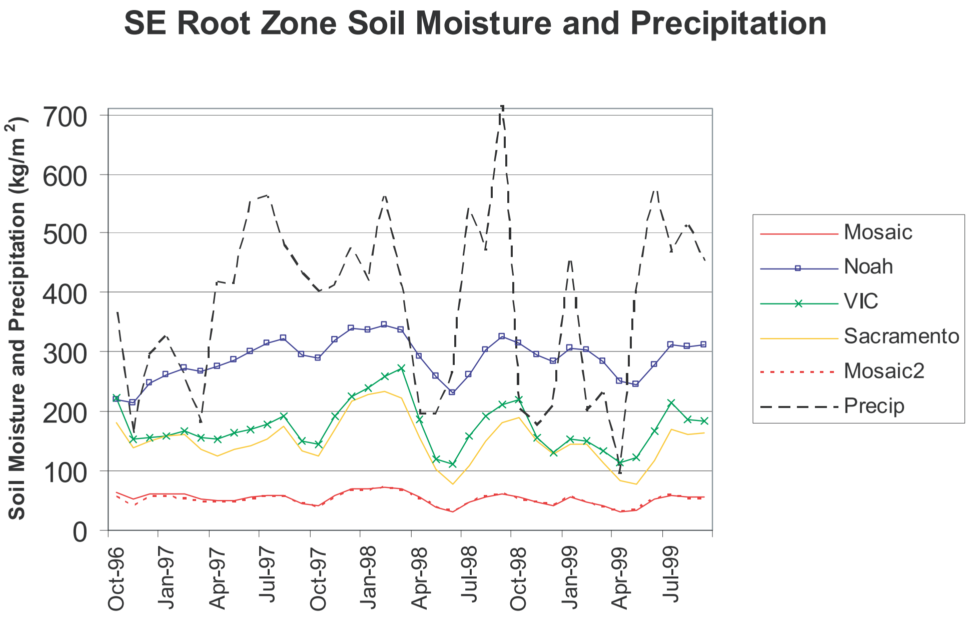
5.5. Summary

[39] Because of the limited length and nonrecursive nature of the Retrospective simulations, it was impossible to make use of many of the rigorous statistical measures used in the Wet, Dry and Control runs. However, magnitude and anomaly time series plots were used to identify any large scale spin-up trends which were present. Additional smaller scale trends were identified through comparison of Mosaic results with the Mosaic2 simulation described above. Although an attempt was made to reduce spin-up by initializing NLDAS LSMs with NCEP/DOE R-2 plant-available soil wetness data instead of absolute values of soil moisture, significant spin-up trends were still present. In general, the total column soil moisture field appears to be the most affected by model spin-up, with trends often persisting through the first 1 to 1.5 years, and in some VIC and Noah model cases through, respectively, years 2 and 3. Root zone soil moisture, especially in the Noah model, spins up slightly more quickly and reaches equilibrium in almost all regions within the first year. Spin-up trends were much smaller in the evaporation and deep soil temperature variables than in the soil moisture variables, and any trends that were identifiable almost always disappeared within the first 6 months. Overall, the Sacramento model appeared to reach rough equilibrium most quickly, followed by the Mosaic, VIC and Noah models. In the case of the Mosaic model, where comparison with Mosaic2 results made it possible to more clearly diagnose attainment of equilibrium, Mosaic output converged to within 2% of Mosaic2 generally within the first 1 to 2 years. Of note, the initial ordering of LSMs from driest to wettest was a poor indicator of the postspin-up ranking, as Noah and VIC often started out the Retrospective simulation the driest, but finished the wettest.

[40] Assuming similar behavior between the four LSMs, results from the 11 year recursive simulation imply that soil moisture and flux values in all four models do not reach fine scale equilibrium within the three year Retrospective simulation. However, results from the 11 year Control Mosaic simulation do support the general conclusions drawn from time series analysis of the Retrospective simulation—that in most cases, all four models reach rough equilibrium within 1 to 2 years. This information also validates the decision of NLDAS participants to set aside the first year of NLDAS output as spin-up, and implies that in a few cases, additional years should be set aside as well. As 6 years of NLDAS forcing are now available (1996–2002), the NLDAS Retrospective simulation will be expanded to cover the 1996–2002 time period in the near future, which will provide several more years of data free from rough spin-up effects.

