In this article, we illustrate the link between soil moisture and the groundwater reservoir at the continental scale, and contribute our simulated water table and the water table–influenced soil moisture climatology over North America to the community. Soil moisture has been shown to be an active participant in continental climate dynamics (e.g., Betts 2004). Spatial organization in soil moisture fields can lead to a horizontal gradient in atmospheric states, influencing circulation and vapor convergence (e.g., Avissar and Pielke 1989; Small 2001; Pal and Eltahir 2002; Georgescu et al. 2003; Kanamitsu and Mo 2003). Soil water storage and memory can enhance droughts and floods through positive soil moisture–rainfall feedbacks (e.g., Entekhabi et al. 1992; Eltahir 1998; D’Odrico and Porporato 2004; Hong and Kalnay 2000; Koster et al. 2004). Here, we examine these features in the simulated soil moisture climatology, that is, large-scale spatial features and root-zone total storage, as influenced by the presence of a water table below.

Figure 1 illustrates the theoretical link between soil moisture and the water table depth for the following three typical soil types: clay, silt, and sand; it is based on the soil water profile above a water table at 10, 5, 2, and 1 m below land surface for three typical soil types (modified from Salvucci and Entekhabi 1994, 1995). [Reproduced from Fan et al. (2007) by permission of American Geophysical Union.]
on Salvucci and Entekhabi (1994, 1995), from their solution of the Richard’s equation (Dingman 2002) of soil water flux, with the water table depth prescribed as saturation (neglecting capillary fringe). The influence of the water table on soil moisture is different in different soils. For clay, where capillary is strong, a water table depth of 10 m can still be “felt” in the root zone and near surface. For sand, the water table has little role as a source if it is below the root zone. This simple result points to the theoretical link between soil moisture and the water table: by influencing soil water from below, the water table acts as the lower boundary condition of the soil column, much in the same sense that the atmosphere acts as its upper boundary. Both can drive soil water flux at their own characteristic spatial and temporal scales.

In a typical land surface scheme of a climate model, the top boundary is represented with sophisticated physics, with multiple vegetation and soil layers and detailed parameterization of resistance terms controlling water and heat fluxes; however, the handling of bottom flux is much more simplistic. A common approach is a free-gravity drain from the bottom layer. In nature, this drainage enters the saturated store and raises the water table. While slowly draining toward local and regional streams, the water table may remain high long after the storm, and if it is sufficiently shallow (within either the root zone or capillary reach), it will serve as a moisture source to sustain upward evapotranspiration (ET) flux in dry periods.

The difference in the degree of sophistication in treating the top and the bottom boundaries reflects the origin of these land surface schemes; they are designed to quantify the land–atmosphere fluxes at the top of the soil. However, because the bottom condition affects the soil water state in the column, which may affect the top boundary flux, it is desirable to constrain the bottom with similar degrees of physical realism. Recent reports demonstrate that near-surface and root-zone soil moisture is influenced by the presence of a shallow water table (e.g., Salvucci and Entekhabi 1994, 1995; Gutowski et al. 2002; Liang et al. 2003; Maxwell and Miller 2005; Yeh and Eltahir 2005; Yu et al. 2006; Niu et al. 2007; Miguez-Macho et al. 2007), and because groundwater operates at greater spatial and temporal scales than soil water, this link may influence the spatial and temporal features of soil moisture, introducing a pronounced large-scale spatial structure and long-term memory (Miguez-Macho et al. 2007). It has been shown that large-scale groundwater convergence can be a mechanism for soil water persistence, locking precipitation into prolonged anomalies through soil moisture–rainfall feedbacks (Bierkens and van den Hurk 2007).

