An intercomparison of soil moisture fields in the North American Land Data Assimilation System (NLDAS)

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Received 12 December 2002; revised 1 October 2003; accepted 17 November 2003; published 15 January 2004.

[1] The multiple-agency/university North American Land Data Assimilation System (NLDAS) project is designed to provide enhanced soil and temperature initial conditions for numerical weather/climate prediction models. Currently, four land surface models (LSMs) are running in NLDAS both in retrospective mode and in real-time mode. All LSMs are driven by the same meteorologic forcing data and are initiated at the same time with the same relative soil wetness. This study intercompares these NLDAS soil moisture fields with each other and with available observations. The total water storage and the storage variability range are the foci of the study. The mean statistical properties and the spatial variation of these soil moisture fields along with their temporal change are investigated. Model soil moisture fields are compared to soil moisture observations in Illinois. The storage variability range in Arkansas-Red River basin is validated against a water balance diagnostic analysis using historical precipitation and streamflow data. There is better agreement between observed and simulated ranges of water storage variability than between observed and simulated amounts of total water storage. Significant differences are found between NLDAS-simulated soil moisture fields from the different models. Total water storage is found to be highly model dependent. There is better agreement between models in the water total water storage range than in the model values of total water storage. Total water storage ranges agree best in humid areas where variation in water storage is strongly driven by variation in precipitation. In very dry areas, agreement between simulated water storage ranges is weak because model differences have as much influence on water storage range as climate variability in these areas. Finally, the spin-up properties of the models and relationships between water storage properties and climate are investigated. The results of this study should provide important insights into the similarities and differences of the four LSMs in NLDAS. Differences in NLDAS soil moisture fields pose challenges to land surface modelers who intend to use soil moisture field from one model to initialize another model. *INDEX TERMS:* 1836 Hydrology: Hydrologic budget (1655); 1866 Hydrology: Soil moisture; 1878 Hydrology: Water/energy interactions; 1655 Global Change: Water cycles (1836); *KEYWORDS:* soil moisture, total water storage, land surface models

Citation: Schaake, J. C., et al. (2004), An intercomparison of soil moisture fields in the North American Land Data Assimilation System (NLDAS), *J. Geophys. Res.*, *109*, D01S90, doi:10.1029/2002JD003309.

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0148-0227/04/2002JD003309$09.00

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1. Introduction

[2] This study examines the water storage simulations produced by four different models participating in the North American Land Data Assimilation System (NLDAS) project. Currently, there are four land surface models (LSMs) running in NLDAS: Noah model from National Center for Environmental Predictions (NCEP) [*Chen et al.*, 1996], Mosaic model from Goddard Space Flight Center (GSFC) of the National Aeronautics and Space Administration (NASA) [*Koster and Suarez*, 1996], VIC model from Princeton University [*Liang et al.*, 1994] and the Sacramento model (SAC) from the National Weather Service (NWS) River Forecast System (NWSRFS) [*Burnash et al.*, 1973]. These models are operated both in retrospective mode as well as in real time. Common soils and vegetation databases were used to estimate model parameters for all of the models [*Mitchell et al.*, 2004]. However, the procedures used to estimate model parameters from these data are model dependent. All LSMs were initiated at the same time with the same relative soil wetness and were driven by the same water and energy forcing [*Cosgrove et al.*, 2003a].

[3] The primary goal of this study is to intercompare the water storage simulations of the four LSMs and to compare model results with the few available observations. An objective is to see if water storage state variables from one model can be used to estimate water storage state variables from the other models. If water storage state variables are strongly model dependent, then the models cannot all be correct and estimates of water storage from reanalysis results [*Kistler et al.*, 2001] are also model dependent and should be used with caution to initialize other models with different land surface representations than were used in the reanalysis.

[4] This study focuses on water storage as opposed to soil moisture. Water storage refers to water content of a storage component (e.g., a layer of a soil column or a storage component of a conceptual hydrologic model), expressed as an average depth of water over a given area. Soil moisture refers to the water content of a volume of soil, expressed as a fraction of the total volume. For a given volume of soil the two variables are related. Given soil moisture, water storage is

$$s = w \cdot d \tag{1}$$

where s is the water storage (cm), w is the average soil moisture (dimensionless) in a soil column and d is the thickness (cm) of the soil column over a given area. Given water storage in a soil column, soil moisture is given by

$$w = s/d \tag{2}$$

[5] If all of the models represented the water content for the same soil layers, the relationship between water storage and soil moisture in different models would be simple and that would simplify model intercomparison. However, important differences between model representations of water content exist because the models do not use the same soil layers. Conceptual storage components included in some models (e.g., SAC and VIC) are not explicitly related to soil layers. Some of the storage components in conceptual models may represent water stored in aquifers rather than water stored in soil columns.

[6] The water content of storage components of the SAC model represents only the active water storage. Accordingly, the total water storage, s_T, is

$$s_T = s_A + s_R \tag{3}$$

where s_A is the active storage and s_R is the inactive part (e.g., water content in the root zone below the wilting point). Note that the inactive part of water storage does not affect the change in total water storage with time since the inactive part does not change with time. Therefore it might be expected that different model estimates of total water storage changes would be more comparable than estimates of total water storage. Also, changes in water storage associated with soil moisture measurements might be more comparable to model estimates of changes than to model estimates of water storage.

[7] A brief description of each model is presented in the next section. The data sets used in the study are explained in section 3. Values of both maximum and active total water storage capacity of the four models are presented in section 4. Time series of total water storage produced by each model are analyzed in section 5. Simulated ranges of total water storage are considered in section 6. Intercomparison of total water storage simulations of the different models is evaluated in terms of a statistical analysis in section 7.

[8] It is extremely difficult to compare model estimates of water content with observations because there are no direct observations of the area average model state variables. Nevertheless, an attempt has been made to compare model results with observations of water storage in Illinois in section 8 and with analyses of water storage in the Arkansas-Red River basins in section 9. A further attempt has been made to intercompare how the models represent the vertical distribution of water storage in section 10. This is difficult because each model represents water storage differently so there is no direct relationship between the individual water storage state variables of the different models.

[9] Finally, the results of the study are summarized and presented together with conclusions in section 11.

2. Model Representations of Water Storage and Soil Moisture

[10] The actual total water storage over an area can be represented in three parts: the root zone, the vertical profile below the root zone, and the groundwater aquifers. Each of the four NLDAS models account for water in these components differently. A comprehensive summary of each model including details about how each is implemented over the NLDAS domain is presented by *Mitchell et al.* [2004]. Below is a brief description of how water storage and soil moisture are represented in each of the four LSMs in NLDAS.

[11] The Noah model represents water storage in a vertical profile that extends two meters below the surface. The profile is partitioned into four layers of increasing thickness from 10 cm at the surface to one meter for the lowest layer. The rooting depth of the Noah model is fixed

at 100 cm. The physics of water movement between the layers is governed by a discrete representation of the Richard's equation, except that infiltration is governed by a conceptual parameterization that considers the heterogeneity over the area of precipitation and the local potential for infiltration. The total water storage from Noah model is calculated by aggregating soil water from all four soil layers.

[12] The Mosaic model also has a multilayer soil column structure, but each column is further divided into several tiles representing different vegetative surfaces. Up to 10 tiles can be used in current Mosaic configuration. The soil layer thicknesses from top to bottom are fixed at 10, 30, and 160 cm, respectively, with a uniform rooting depth of 40 cm. The Mosaic model was derived from the Simple Biosphere (SiB) model developed by *Sellers et al.* [1986]. The soil water and energy balances in each tile are simulated independently. The water balance uses the one dimensional Richard's equation. The water storage in each layer a soil column is calculated as a weighted average of the water storage from all tiles.

[13] The VIC model implemented in NLDAS has a three soil-layer structure. Each layer is operated as a conceptual water storage. A 10 cm topsoil layer (layer 0) is intended to capture the fast dynamics of water flux near the land surface. Water can only be extracted from this layer through evapotranspiration. The upper zone soil water storage (layer 1) determines the partition of rainfall into surface runoff and infiltration. The lower zone water storage determines the amount of base flow. The hallmark of VIC model is the consideration of spatial heterogeneity in soil moisture distribution over the model grid in determining surface runoff, infiltration and base flow. Because the lower two VIC water storages are conceptual and do not correspond explicitly to soil layers, their storage capacities must be estimated through model calibration. The VIC storage capacities and other parameters for some parts of the NLDAS domain were calibrated using retrospective monthly historical hydrometeorological data [*Nijssen et al.*, 1997], while default values were used for other places. Later sections will show that this difference in parameter values affects simulated water storage values.