6. Concluding Remarks

[41] The land surface is an active part of the Earth system, influencing the weather through fluxes of moisture and energy, and affecting society through changes in vegetation, soil moisture and water resources. Land surface models like those in the NLDAS project are important tools in the effort to understand such interactions, and to predict how this system may change in the future. Unfortunately, results from LSMs can be easily tainted by spin-up-induced biases, and until the model states come into equilibrium with the supplied meteorological forcing, model output will not be realistic. In order to gain further insight into the spin-up characteristics of land surface models, and to determine how model spin-up processes might impact the three year NLDAS Retrospective simulation, two separate analyses were conducted. Serving as a broadening of previous, single-vegetation, single-soil type experiments, the first analysis concentrated on a series of three LSM experiments conducted with the Mosaic model. These experiments were conducted over six large spatial windows encompassing a



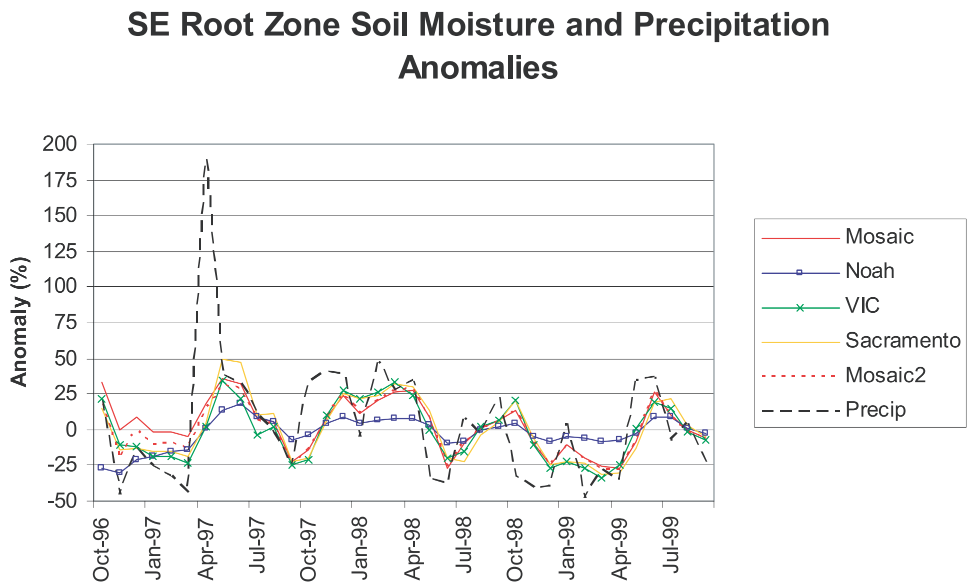
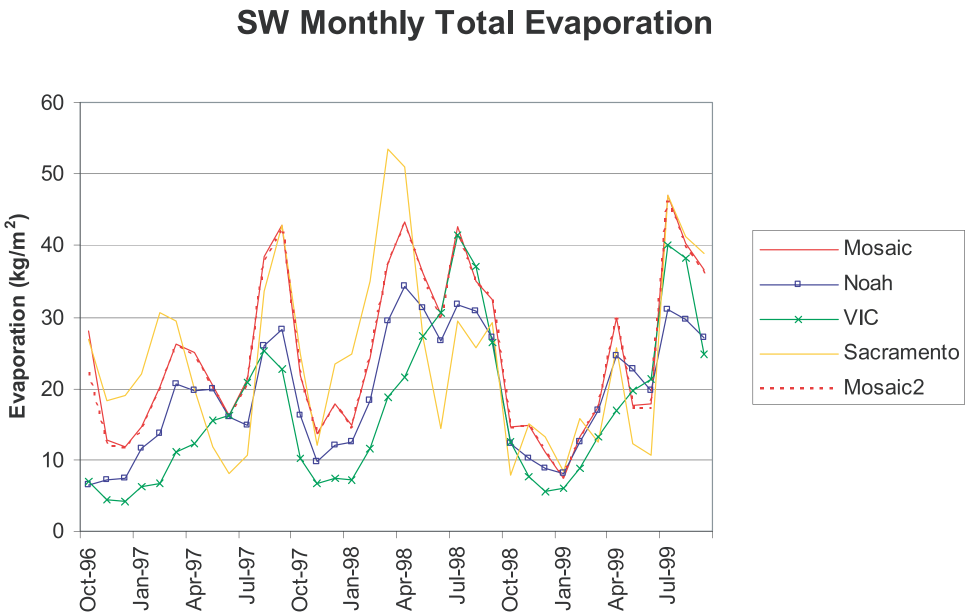