In this article, we illustrate the effect of this lower boundary condition on simulated soil moisture climatology across the wide spectrum of climate, soil, and drainage conditions in North America. We focus on two aspects—large-scale spatial features and total soil water storage in the root zone (top 2 m). We ask the following questions: Will the water table introduce new spatial features in the simulated soil moisture fields, and will it lead to greater soil water storage in the root zone? Our approach is to construct a climatological water table over North America and calculate the soil water profile bounded below by this water table (“Water table and soil moisture climatology” section). We then compare this with soil moisture observations and two other products (“Comparison with VIC, NARR, and observations” section), and summarize the implications of our findings to climate modeling (“Summary and discussion” section). Finally, we provide the link to download the observed and simulated water table depth and soil moisture fields at 14 depths (down to 4 m), in response to several individual requests since the publication of our earlier results (Fan et al. 2007; Miguez-Macho et al. 2007).

**WATER TABLE AND SOIL MOISTURE CLIMATOLOGY.** Construction of the water table climatology (WTC) is discussed in detail in Fan et al. (2007). It is defined as the climatological mean water table, a result of the long-term hydrologic balance between the vertical, atmospherically induced flux across the water table (recharge), and the lateral, geologic, and topographically induced flow below and parallel to the water table (drainage). The result is a smooth, undulating surface beneath the land topography, occasionally appearing at the land
surface as wetlands, rivers, and lakes. Calculation of WTC is based on equations of two-dimensional groundwater flow (mass balance plus Darcy’s law; Dingman 2002). In a hillslope cell, recharge dissipates laterally to its neighbors, and in a river cell, lateral groundwater convergence discharges into the rivers. In the absence of a continental database on hydraulic conductivity and porosity at greater depths, it is assumed that both decay exponentially with depth, and that the e-folding length of decay is an inverse function of terrain slope (flat land leads to deep soil). For a detailed discussion and parameterization see Fan et al. (2007).

In the absence of direct observations, water table recharge is obtained from the 50-yr (1950–2000) model simulation by variable infiltration capacity (VIC; Maurer et al. 2002). It is calculated as 50-yr mean precipitation ($P$, observation based) minus evapotranspiration and surface runoff (both of which are model estimated). Uncertainty associated with this approach is addressed later.

The simulation is performed at a grid resolution of 30-arc-s (<1 km), starting at the water table at the land surface and iteratively achieving mass balance at all cells. The resulting WTC is shown in Fig. 2, with details over selected regions. We validate the WTC with 549,616 site observations by the U.S. Geological Survey (USGS) over the period of 1927–2005. Temporal means at the sites are shown in Fig. 3a. Note that over 81% of the sites have only one reading over the record (large temporal noise), and that most of the observations are located in low elevations near population and agricultural centers (large spacial gaps), rendering the observations less ideal for validating the climatological condition. Figure 3b plots the simulated versus the observed head, the latter of which as the mean of point observations (if >1) within a 30-arc-s grid cell. Only observations with site elevations within 100 m of the model grid elevation are retained for comparison, because the water table depends sensitively on local topography. We examine the residual (simulated – observed), which must follow a Gaussian distribution with zero mean. Figure 3c is the residual histogram. The histogram made is after subtracting 1.5 m from the simulated head over the domain. The shift serves two purposes: first, to center the residual histogram, and second, to compensate for the high bias in the simulated head resulting from allowing WTC to rise to the land surface. At 30-arc-s resolution, the river elevation

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**Fig. 2.** Simulated climatology of water table depth (m), with details over four regions. Black dots indicate soil moisture observation sites.
is likely below the mean land elevation. This bias is propagated upland, causing a bias high everywhere. Because there are no observation-based river-level data (scale dependent) for the continent, we resort to a simple shift of WTC as guided by the residual histogram. The histogram is slightly skewed to the right; there are more cells where the simulated head is higher than that observed. To examine where the biases occur, we plot the residual versus gridcell elevation in Fig. 3d and terrain slope in Fig. 3e. The slight negative correlations suggest that the high bias mostly occurs on lower and flatter terrain. We made no attempt to correct it, because widespread groundwater pumping (information online at http://pubs.usgs.gov/fs/fs-103-03/#pdf) has lowered the water table, leading to a low bias in the observations. Because pumping occurs in agricultural and urban areas in river valleys and coastal regions, its effect is greater at low and flat lands. However, the greatest residuals are linked to the lack of geologic information and the fact that an exponential decay of permeability is inadequate in many geologic settings, as discussed in detail in Fan et al. (2007), calling for an effort to extend our hydrologic database deeper into the Earth’s crust.