[14] The SAC model represents water storage using five conceptual water storage components together with a sixth variable water storage component that accounts for effects of varying areas of saturation near streams. The five storage components are partitioned into upper and lower zones. These are further partitioned into tension and free water storage. The model implicitly recognizes that the equations that describe the variability of bulk storage over a large area are different from the equations that describe the variability of water storage at a point. One manifestation of this is in the separation of water storage into tension and free water components controlled by capillary and gravitational forces, respectively. Water storage in the SAC model represents only the active part of the total water storage in an area. Also, the storage components of the SAC model are conceptual and do not explicitly consider where they are located. *Koren et al.* [2003; see also *Duan et al.*, 2001] developed an approach to relate the SAC water storage capacities and other SAC parameters to soil properties as defined in the State Soil Geographic (STATSGO) Data Base [*Miller and White*, 1998]. The SAC water storages are related to different soil layers in a representative column over an area. Therefore the sum of water from all SAC storages represents the total water storage from the soil column.

3. Development of the Data Sets

[15] The NLDAS project is designed to provide enhanced initial land surface states such as soil moisture and soil temperature for coupled land/atmosphere forecast models operating at continental scale. This is done by running the LSM offline from the coupled model with forcing data comprised of observed precipitation and solar insolation, together with analyzed fields of air temperature, surface pressure, humidity and wind speed [*Mitchell et al.*, 2004].

[16] Because NLDAS uses observed values of precipitation and solar insolation, systematic biases inherent in estimates of these variables from coupled models are avoided. Another benefit of NLDAS is that the outputs from NLDAS can be analyzed to gain valuable insights into climate variability at continental scale and into strengths and limitations of LSM model physics.

[17] NLDAS operates in two modes: real time and retrospective. In the real-time mode, forcing data for the current day are used to drive the LSMs. Real-time runs were initiated on 11 April 1999. However, there are some data quality control issues associated with the real-time forcing data, so the results presented here are based on retrospective runs.

[18] Retrospective runs focus on a three-year time period from 1 October 1996 to 30 September 1999. Retrospective data sets are more reliable than the real-time data because more data quality control measures were exercised [*Cosgrove et al.*, 2003b]. The analysis presented in this paper uses retrospective forcing data. All LSMs were assigned the same relative soil wetness values at the end of 30 September 1996. Snapshots of the water storage fields from all four LSMs were obtained at the end of the first and fifteenth days. A total of 72 water storage snapshots were collected from each of the LSMs for the entire NLDAS domain.

[19] This paper presents preliminary analyses of these 72 water storage snapshots. Ideally, we would like to compare water state variables for each storage component across the different models. This is difficult to do because there are important differences in how the water storage components are defined in each model. However, there is enough similarity in definition of the total water storage in all components of a given model to permit a straightforward comparison of total storage across models. Also, water storage components for each model can be grouped into upper and lower zone components and comparisons are made for these as well.

4. Model Water Storage Capacity

[20] Each storage component of each LSM has a maximum total capacity to store water. This essentially is equivalent to the product of soil porosity and layer thickness. Not all of the water that can be stored in this total water capacity can be removed by natural hydrologic processes such as evapotranspiration. In the root zone water

Table 1. Maximum Total Water Storage Capacity Statistics for Each of the Four LSMs

Model	Average, mm	Standard Deviation, mm	Minimum, mm	Maximum, mm
Sacramento	435	99	74	645
Noah	917	31	808	936
Mosaic	879	51	678	952
VIC	618	207	321	1427

that remains in the soil beyond what can be removed by evapotranspiration is below the wilting point of the soil. Below the root zone water that does not drain and does not evaporate is held inactive by capillary forces. Accordingly, the maximum active total capacity is less than the total capacity.

[21] Summary statistics, spatially averaged over the NLDAS domain, of the values of maximum total water storage capacity for each of the models are presented in Table 1. This includes values of the average, standard deviation, minimum and maximum total water storage capacity. Values for Noah and Mosaic are nearly constant (lowest standard deviation) over the NLDAS domain because porosity is almost the same for all soil types and both models have constant depth of soil profile over the NLDAS domain. Both Noah and Mosaic soil depths are 2.0 meters everywhere. The total water storage capacity for SAC takes into account variations in thickness of the soil as given by the STATSGO database [*Miller and White*, 1998]. Total water storage capacity for the SAC model is less than the capacities for the other models (see Table 1) because water storage capacity in the SAC applies to space in the soil profile above the wilting point.

[22] Values of maximum active capacity to store water for each of the models are presented in Figure 1. Summary statistics, spatially averaged over the NLDAS domain, of the values of active total water storage capacity for each of the models are presented in Table 2. Active capacity is less than the maximum capacity because water cannot be removed from soil below the wilting point in the root zone nor below field capacity below the root zone. It should be noted that the Mosaic model does not limit extraction of water from below the wilting point in its lowest, 1.6 m, storage component, but such extraction is not likely to occur. Therefore, in order that the effective difference between total and maximum active storage capacity can be illustrated more clearly, the maximum active storage capacity for the Mosaic model shown in Figure 1 excludes storage below the wilting point for all layers, including the lowest layer. Maximum active water storage capacity for the SAC model in Figure 1 is the same as total water storage capacity because SAC considers only active water storage. Note in Table 2 that the average values of active water storage capacity for SAC and VIC are about the same and much less than the average active capacity of Noah and Mosaic. The large spatial standard deviation of

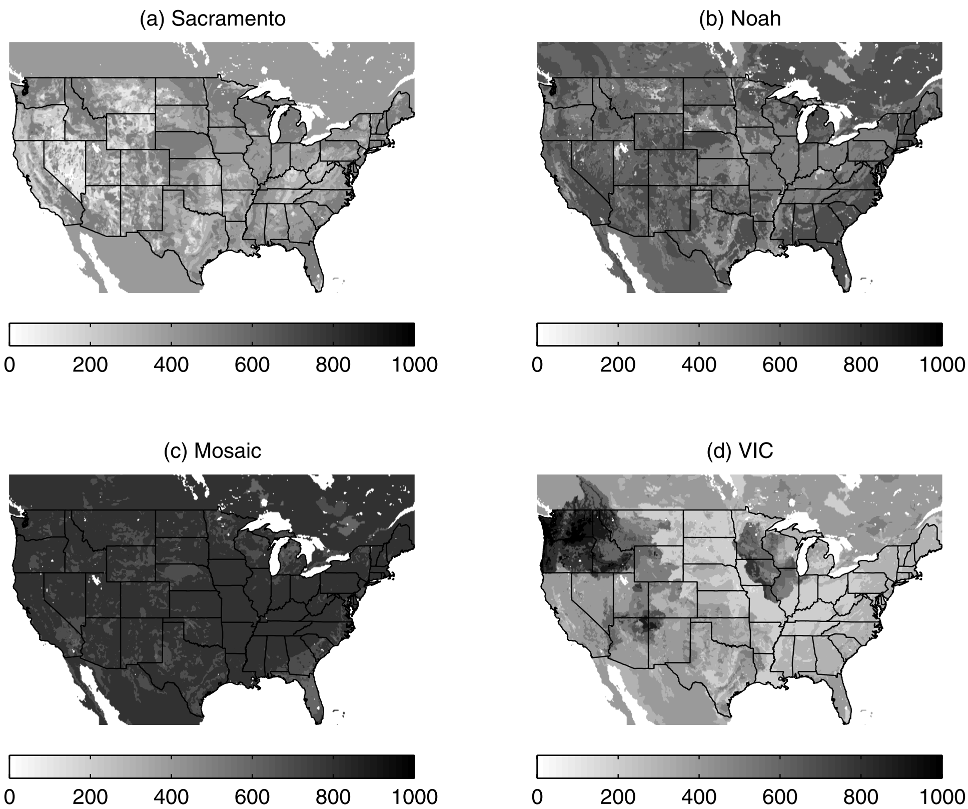

Figure 1. Maximum active storage capacity of each of the four LSMs over the NLDAS domain: (a) SAC, (b) Noah, (c) Mosaic, and (d) VIC. See color version of this figure in the HTML.

Table 2. Maximum Active Water Storage Capacity Statistics for Each of the Four LSMs

Model	Average, mm	Standard Deviation, mm	Minimum, mm	Maximum, mm
Sacramento	435	99	74	645
Noah	643	95	292	798
Mosaic	826	40	624	907
VIC	436	163	167	1188

active storage capacity of VIC is a result of having different parameter estimation procedures in different parts of the NLDAS domain.

5. Time Series of Basin Average Total Water Storage

[23] Time series of areal average total water storage were computed for the forecast area of each of the 12 NWS River Forecast Centers (RFCs) within the NLDAS domain for each of the four LSMs for water years 1997–1999. The locations of the RFC forecast areas are shown in Figure 2.