Figure 12. (top) Time series plot of NLDAS Retrospective root zone soil moisture (kg/m^2) and precipitation (kg/m^2) over the SE region. Although models were initialized with identical plant available soil wetness (%) data, initial values on plot differ due to conversion from % to kg/m^2 units involving model-specific parameters. (bottom) Time series plot of anomalies (%) for the same region and time period based on the last two years of the Retrospective run.

variety of soil, vegetation and climate types. In order to establish typical spin-up times as well as maximum spin-up values, these runs were initialized with a) Zero soil moisture (Dry run), b) Saturated soil moisture (Wet run), and c) NCEP/DOE R-2 soil moisture conditions (Control run) which were also used to initialize the NLDAS Retrospective simulations. The second analyses focused on the NLDAS Retrospective simulation, drawing on information gleaned from time series and anomaly plots as well as data from the 11 year runs to explore the spin-up behavior of the Noah, VIC, Sacramento and Mosaic models over the Retrospective time period.

[42] Results from the two analyses described above indicate that initialization of Mosaic with NCEP/DOE R-2 soil moisture is far more desirable than either a saturated or dry initialization. Overly moist though it was, the Control run reached practical equilibrium 1 to 2 years more quickly than the Wet run, and 3 to 4 years more quickly than the Dry run in which spin-up was slowed by the dependence on precipitation events. Over the region of study as a whole, practical drift generally ended within 1 year, and fine scale equilibrium was achieved after 5.5 years. E-folding times generally ranged from 0.25 years to 0.75 years, often