Compared to Fan et al. (2007), an important improvement is that the simulation here is performed at a finer resolution of 30-arc-s (versus the 1.25 km used earlier). The advantage is that hillslope and valley cells are better resolved, so that the separate formulation for them is better justified. Recall that over a hillslope cell, recharge is dissipated laterally to its neighbors, and in a river cell, lateral groundwater convergence is discharged into the rivers. The finer resolution also improved the comparison between a model cell and an observation point; indeed, it has improved the validation statistics by reducing the overall residuals.

Questions arise regarding the uncertainty in VIC-estimated recharge and the sensitivity of the resulting

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**Fig. 3.** (a) Water table observations, (b) simulated vs observed head, (c) histogram of residual, (d) residual vs gridcell elevation, and (e) residual vs terrain slope are shown.
water table to errors in recharge. We compared VIC \( R \) with several USGS studies, including Wolock (2003) and Delin and Risser (2007). The values reported in Wolock (2003) agree well with VIC over the western and central part of the United States but not in the humid east. The study by Delin and Risser (2007) used several different methods, which gave a range of estimates over the humid east, and we found that VIC results fall right in the middle of the ranges. In our home state of New Jersey, several USGS modeling studies report calibrated recharge values that are very close to the VIC estimates. More importantly, Delin and Risser (2007) illustrate the sensitivity of recharge estimates to the method used. Because recharge is not directly observable, it must be inferred from other observable quantities, such as streamflow components and water table level. Assumptions are inevitable, and their validity depends on local factors. However, we argue that VIC estimates are more physically based (water and energy balance in the soil and vegetation) compared to the traditional methods, such as hydrograph separation; VIC forcings are observation based and are compared with several reanalyses products; and VIC-estimated fluxes and fields are validated against observed river flow from 10 basins, the snowwater equivalent in the Mississippi drainage, and soil moisture in Illinois. Therefore, VIC estimates seem to represent the best-available proxy data for recharge over the continent.

An equally important question is how sensitive our simulated water table is to uncertainties in recharge. Note that it is the balance of recharge versus drainage that determines the water table. In other words, the ratio \( R/K \), where \( K \) is the hydraulic conductivity, or the balance of source strength versus drainage efficiency, sets the water table that perfectly fulfills the land drainage. Recall that because of the lack of observed \( K \) at depths, we assumed that it decays with depth exponentially, the rate depending on terrain slope (steep slope leads to shallow soil). Such determined \( K \) values likely contain more uncertainty. However, because the resulting water table is constrained by observations, errors in \( R \) can be offset by errors in \( K \), resulting in a balance of source versus drainage, and yielding the observed water table. By doing so, we might have achieved the right water table for the wrong reasons. However, our goal here is the right water table that agrees with observations in a statistical sense. By seeking the best overall fit, large errors can occur at specific locations. Note that the observation sites are biased toward lowlands and river valleys near population and agricultural centers (shallow water table areas). Thus, nudging the model with observations certainly favors a better fit at these locations. Because this is precisely where groundwater is shallow and can be linked to soil moisture and affect land–atmosphere interactions, we believe that the resulting water table is sufficiently suited for studying these processes and links.

We note that the water table shown in Fig. 2 is likely too deep in the northern part of the domain where permafrost limits drainage depth and raises the water table. The effect of shallow frozen soil is not considered in our groundwater model, and we note this limitation.