[24] These RFC areas were chosen for this analysis because each RFC has a different average climate regime. *Duan and Schaake* [2003] found that the range of total water storage in the Arkansas-Red River basin is closely related to the local climate. The RFC names corresponding to the RFC labels in Figure 2 are given in Table 3. Also given in Table 3 is the RFC-average value of the ratio of mean annual precipitation, P, to mean annual potential evaporation, PE. The P/PE ratio is known as climate index or aridity index [*Dooge*, 1997; *Sankarasubramanian and Vogel*, 2002]. A value below 0.5 indicates desert climate; between 0.5 and 1.0, grassland and above 1.0, forest. The mean annual precipitation, P, is from the PRISM analysis for the period 1961–1990, where PRISM stands for Parameter-elevation Regressions on Independent Slopes Model [*Daly et al.*, 1994]. The mean annual potential evaporation, PE, is from the NOAA evaporation atlas [*Farnsworth et al.*, 1982] and is based on free water surface evaporation estimated from an analysis of evaporation pan data. The interannual variation of PE everywhere in the United States has an annual coefficient of variation of less than 10% so

Table 3. RFC Names and Average Values of the P/PE Climate Index

Label	RFC Name	P/PE
CBRFC	Colorado Basin RFC	0.29
CNRFC	California/Nevada RFC	0.37
WGRFC	West Gulf RFC	0.37
MBRFC	Missouri Basin RFC	0.50
ABRFC	Arkansas Basin RFC	054
NCRFC	North Central RFC	0.82
NWRFC	North West RFC	0.96
MARFC	Middle Atlantic RFC	1.03
SERFC	South East RFC	1.04
NERFC	North East RFC	1.22
LMRFC	Lower Mississippi RFC	1.29
OHRFC	Ohio RFC	1.33

there is very little variation in long term averages of PE. The RFCs are listed in Table 3 in order of increasing value of P/PE.

[25] The resulting time series for each of the four models for each of the RFCs are shown in Figure 3. These are organized from dry to wet climate regime proceeding from upper left to lower right in the figure. Some consistent patterns can be observed in Figure 3 as climate changes. For example, the spin-up time for model total water storage to come to equilibrium with climatology is much longer for dry climates than for wet. This may also depend on how far away the initial conditions at the start of the simulations were assumed to be from where they needed to be to avoid spin-up problems. With the exception of the CNRFC, RFC areas with P/PE less than 0.6 have spin-up effects that may last as long as 2 years. CNRFC does not follow the typical pattern for dry areas because CNRFC includes the Sierra and the Coastal Range. The spatial coefficient of variation, C_v, of P/PE for the CNRFC is 1.13. This is much larger than C_v of P/PE for any other RFC except NWRFC (for which C_v is 1). RFCs with P/PE greater than 0.60 have larger amplitudes of seasonal variation of total water storage. The seasonal variation of total water storage in the dry areas is not very strong. This observation is consistent with the findings of *Duan and Schaake* [2003].

[26] Generally, the magnitude of total water storage tends to be greatest in the Noah model and least in the

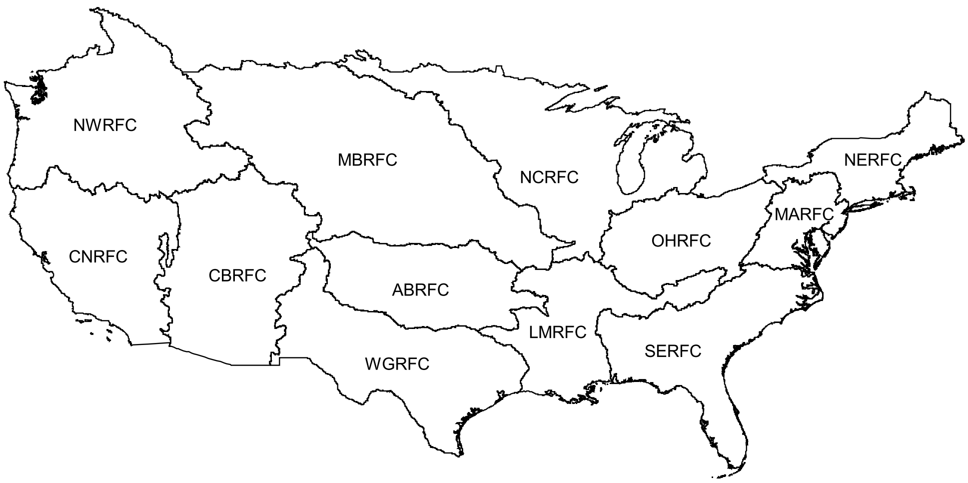

Figure 2. Locations of RFC forecast areas.

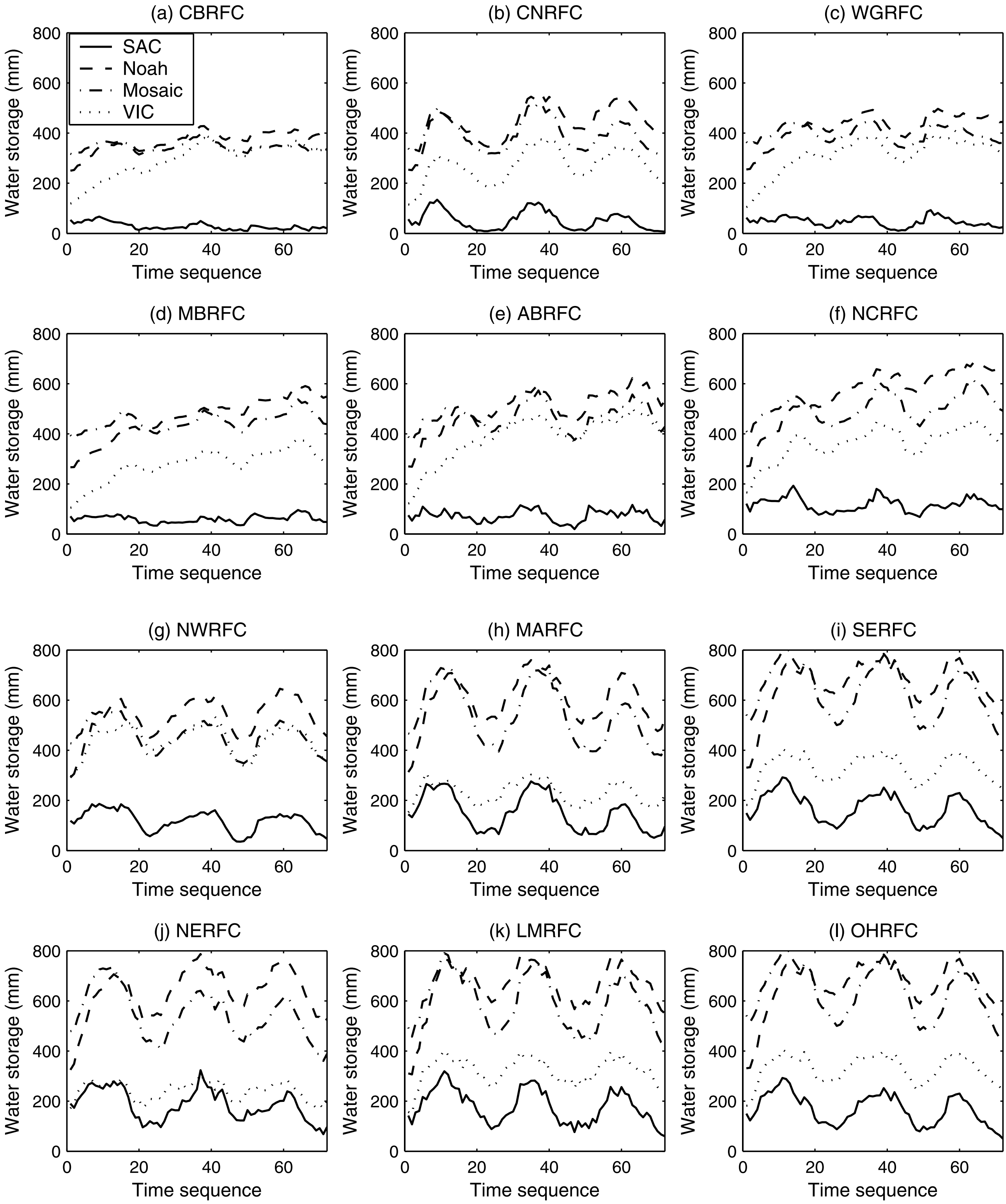

Figure 3. (a–l) Total area average water storage time series for each of the RFC forecast areas.

SAC model. Total water storage in the VIC model tends to be less than in the Mosaic model. The Noah and Mosaic models have the most similar values of total water storage. This is consistent for all RFCs. The SAC and VIC models have similar total water storage variability in wet areas but not in dry areas where storage in the VIC model is more similar to Mosaic and Noah. The SAC model does not seem to have any significant spin-up effects for any of the RFCs.