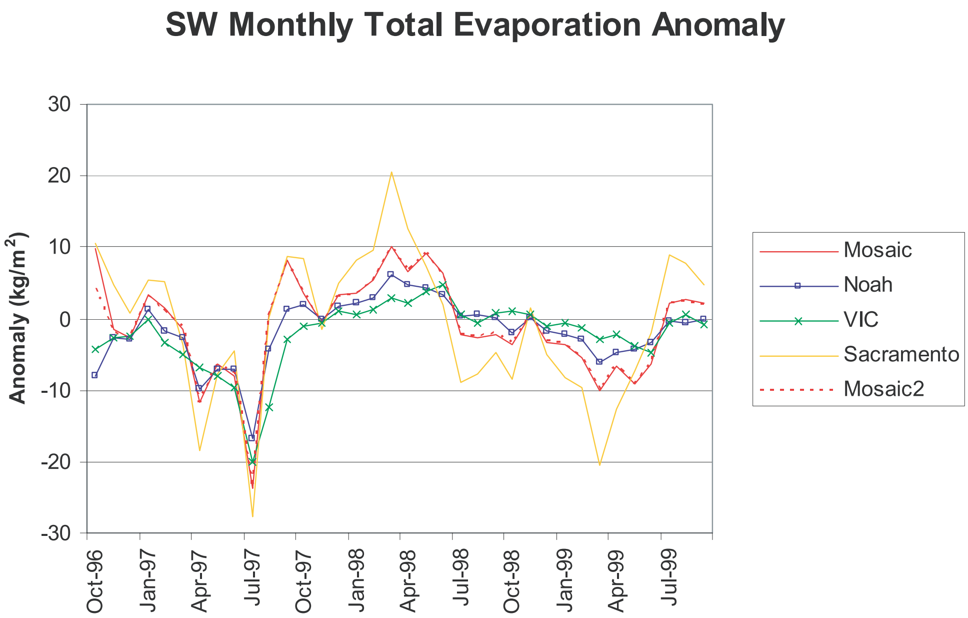


Figure 13. (top) Time series plot of NLDAS Retrospective evaporation (kg/m^2) over the SW region. (bottom) Time series plot of anomalies (kg/m^2) for the same region and time period based on the last two years of the Retrospective run. This is an example of initial disagreement between evaporation anomalies of NLDAS LSMs.

exceeding the observation-based values of *Entin et al.* [2000], and were longest in arid regions and regions in which negative soil moisture anomalies were present. Spin-up was not temporally or spatially uniform, varying greatly by region and often clustered by season. In fact, differences within regions were often higher than those seen between simulations. PC times were generally lowest for deep soil temperature and for the SE region. They were generally highest for total column soil moisture and for the SW region which often did not reach fine scale equilibrium in the 11 year simulation. Significantly, evaporation often reached practical equilibrium more slowly than root zone and total soil moisture, but reached fine scale equilibrium more quickly.

[43] PC equilibrium times are well-correlated most commonly with precipitation and temperature values, but soil and vegetation parameters also appear to impact the spin-up process. In general, correlation values associated with 0.01% PC times are larger those associated with 1% PC times. However, even when examining these stronger correlations, it was found that the spatial heterogeneity of single climate and land surface parameters does not often