The maps in Fig. 2 describe the wetness at the bottom boundary of the soil column that we attempt to represent in climate models. Certain predictable features are apparent. A shallow water table can be expected in two types of settings: The first is in a humid climate with flat terrain, with abundant vertical surplus and slow lateral drainage. (Examples are the lower Mississippi valley, the southeast coastal plains, and the Hudson Bay drainage; the inset in Fig. 2 over the mid-Atlantic coast gives the spatial details of a shallow water table in such settings where many freshwater wetlands are found.) The second is in an arid climate with regional groundwater convergence, such as in the intermountain valleys of the West, where snowmelt in the high mountains feeds the aquifers in the low valleys. The detailed map of Nevada and California in Fig. 2 shows this pronounced and well-structured water table variability. In fact, the name of the city Las Vegas, Nevada, implies wetland conditions. It is in these two types of hydrologic settings that we may expect that the water table is responsible for the wet soils found in nature, and that introducing the water table will result in wet soils in land hydrology simulations.

Given \( WTC \) as the lower boundary condition, we calculate the soil moisture climatology (SMC) by numerically solving the Richard’s equation of soil water fluxes as in obtaining Fig. 1, with VIC recharge as the upper boundary (as in obtaining WTC). Soil parameters are obtained from the Land Data Assimilation System (LDAS) soil database (online at http://ldas.gsf.nasa.gov/). Solution is obtained at 14 depths (down to 4 m), with the top 11 layers (down to 2.5 m) having the same depths as in LDAS. Details on calculating soil water storage and flux with a varying water table below are given in Miguez-Macho et al. (2007). These simulation results (water table depth, \( WTC \), 14 soil moisture layers, and SMC) can be downloaded by any interested researchers, with the specifics provided at the end of this article.
COMPARISON WITH VIC, NARR, AND OBSERVATIONS. The simulated SMC fields are shown in Fig. 4 (top panels, labeled SMC) for the top 10 cm and top 2 m of the land surface. A salient feature in SMC is that soil moisture reflects the spatial structure in water table depth, and more so in the top 2 m; soil is wet where the water table is shallow and dry where the water table is deep. Hence, shallow

![Fig. 4. Soil moisture climatology in (left) top 10 cm and (right) top 2 m from SMC, VIC, and NARR. (bottom) The 1/2° mean along the 36°N latitude, with the transect shown as blue line in all maps.](image-url)
water tables and wet soil are found in the humid and flat river valleys and coastal regions of the east as well as in semiarid intermountain valleys of the west. The driest soil is found where the water table is deep and the soil is sandy, as in the Sand Hills of Nebraska (the dark brown patch).

To further understand the effect of the water table, we plot the 50-yr mean VIC-modeled soil moisture over the same depths (Fig. 4, second row). The difference between SMC and VIC is attributable to the water table in SMC, because the land surface flux is identical. The difference is better seen in a transect across the continent (bottom panels), obtained by averaging grid cells in 0.5° windows. In the top 10 cm, SMC gives wetter soil in the intermountain valleys of the west, drier soil in Nebraska, and wetter and spatially more variable soil water over large regions of the Midwest. The domain average in the top 10 cm is very similar between the two, reflecting the identical land surface flux. In the top 2 m, SMC is significantly wetter, with the largest difference being in the intermountain valleys in the west and the eastern seaboard from Maine to Alabama. Although the top flux is the same, lateral convergence of river and groundwater in the west kept the valleys wet, and along the east coast, the humid climate, flat terrain, and close proximity to sea level kept the water table high and soil wet. The widespread freshwater wetlands found in the coastal plains of the region are evidence that wet conditions indeed prevail.

The comparison between SMC and VIC also brings in the role of sea level in controlling land drainage. Because the water table cannot drop below sea level (except in a few internal, low-lying desert basins in the world), and because soil drainage cannot occur below the water table, wet conditions prevail in the low-lying regions of the lower Mississippi valley and the Atlantic and Gulf coastal plains. Thus, the water table provides an important link between continental drainage and sea level change. Land hydrology is driven not only by P–ET balance over the continents, but also by sea level ups and downs.