6. Range of Total Water Storage

[27] Because land surface models conserve water and energy, changes in any part of a model have effects on

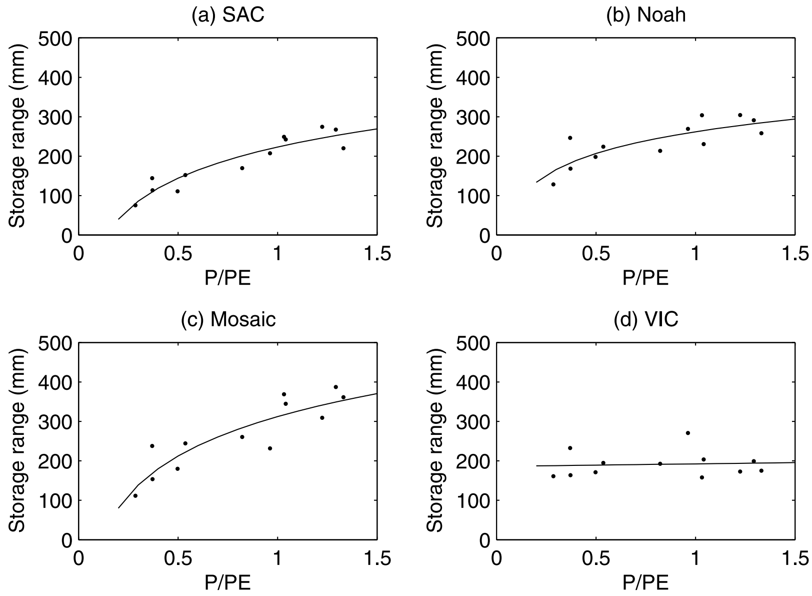

Figure 4. (a–d) Range of total water storage change versus P/PE for RFC forecast areas.

every other part of the model. Therefore the total amount of water stored in a model at any given time depends on both model structure and parameter values. It would be expected that changes in total water storage might be more comparable between models than the amount of total water storage since the rate of change of water storage (as opposed to total water storage) appears in the continuity equation that governs the water balance.

[28] A variable associated with change in water storage over a period of time is the range of total water storage for the period. The range of total water storage is the absolute difference between the maximum and minimum levels of total water storage that occurred during the period. The range of total water storage is independent of the soil hydraulic properties assumed by any model. Also it is independent of the magnitude of the water storage levels that vary from model to model. However, the maximum possible range for any model is necessarily limited by the total water storage capacity for the model. *Duan and Schaake* [2003], as well as the time series in Figure 3, suggest that the range of total water storage depends on climate regime. Therefore RFC basin-average values of the range of total storage change are compared to the P/PE climate index in Figure 4. To avoid including possible spin-up effects, the ranges shown in Figure 4 were computed for the 2-year period 1 October 1997 to 30 September 1999. This allows for a one-year spin-up period. In very wet climates Mosaic has the greatest total storage range. Mosaic

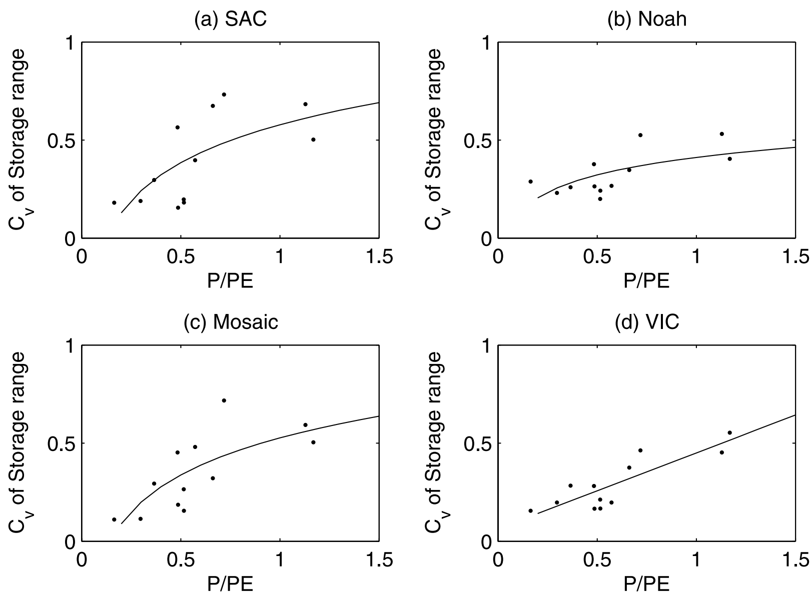

Figure 5. (a–d) Spatial C_v of range of total water storage change versus C_v of P/PE for RFC forecast areas.

Table 4. Spatial Statistics of Average Simulated Water Storage for Each of the Four LSMs

Model	Average, mm	Standard Deviation, mm	Minimum, mm	Maximum, mm
Sacramento	27	18	1	78
Noah	143	33	52	206
Mosaic	119	28	49	193
VIC	88	27	34	261

Table 6. Spatial Statistics of Maximum Simulated Water Storage for Each of the Four LSMs

Model	Average, mm	Standard Deviation, mm	Minimum, mm	Maximum, mm
Sacramento	220	114	18	550
Noah	688	161	137	928
Mosaic	614	159	146	947
VIC	456	141	108	1380

and SAC exhibit the strongest relationships between range of water storage and P/PE. The VIC model exhibits only a weak relationship between water storage range and P/PE in Figure 4.

[29] The local relationship between water storage range and P/PE within an RFC area can be detected by comparing the spatial coefficient of variation of the range of total water storage within the RFC area to the corresponding spatial coefficient of variation of P/PE. The results, illustrated in Figure 5 are similar to the results in Figure 4, except that the scatter of points about the trend lines is slightly greater than in Figure 4. One notable result in Figure 5 is that there is a strong local relationship for the VIC model between storage range and P/PE in Figure 5 but there is no noticeable global relationship for the VIC model in Figure 4.

[30] Figure 6 compares the range of total water storage for each of the four LSMs for the period 1 October 1997 to 30 September 1999. Summary statistics, spatially averaged over the NLDAS domain, of the values of average, minimum, maximum and range of total water storage for each of the LSMs are presented in Tables 4–7, respectively. The average value of total water storage (Table 4) is model dependent. Some of the reasons for this have been discussed by *Koster and Milly* [1997]. The minimum storage (Table 5) as well as the minimum average storage (Table 4) is near zero in dry areas. The minimum storage for the other models (Table 5) is limited by the wilting point used in the models. The range of the Mosaic model in wet areas (Figure 6) is much greater than the range of the other models. The SAC model has the smallest range in the dry areas. The minimum water content of the Noah model is greater in the Ohio river valley than other models.

[31] The ratio of the range of the total water storage in Figure 6 to the active water storage capacity (Figure 1) was computed. Summary statistics, spatially averaged over the NLDAS domain, of these values for each of the LSMs are given in Table 8. The average range of water storage in the SAC model is a larger fraction of the average active capacity than in the other LSMs. Also, Table 8 shows that the maximum range of SAC is almost equal to the active capacity whereas the other LSMs did not use more than about 75% of their active capacity during the 2-year analysis period. These differences can be attributed to the definition of active storage capacity (porosity - wilting point) assumed in this analysis for the different models. Below the root zone, water cannot be extracted below field capacity so the storage capacity between field capacity and the wilting point below the root zone is not actually active.

[32] The local relationship between storage range and P/PE climate index for each of the models was further explored by computing the average storage range over 1-degree areas and comparing the results to the corresponding average P/PE value. The 1-degree area was chosen both to limit the number of points to be plotted and to smooth some of the noise in the model output data. The results are shown in Figure 7. The relationship seems slightly stronger for the SAC model. The relationship is quite weak for the VIC model where some relationship seems to exist for dry areas, but it does not continue beyond P/PE values greater than 0.5. The relationship is slightly stronger for the Mosaic model than for the Noah model.

7. Statistical Analysis of Relationships Between Total Water Storage in Different Models

[33] Two statistical questions are addressed in this section. First, how different are the models relative to each other and do the differences vary with climate regime? Second, can values of total water storage in one model be used to estimate total water storage in another model?

[34] Answers to these questions are found by analyzing the statistical properties of values of water storage within 1-degree grid areas over the entire NLDAS domain. Each 1-degree grid area contains 64 1/8-degree computational elements. The 1-degree areas were used to obtain a large enough sample size for the analysis.

[35] First, the 1/8-degree data were standardized by subtracting the 1-degree mean and dividing by the standard

Table 5. Spatial Statistics of Minimum Simulated Water Storage for Each of the Four LSMs

Model	Average, mm	Standard Deviation, mm	Minimum, mm	Maximum, mm
Sacramento	38	44	0	236
Noah	456	129	60	739
Mosaic	375	103	97	852
VIC	264	107	54	908

Table 7. Spatial Statistics of Average 2-Year Range of Water Storage for Each of the Four LSMs

Model	Average, mm	Standard Deviation, mm	Minimum, mm	Maximum, mm
Sacramento	182	91	18	514
Noah	232	93	29	637
Mosaic	239	115	0	575
VIC	192	78	14	826