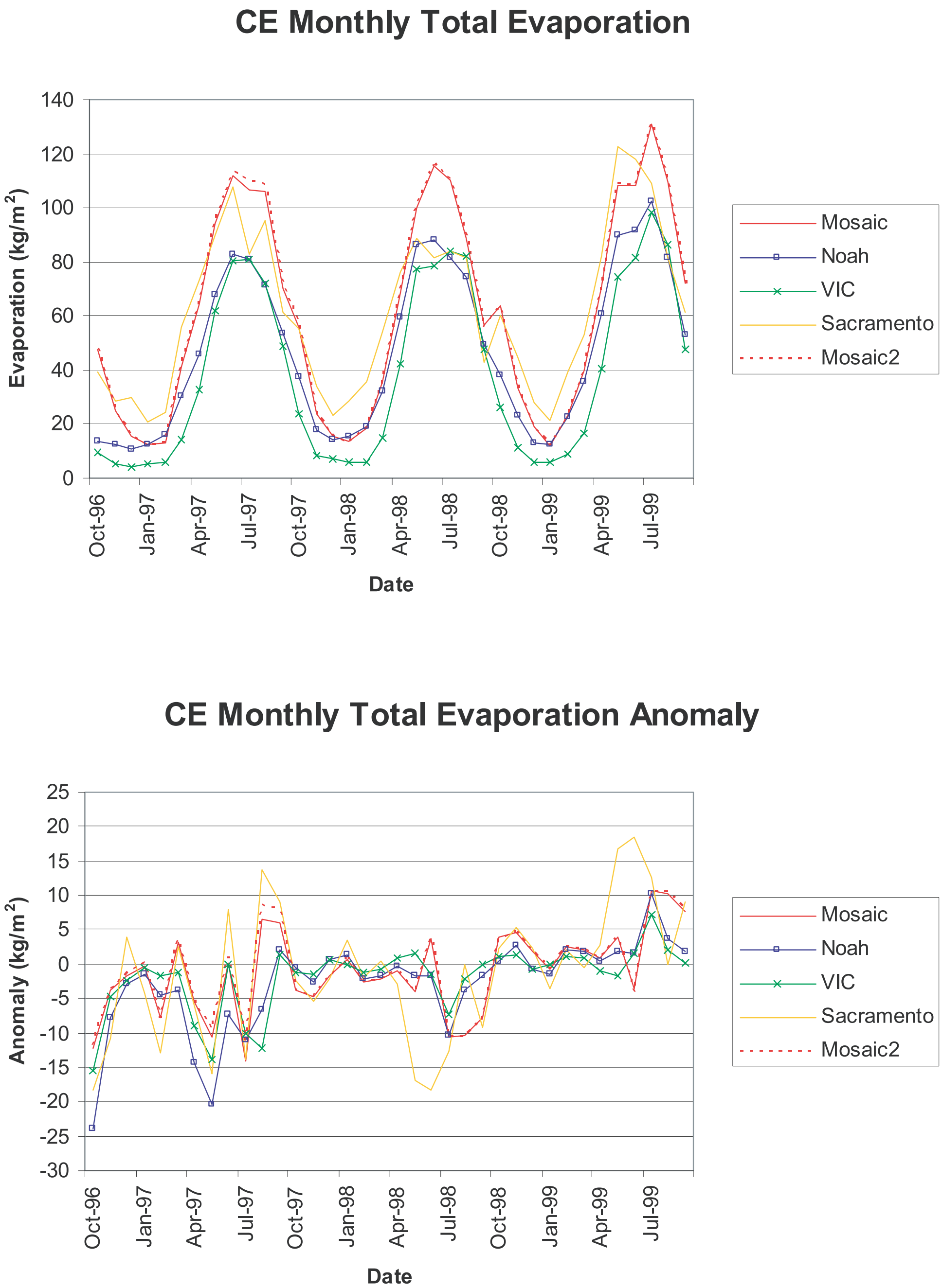


Figure 14. (top) Time series plot of NLDAS Retrospective evaporation (kg/m^2) over the CE region. (bottom) Time series plot of anomalies (kg/m^2) for the same region and time period based on the last two years of the Retrospective run. This is an example of initial agreement between evaporation anomalies of NLDAS LSMs.

serve as the dominant influence on spin-up times, and that these times are most often affected by the complex interaction of the spatial distribution of the entire range of LSM parameters, making it extremely difficult to isolate a single dominant influence.

[44] Building on this information, analysis of the NLDAS Retrospective simulation provided insight into the spin-up behavior of the four participating models. Assuming a level of similarity with the Mosaic model, none of the LSMs in the Retrospective run reach an overall state of fine scale equilibrium within the 1996–1999 time period. However, inspection of Retrospective time series and anomaly plots, along with information from the Control run described above point toward the following result—that with a few notable exceptions, the Sacramento, VIC, Noah and Mosaic models each reach rough equilibrium within 1 to 2 years. Given NCEP/DOE R-2 conditions as a starting point, Sacramento appears to spin up most quickly, and is followed by the Mosaic, VIC and Noah LSMs. In general, root zone soil moisture spins up more quickly than does total column soil moisture, an occurrence especially apparent in the Noah model. Trends in deep soil temperature and

evaporation were smaller and any spin-up behavior that was identified disappeared within the first 6 months. With this in mind, it appears that the NLDAS project's decision to set aside the first year as a spin-up year was a valid one, and that in a few cases, additional years may need to be considered spin-up as well.

[45] Overall, the results described above underline the fact that LSM spin-up can take a significant amount of time, and can vary greatly between models even when such models use identical soil moisture initialization data. This spin-up time varies for each land surface state, and is affected differently by soil, vegetation, and climate variables depending on the geographic region of study. Using some measures of spin-up, it may take greater than 10 years for a model to reach fine scale equilibrium. However, many experiments have been conducted utilizing results from LSMs which were allowed to spin-up for 1 month or less. This study has shown that this is generally not an adequate amount of time, and care must be taken to allow sufficient spin-up time so that model output is not severely biased or unrealistic.

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