Comparison is also made with the North America Regional Reanalysis (NARR) soil moisture products using the Noah Land Community Model (Mesinger et al. 2006). NARR assimilates observed precipitation, which, from the hydrology stand, is a significant improvement over other reanalysis products. Plotted in Fig. 4 (the third row) is the 25-yr (1979–2004) monthly mean soil moisture. NARR predicts much wetter conditions in the western half of the domain, as seen in the transects. Over the eastern half of the domain, NARR is wetter in the top 10 cm, but is very similar to SMC in the top 2 m.

In understanding the spatial structure in soil moisture fields, as influenced from above by P–ET and from below by the water table, we note that NARR soil wetness has a strong resemblance to precipitation climatology. In the west, high precipitation in the mountains leads to high soil moisture, such as on the Sierra Nevada range. On the other hand, soil wetness in SMC strongly resembles the water table depth, which is shallower in the valleys. The difference caused some of the exactly opposite patterns in soil moisture. Indeed P–ET is high in the mountains, but this large surplus is likely to move laterally in steep terrain, through rivers and groundwater flow, to fill the large deficit in the valleys, as manifested by the shallow water table observations in the Central Valley (Fig. 3a).

Another apparent difference among the three is how soil wetness varies with depth. Whereas VIC and NARR show an overall drying with depth, as indicated by the domain average at two depths, SMC shows a wetting trend. One reason is that VIC and NARR climatology are obtained by 3-hourly simulations, which capture those events that wet the surface but do not penetrate deeper into the soil column; these shallow, top-wetting episodes will appear in the long-term mean. In SMC, the 50-yr mean recharge is applied, missing these surface-wetting events. Another reason is the presence of the water table in SMC, which provides a “bottom wetting” mechanism that is absent in VIC and NARR. Thus, the observed difference is likely a combination of wetting from above in VIC and NARR, and wetting from below in SMC. The question is, what does the soil moisture profile in nature look like, where both mechanisms may operate?

Intuitively, if the water table is deep and the soil is sandy, that is, beyond the capillary reach, then the top-wetting events should bear out in the climatology, and the soil should get drier with depth. An example is the Sand Hills in Nebraska, where the semiarid climate and the deep, sandy soil produce a deep water table. This drying trend is captured in VIC and NARR, but not in SMC. The same intuition suggests that if the water table is shallow and the soil is clay rich, then the bottom-wetting mechanism should emerge in the climatology. Examples are the intermountain valleys in the west and the humid valleys and coastal regions in the east. This feature is captured in SMC, but not in VIC and NARR. However, the surface-wetting events should also bear out in shallow water table environments, a feature that SMC cannot capture. It is expected that the observed soil moisture profile exhibits both mechanisms to various degrees.
degrees, depending on the event characteristics, soil texture, and water table depth.

Figure 5 plots the observed soil moisture profile in three areas with observations: Oklahoma Mesonet, Illinois, and Iowa. Observation sites are shown in the detailed maps in Fig. 2 (black dots). Details on the observations are given by either Robock et al. (2000) or at the Global Soil Moisture Data Bank (online at [http://climate.envsci.rutgers.edu/soil_moisture/](http://climate.envsci.rutgers.edu/soil_moisture/)). Regional means at different depths for Illinois and Oklahoma are obtained using an optimal averaging technique (Kalgan 1997). We note that Iowa observations might contain a dry bias because they only cover the growing season (April–October). There might also be a small dry bias in Illinois because observations are made biweekly in the growing season, but only monthly in winter.