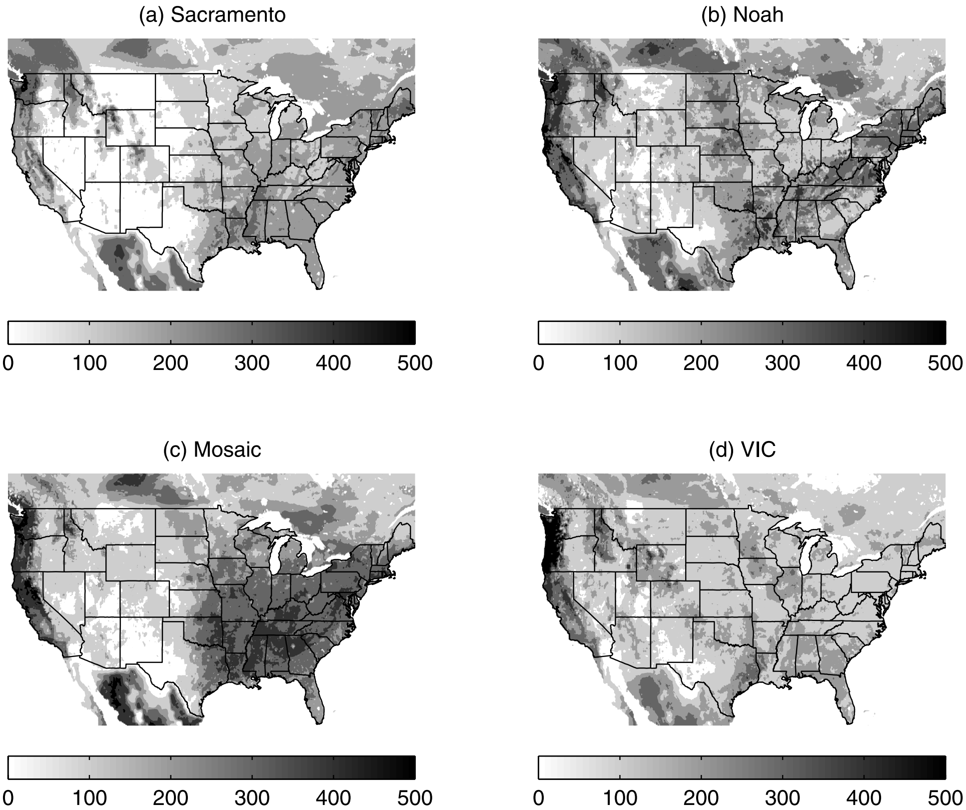

Figure 6. Range of total water storage for each of the LSMs over the NLDAS domain: (a) SAC, (b) Noah, (c) Mosaic, and (d) VIC. See color version of this figure in the HTML.

deviation of all of the 1/8-degree data values. Then the 4 × 4 matric of cross-correlation coefficients between standardized values for each model was computed. This correlation matrix was used to analyze both of the above questions as follows.

[36] The difference between the models can be measured in terms of the dimensionality of the correlation matrix. The eigenvectors and eigenvalues of the correlation matrix can be used to assess dimensionality. The variance of the standardized values for each model is equal to 1.0, and the total variance of the standardized values for all four models is equal to 4.0. The eigenvectors can be used to transform the standardized data to a new set of variables having variances given by the eigenvalues. If the water storage values of each of the four models were linearly related to the others, the first variable in the transformation would contain all of the information in the data, the first eigenvalue would equal 4.0 and the other three eigenvalues would be zero. Values close to 0.0 suggest the models are very different. Therefore the first eigenvalue of the model correlation matrix can be used to assess the magnitude of the differences between the models. Small values of the first eigenvalue suggest greater differences between the models. Large values suggest smaller differences. Figure 8 presents values of the first eigenvalue (as a fraction of the total variance = 4.0) for each 1-degree grid element over the NLDAS domain. It appears in Figure 8 that the largest values of the first eigenvalue, indicating the models are similar, tend to occur in the wet areas where model performance is driven primarily by model forcing. The smallest values of the first eigenvalue, indicating the models are different, tend to occur in dry areas where model performance is driven primarily by model structure.

[37] Because the values of the first eigenvalue seem to be related to climate, the values of the first eigenvalues for each 1-degree grid area in Figure 8 are compared in Figure 9 to the corresponding value of the P/PE index. Although there is much scatter, the trend line through the data clearly shows a strong tendency for the first eigenvalue to be much larger for areas with greater values of P/PE. This means that the difference between models is greater in dry areas than in wet.

[38] The second question regarding the possibility of estimating total water storage for one model from values in another model can be addressed by considering the joint correlation coefficient when values for each model are estimated by linear multiple regression with values from the other models. Summary statistics, spatially averaged over the NLDAS domain, of the values of the joint correlation coefficient for estimation of total water storage

Table 8. Spatial Statistics of Ratio of Average 2-Year Range to Active Storage Capacity for Each of the Four LSMs

Model	Average	Standard Deviation	Minimum	Maximum
Sacramento	0.43	0.20	0.03	0.96
Noah	0.13	0.10	0	0.74
Mosaic	0.18	0.12	0	0.61
VIC	0.19	0.14	0	0.76

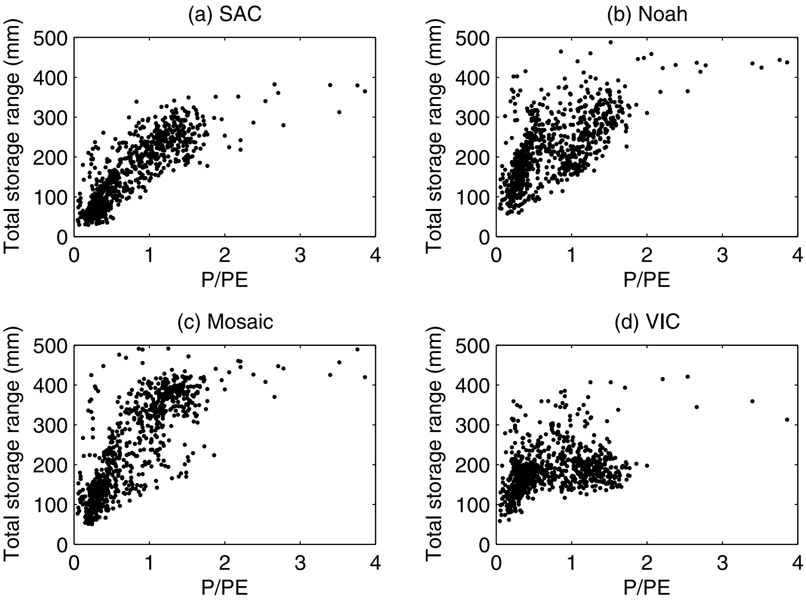

Figure 7. (a–d) Range of total water storage versus P/PE.

for each of the LSMs from the others are presented in Table 9. Mosaic has the highest average value indicating Mosaic water storage is easiest to estimate from the other models. On average, only about half of the variance of total water storage in one model can be estimated form the others. Minimum values of the joint correlation coefficient occur in dry areas; maximum, in wet. Spatial patterns of the joint correlation coefficient for different models are similar and resemble the spatial pattern of the first eigenvalue in Figure 8.

[39] Even though this analysis suggests that total water storage may be possible to estimate for some models, in some areas, this cannot be done unless there is an adequate historical archive of data from both the model to be estimated and from the models to be used to make the estimates to calibrate the statistical relationships. These

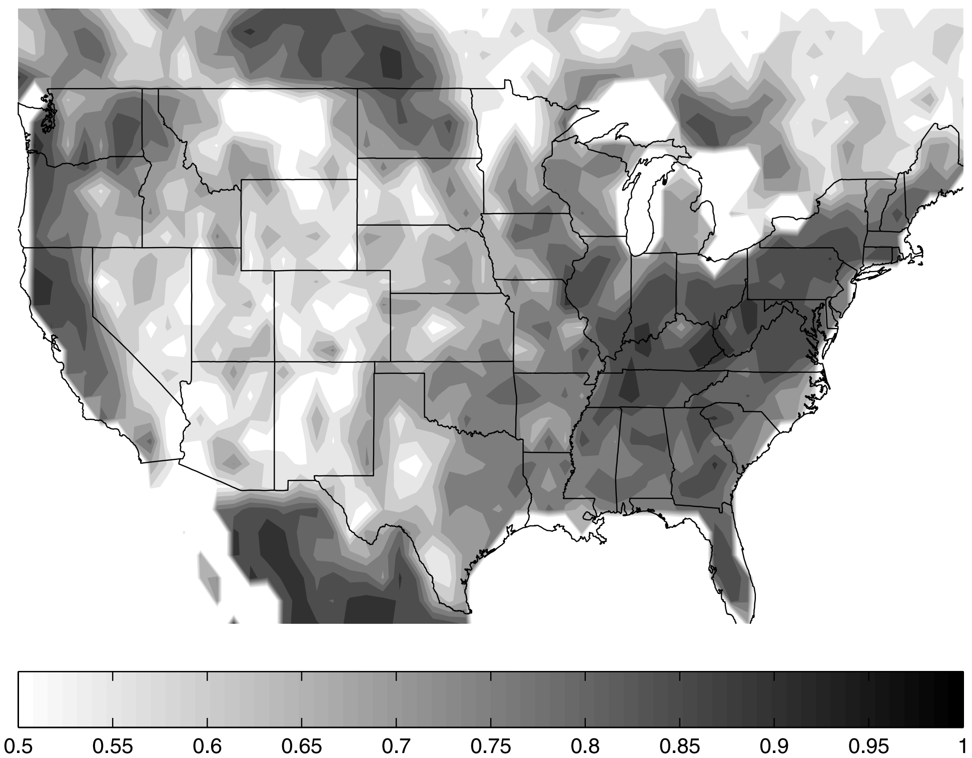

Figure 8. Fraction of variance of total water storage explained by first eigenvalue if intermodel correlation matrix over the NLDAS domain. See color version of this figure in the HTML.

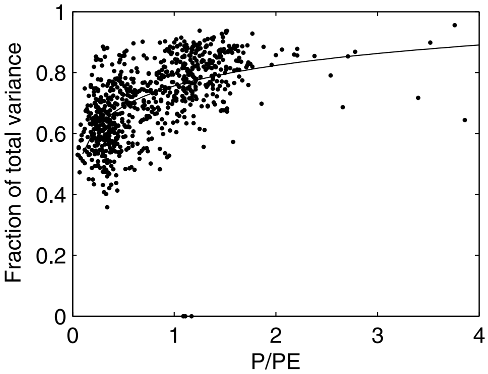

Figure 9. Fraction of variance of total water storage explained by first eigenvalue versus P/PE.

relationships vary spatially so they must be developed for each location where they might be used.

8. Comparison of Simulated and Observed Total Water Storage in Illinois

[40] The Illinois State Water Survey has made soil moisture measurements in the top 2 m of the soil profile since 1981. These are currently made twice per month at 18 sites. Data from one of the 18 sites are not used in this study because soil properties and soil moisture measurements at that site are much different from any of the other 17 sites.

[41] Because LSMs estimate the average value of soil moisture over an area, individual comparisons are not made between point soil moisture measurements and area average model estimates at the corresponding grid points. Instead, a composite 17-site average of observed total column water content is compared to the average total water storage for the corresponding grid points for each LSM. To make these comparisons, the time series of total column observed water content at each site is interpolated in time to get the observed total column content corresponding to the time of each of the 48 snapshots of total water storage. Comparisons are made for each of the four LSMs during the last 2 years of the retrospective simulation. The first year of simulation is not used for the comparison to avoid possible spin-up effects. Comparisons of the 48 pairs of observed and simulated total water storage values are presented in Figure 10.

[42] Because the SAC model simulates water storage above the wilting point, the water stored below the wilting point at each of the 17 Illinois sites was added to the SAC results to facilitate comparisons among the models. Results for the VIC model are presented separately for the northwestern and southeastern parts of Illinois because there is an abrupt change in the total storage capacity between northwest and southeast Illinois. This is a result of VIC model parameters having been estimated differently in these two parts of Illinois and clearly shows that model values of total water storage depend on model parameters as well as model structure. The active storage capacity of the VIC model is much greater in northwest Illinois than in southeast, as can be seen in Figure 1. Accordingly the 17 soil moisture sites were partitioned into northwest and southeast data sets and the average measured and simulated water storage was computed separately for each set. Figure 10 shows that the simulated VIC total storage is much greater for the northwest sites than for the southeast. However, the corresponding measured values are similar in both regions.

[43] Total water storage from each of the models is highly correlated with the observations. Simulated values from both SAC and Noah models agree well with the measured values. The absolute values of water storage from Mosaic and VIC do not agree well with observed values but a strong linear relationship exists for both models. The range of variation of total storage is related to the slope of the trend lines between simulated and measured values. Except for Mosaic all of the slopes are close to 45-degrees indicating close agreement between simulated and observed variability.

[44] The ranges of the simulated and observed total water storage are given in Table 10. The ranges of variability of SAC, Noah and VIC simulated water storage are close to the observed range. The range of variability of Mosaic simulated water storage is greater than measured.

[45] The serial correlation of water storage at individual sites and the serial correlation of the average water storage over all of the sites was computed for lags up to three months. The average of the serial correlation values for individual sites was found to be about the same as the serial correlation of the average water storage across all of the sites. This was true for all of the model simulations and for the observed values. Figure 11 compares the serial correlation functions for the observations with the serial correlation functions for the model simulations. Mosaic gave slightly higher correlations than the observed values; VIC gave slightly lower correlations. SAC and Noah serial correlations were between those for Mosaic and VIC. The serial correlation values in Figure 11 apply to deviations of soil water storage values from the long-term mean value. There is not enough data for the 2-year period of the analysis to allow computation of deviations from a seasonally varying mean. If that were done, the serial correlation values would likely be much smaller than given in Figure 11.

[46] The spatial de-correlation properties of total water storage also were analyzed. The results are given in Figure 12. Spatial correlation between observed point values of total water storage decrease more rapidly with distance than between model-simulated values for the corresponding 1/8-degree grid elements. This likely reflects both (1) the fact that point water storage measurements respond to point precipitation whereas model-simulated water storage depends on spatially average precipitation

Table 9. Spatial Statistics of the Joint Correlation Coefficient Associated With the Linear Regression to Estimate Total Water Storage for Each of the LSMs From Values of the Other Three LSMs

Model	Average	Standard Deviation	Minimum	Maximum
Sacramento	0.75	0.16	0.16	0.99
Noah	0.73	0.15	0.20	0.98
Mosaic	0.84	0.11	0.23	0.99
VIC	0.79	0.13	0.18	0.98

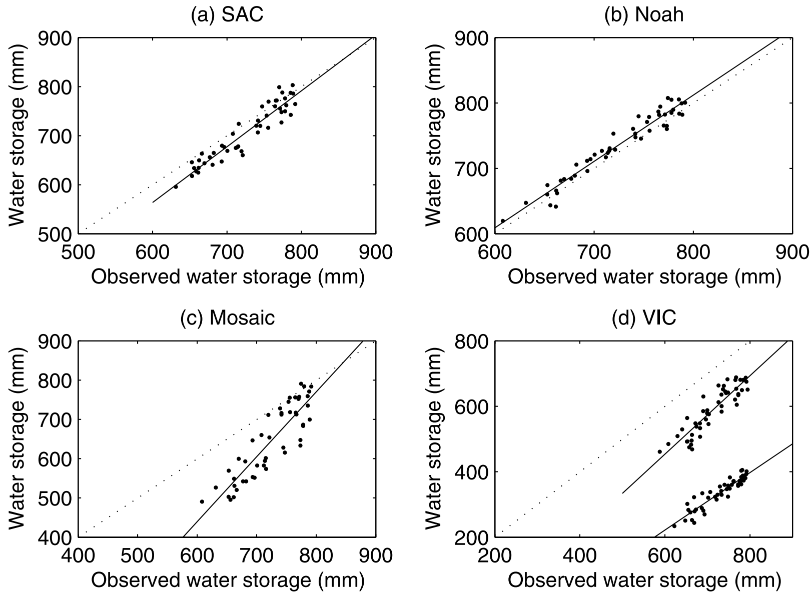

Figure 10. (a–d) Comparison of simulated total water storage from four LSMs versus observed total water storage at 17 locations in Illinois.

and (2) the fact that point water storage measurements depend on local hydraulic properties of the soil.

9. Comparison of Simulated and Observed Storage Range in the Arkansas-Red River Basin

[47] Areal average total water storage change cannot be observed directly. However, *Duan and Schaake* [2003] developed an approach to estimate the expected range of total water storage change as a function of duration of data record length. This approach uses monthly observed precipitation and streamflow data for a given river basin. A hydrologic model is not used but an assumption is made about how much water will evaporate in a given month depending on the precipitation during the month and the total water storage at the beginning of the month. The approach produces monthly time series of evaporation and storage that are consistent with the observed precipitation and streamflow. The resulting average monthly evaporation estimates over the Arkansas-Red River basin were shown to match very well the monthly average evaporation amounts derived by analysis of the atmospheric water budget.

[48] Values of the average 2-year range of total water storage for 27 river basins in the Arkansas-Red River basin [*Duan and Schaake*, 2003] are compared in Figure 13 to the 2-year range of total water storage simulated by each of the four LSMS. The SAC model reproduces best the storage ranges for the 27 basins that are located in a wide range of climate regimes. There appears to be a slight low bias but 2-year storage range for any given period of time can be quite different than the long-term average that is given in the figure for each of the 27 basins. The Noah model has the next strongest relationship but the slope of the trend line through the data for the Noah model suggests there is more real difference range of total water storage across the Arkansas-Red River basin than is simulated by the Noah model. The VIC model has reasonable good agreement with the expected 2-year ranges for the 27 basins, but there is more real difference range of total water storage across the Arkansas-Red River basin than is simulated by the VIC model. The range of total water storage produced by the Mosaic model appears to be excessively large. It was noted above that the range of total water storage from the Mosaic model in wet areas is greater than the range produced by any of the other models.

Table 10. Range of Average Total Water Storage at 17 Soil Moisture Observation Sites in Illinois

Source	Range, mm
Measured (2 m)	184
Sacramento	208
Noah	188
Mosaic	300
VIC	193

10. Analysis of Upper and Lower Zone Storage

[49] There is no direct way to compare water storage in individual storage components of the different NLDAS

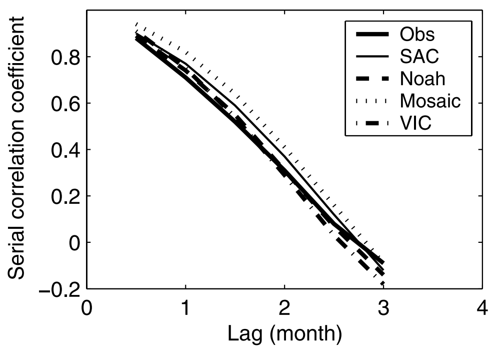

Figure 11. Serial correlation of water storage in Illinois for four LSMs versus serial correlation of observed water storage.