In Oklahoma, a slight wetting trend is seen within the shallow observed depth. In Illinois, soil moisture decreases with depth near the surface, perhaps reflecting the surface-wetting events and/or root distribution, and then it increases with depth, perhaps reflecting the bottom-wetting mechanism due to the water table. In Iowa, a similar drying and then wetting trend is observed. Plotted with observations are NARR, VIC, and SMC profiles. NARR seems to capture both top- and bottom-wetting mechanisms, but the inflection point occurs at the same depth in all three regions, which may suggest that it could be linked to plant roots no deeper than the third layer in the reanalysis land model in these regions. VIC has a monotonic trend, wetting in Oklahoma and Iowa, but drying to Illinois, where the water table is the shallowest. SMC, without the top-wetting events, can only capture the wetting trend as induced by the water table.

Last, we note that over the entire domain, SMC has the largest soil water storage in the top 2 m of the land surface, followed by NARR, despite its much wetter conditions in the western half of the domain, and then by VIC, the driest of the three. Because VIC land surface flux has been constrained by observed river flow (Maurer et al. 2002), it is likely quite reasonable, but how this flux leaves the bottom of

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**Fig. 5.** Observed (black) and simulated (color) soil moisture profile averaged over record or simulation length and across observation sites or model grid cells.
the soil column can make a large difference in total column storage.

**SUMMARY AND DISCUSSION.** The goal of this article is to illustrate the link between two terrestrial reservoirs: soil moisture and groundwater. We examined the role of the water table in controlling the simulated soil moisture climatology, and, in particular, how the water table affects its large-scale spatial features and the soil water storage. Our approach was to construct the water table climatology (WTC), which reflects the long-term hydrologic balance between the land surface flux and lateral drainage. Using WTC as the lower boundary, we then simulated the soil moisture climatology (SMC) and compared to VIC and NARR products and available observations. Our findings are the following: First, SMC reflects the spatial structure of the water table depth. Second, despite an identical land surface flux, there is a large difference between SMC and VIC soil water, which is attributable to the water table in SMC. Third, whereas NARR and VIC better capture the effect of surface-wetting events, SMC better captures the bottom-wetting mechanism from a shallow water table. Last, SMC gives the largest total soil water storage, a direct consequence of the water table inclusion.

These differences in soil moisture climatology may have climatic implications. The wetter soil in the arid intermountain basins in SMC enhances evapotranspiration and subsequent precipitation in this water-limited environment (Anyah et al. 2008). The alternating wet and dry fields may enhance ET spatial contrast, affecting lateral moisture and heat transport. Higher root-zone water storage in SMC can directly enhance ET in dry seasons and stabilize the land response. Van den Hurk et al. (2005) found that most regional climate models predict a warm-season soil that is too dry and runoff that is too sensitive to atmospheric anomalies, largely due to insufficient water storage in the land in these models.

There are several important limitations in our study. We considered climatologic water balance only, which has two drawbacks. First, without the ability to capture the event-scale surface-wetting mechanism, the simulated soil profile can be too dry near the top. Second, little can be learned about the dynamic influence of the water table, such as its effect on buffering event and seasonal variability and enhancing interannual anomalies. Our next step is to perform a 3-hourly, multidecade simulation of coupled water table and soil moisture dynamics, which will allow us to examine the memory exchange between the two reservoirs. Another limitation of our study is that it does not include the effect of groundwater pumping, which can lower the water table significantly and decouple it from the soil moisture above. In addition, the lack of consideration for the permafrost in the Arctic region most likely overestimated water table and soil drainage, and underestimated the soil moisture.

Finally, we provide our results to anyone interested in using them for model initialization or intercomparison (information online at [http://envsci.rutgers.edu/~yreinfelder/SMC/README.html](http://envsci.rutgers.edu/~yreinfelder/SMC/README.html)). They include the observed water table depth as a text file, and the simulated water table depth and soil moisture fields at 14 depths as NetCDF files at 30-arc-s grid resolution. Questions regarding these files and requests for additional files should be directed to the first author.

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