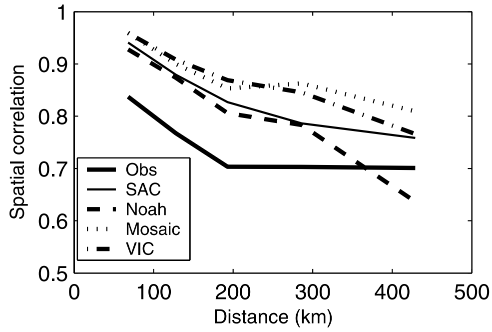

Figure 12. Spatial correlation of water storage in Illinois for four LSMs versus spatial correlation of observed water storage.

LSMs because the storage components of different models have different definitions. For example, storage in the SAC model is defined in terms of water storage capacity and is not explicitly related to soil layers with prescribed soil depths. The top layer of the Noah, Mosaic and VIC models correspond to the top 10 cm of soil. The second layer of the VIC model has a variable depth over the NLDAS domain, while the second layer in the Noah and Mosaic models corresponds to the next 30 cm below the top layer.

[50] Recognizing that exact comparison between individual model components is not possible, it nevertheless seems worthwhile to seek at least a general understanding of how model storage varies between upper and lower zones in the models. Accordingly, for this analysis, upper and lower zones are defined for each model as given in Table 11.

[51] The range of change of total water storage in both the upper and lower zones of each model was determined. The ratio of upper zone storage range to the sum of upper and lower zone storage ranges is shown in Figure 14. SAC, Noah and Mosaic show a clear tendency for the ratio in Figure 14 to be greater in the west than in the east. This means that variability in the lower zone in these models is less important in the west than in the east. The SAC model lower zone variability is almost negligible relative to the variability in the upper zone in some parts of the west. The VIC model results in Figure 14 differ from the results of the other three models because the water storage capacity of the top two VIC model layers used to define the upper zone in this analysis is much more variable than the upper zone storage capacities of the other models.

Table 11. Definition of Upper and Lower Zones

Model	Upper Zone	Lower Zone
Sacramento	top two storage components (variable depth)	lowest three storage components
Noah	top two layers (40 cm)	bottom two layers
Mosaic	top two layers (40 cm)	bottom layer
VIC	top two layers (variable depth)	bottom layer

[52] The fraction of variance of water storage in the upper and lower zones explained by the first eigenvalue of the intermodel correlation matrix is shown in Figure 15. The values shown in Figure 15 are related to corresponding values of P/PE in Figure 16.

11. Summary and Conclusions

[53] An analysis is presented of soil moisture data sets produced by four different LSMs running retrospectively for the period 1 October 1996 to 30 September 1999. All LSMs were assigned the same relative soil wetness values at the start of simulation period. A total of 72 snapshots of the water storage fields from all four LSMs were obtained at the end of the first and fifteenth days of each month. A goal of this study is to gain insight into the effects of climate variability at continental scale and into strengths and limitations of LSM model physics.

[54] Steps were taken to ensure meaningful comparisons of the results. Two quantities were compared in this anal-

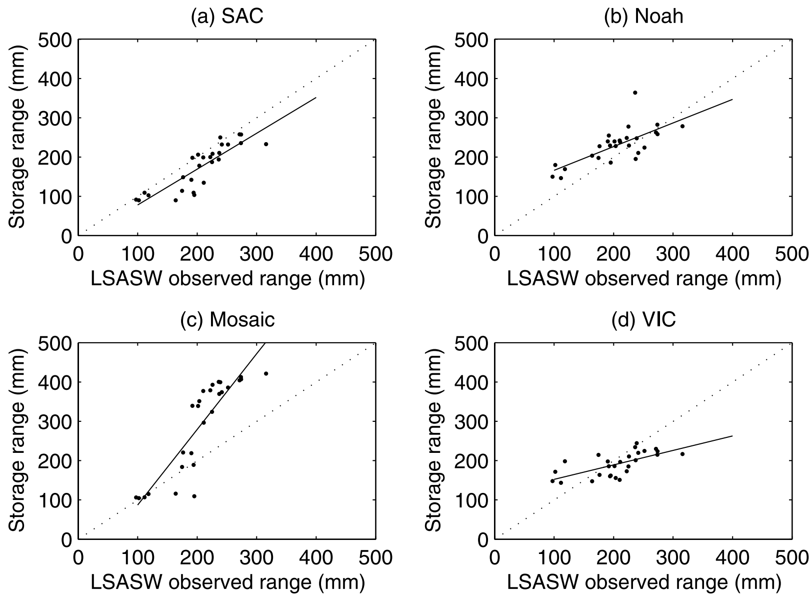

Figure 13. (a–d) Simulated versus observed total water storage range in Arkansas-Red River basins for four LSMs.

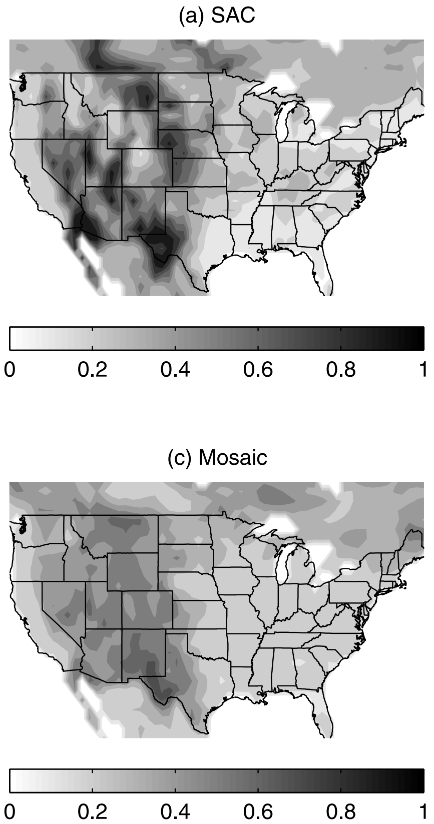

Figure 14. Ratio of upper zone storage range to total storage range for the four LSMs over the NLDAS domain: (a) SAC, (b) Noah, (c) Mosaic, and (d) VIC. See color version of this figure in the HTML.

ysis: the total water storage and the range of water storage variability. Ideally, we would like to compare water storage variables for each storage component across the different models. This is difficult to do because there are important differences in how the water storage components are defined in each model. However, there is enough similarity in definition of the total water storage in all components of a given model to permit a straightforward comparison of total storage across models. The range of water storage variability should have the most agreement among the LSMs because all LSMs have strict water and energy balances. Also, water storage components for each model can be grouped into upper and lower zone components and comparisons are made for these as well. Finally, properties of individual storage components of each model are explored individually.

[55] Special attention was paid to the values of total water storage capacity for each of the four LSMs because they control the total amount of soil water that can be simulated by each LSM. The Noah and Mosaic models have higher and nearly constant total water storage capacity values over the NLDAS domain, while the SAC model has the lowest values. The VIC model has values between those of Noah and Mosaic and those of SAC. Consequently, the magnitude of water storage tends to be greatest in the Noah and Mosaic models and least in the SAC model. The Noah and Mosaic

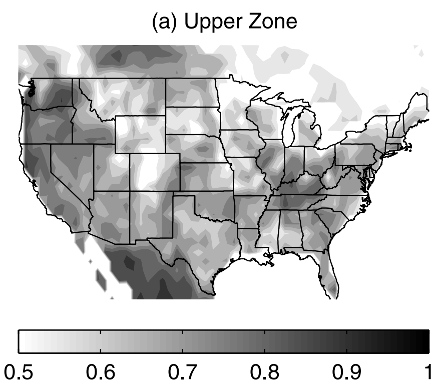

Figure 15. Fraction of variance of (a) upper and (b) lower zone water storage explained by first eigenvalue over the NLDAS domain. See color version of this figure in the HTML.

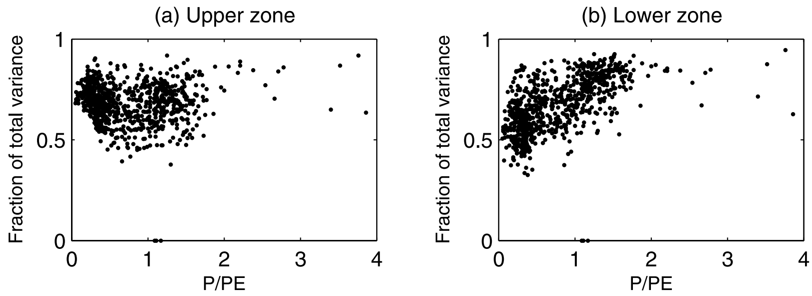

Figure 16. Fraction of variance of (a) upper and (b) lower zone water storage explained by first eigenvalue versus P/PE.

models have the most similar values of total water storage. The SAC and VIC models have similar total water storage variability in the wet areas but not in the dry areas where storage in the VIC model is more similar to Mosaic and Noah. Noah, Mosaic and VIC models have spin-up effects in arid areas during the first year, while the SAC model does not seem to have any significant effects.

[56] Mosaic and SAC exhibit the strongest relationships between range of total water storage and climate index, P/PE. The VIC model exhibits only a weak relationship between water storage range and P/PE. The range of storage of the Mosaic model in wet areas is much greater than the range of the other models. The SAC model has the smallest range in the dry areas.

[57] Two questions relative to estimation of total water storage are addressed. First, how different are the models relative to each other and do the differences vary with climate regimes? Second, can values of total water storage in one model be used to estimate total water storage in another model?

[58] The difference between the models is measured in terms of the dimensionality of the correlation matrix. The first eigenvalue of the model correlation matrix is used to assess the magnitude of the differences between the models. Small values of the first eigenvalue suggest greater differences between the models. This occurs primarily in arid areas. Large values suggest smaller differences. This occurs primarily in humid areas. The models agree better in humid areas because precipitation variability in humid areas produces a wider range of water storage variability. On the other hand model differences have a greater effect on water storage variability in dry areas.

[59] The second question regarding the possibility of estimating total water storage for one model from values in another model is addressed by looking at the joint correlation coefficient when values for each model are estimated by linear multiple regression with values from the other models. Storage values for Mosaic model appear the easiest to estimate from the other models. Storage values for the SAC model in arid areas of the west cannot be estimated well from the other models.

[60] Comparisons were made between simulated and observed values of total water storage at 17 sites in Illinois. Total water storage from each of the models is highly correlated with the observations. Simulated values from both the SAC model and the Noah model agree well with the measured values. The absolute values of water storage from Mosaic and VIC do not agree well with observed values but a strong linear relationship exists for both models. The ranges of variability of SAC, Noah and VIC water storage are close to the observed range. The range of variability of Mosaic water storage is greater than observed.

[61] Values of the average 2-year range of total water storage for 27 river basins in the Arkansas-Red River basin are compared to the 2-year range of total water storage simulated by each of the four LSMs. The SAC model reproduces the best storage ranges for the 27 basins that are located in a wide range of climate regimes. There appears to be a slight low bias but the 2-year storage range for the single 2-year period available for this study can be quite different than the long-term average 2-year that is given in the figure for each of the 27 basins. The Noah model has the next strongest relationship but the slope of the trend line through the data for the Noah model suggests that there is more real difference range of total water storage across the Arkansas-Red River basin than is simulated by the Noah model. The VIC also agrees well with the expected 2-year ranges for the 27 basins but there is more real difference range of total water storage across the Arkansas-Red River basin than is simulated by the VIC model. The range of total water storage produced by the Mosaic model appears to be excessively large.

[62] The range of change of total water storage in both the upper and lower zones of each model was determined. SAC, Noah and Mosaic show a clear tendency for the ratio of upper zone storage to total storage to be greater in the west than in the east. This means that variability in the lower zone in these models is less important in the west than in the east. The SAC model lower zone variability is almost negligible relative to the variability in the upper zone in some parts of the west.

[63] The simulated total water storage by the four LSMs in NLDAS has obvious differences despite being forced by the same forcing data and initiated at the same initial relative soil moisture level. This calls into question whether one can use the soil moisture state variables from one model to initialize another model. The differences between model results could be caused by differences in model structure and by estimates of model parameters. Although both of these factors may be important, more attention should be given to assure that parameter estimates for each model give the best possible representation of water and energy fluxes. Changes in model parameters can produce significant changes in model values of water storage as illustrated for the Vic model in Figure 10. Further diagnosis of the causes of differences in model results should be done for

experimental areas where measurements of streamflow and surface fluxes are available to assure that model parameters are appropriate and to provide an observational basis to complement model intercomparison. The challenge to NLDAS and the land surface modeling community in general is be to find ways to reduce these differences and to strive for consistency between the model results and with observations.

[64] **Acknowledgments.** The work on this project by NWS/OHD, NCEP/EMC, and NESDIS/ORA was supported by the NOAA OGP grant for the NOAA Core Project for GCIP/GAPP (co-PIs K. Mitchell, J. Schaake, and D. Tarpley). The work by NASA/GSFC/HSB was supported by NASA's Terrestrial Hydrology Program (P. Houser, PI). The work by Rutgers University was supported by NOAA OGP GAPP grant GC99-443b (A. Robock, PI), the Cook College Center for Environmental Prediction, and the New Jersey Agricultural Experiment Station. The work by Princeton University was supported by NOAA OGP GAPP grant NA86GP0258 (E. Wood, PI). The work by NCEP/CPC was supported by NOAA/NASA GAPP Project 8R1DA114 (R. W. Higgins, PI). The work by University of Maryland was supported by grants NA56GPO233, NA86GPO202, and NA06GPO404 from NOAA/OGP and by NOAA grant NA57WC0340 to University of Maryland's Cooperative Institute for Climate Studies (R. Pinker, PI). The soil moisture observations provided by Illinois State Water Survey are gratefully acknowledged.

References

Burnash, R. J., R. L. Ferral, and R. A. McGuire (1973), A generalized streamflow simulation system: Conceptual modeling for digital computers, technical report, 204 pp., Joint Fed. and State River Forecast Cent., Sacramento, Calif.

Chen, F., K. Mitchell, J. Schaake, Y. Xue, H. Pan, V. Koren, Q. Y. Duan, M. Ek, and A. Betts (1996), Modeling of land-surface evaporation by four schemes and comparison with FIFE observations, *J. Geophys. Res.*, *101*(D3), 7251–7268.

Cosgrove, B. A., et al. (2003a), Land surface model spin-up behavior in the North American Land Data Assimilation System (NLDAS), *J. Geophys. Res.*, *108*(D22), 8845, doi:10.1029/2002JD003316.

Cosgrove, B. A., et al. (2003b), Real-time and retrospective forcing in the North American Land Data Assimilation System (NLDAS) project, *J. Geophys. Res.*, *108*(D22), 8842, doi:10.1029/2002JD003118.

Daly, C., R. P. Neilson, and D. L. Phillips (1994), A statistical-topographic model for mapping climatological precipitation over mountainous terrain, *J. Appl. Meteorol.*, *33*, 140–158.

Dooge, J. C. I. (1997), Scale problems in hydrology, in *Reflections on Hydrology*, edited by N. Buras, pp. 85–143, AGU, Washington, D. C.

Duan, Q., and J. C. Schaake Jr. (2003), Total water storage in the Arkansas-Red River basin, *J. Geophys. Res.*, *108*(D22), 8853, doi:10.1029/2002JD003152.

Duan, Q., J. Schaake, and V. Koren (2001), A priori estimation of land surface model parameters, in *Land Surface Hydrology, Meteorology and Climate: Observations and Modeling*, *Water Sci. Appl.*, vol. 3, edited by V. Lakshmi et al., pp. 77–94, AGU, Washington, D. C.

Farnsworth, R. K., E. S. Thompson, and E. L. Peck (1982), Evaporation atlas for the contiguous 48 United States, *NOAA Tech. Rep. NWS 33*, 25 pp., U.S. Dep. of Comm., Washington, D. C.

Kistler, R., et al. (2001), The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation, *Bull. Am. Meteorol. Soc.*, *82*(2), 247–267.

Koren, V., M. Smith, and Q. Duan (2003), Use of a priori parameter estimates in the derivation of spatially consistent parameter sets of rainfall-runoff models, in *Calibration of Watershed Models*, *Water Sci. Appl.*, vol. 6, edited by Q. Duan et al., pp. 239–254, AGU, Washington, D. C.

Koster, R. D., and P. C. D. Milly (1997), The interplay between transpiration and runoff formulations in land surface schemes used with atmospheric models, *J. Clim.*, *10*, 1578–1591.

Koster, R. D., and M. J. Suarez (1996), Energy and water balance calculations in the Mosaic LSM, *NASA Tech. Memo., 104606*, vol. 9, 58 pp.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges (1994), A simple hydrologically based model of land surface water and energy fluxes for GCM, *J. Geophys. Res.*, *99*(D7), 14,415–14,428.

Miller, D. A., and R. A. White (1998), A conterminous United States multi-layer soil characteristics data set for regional climate and hydrology modeling, *Earth Inter.*, *2* Paper No. 2.

Mitchell, K. E., et al. (2004), The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system, *J. Geophys. Res.*, *109*, doi:10.1029/2003JD003823, in press.

Nijssen, B., D. P. Lettenmaier, X. Liang, S. Wetzel, and E. F. Wood (1997), Streamflow simulations for continental-scale river basins, *Water Resour. Res.*, *33*(4), 711–724.

Sankarasubramanian, A., and R. M. Vogel (2002), Annual hydroclimatology of the United States, *Water Resour. Res.*, *38*(6), 1083, doi:10.1029/2001WR000619.

Sellers, P., Y. Mintz, Y. Sud, and A. Dalcher (1986), A simple biosphere model (SiB) for use within general circulation models, *J. Atmos. Sci.*, *43*, 505–531.

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