Assessment of Soil Moisture Dynamics of the Nebraska Sandhills Using Long-Term Measurements and a Hydrology Model

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Abstract: Soil moisture, evapotranspiration, and other major water balance components were investigated for six Nebraska Sandhills locations during a 6 year period (1998–2004) using a hydrological model. Annual precipitation in the study period ranged from 330 to 580 mm. Soil moisture was measured continuously at 10, 25, 50, and 100 cm depth at each site. Model estimates of surface (0–30 cm), subsurface (30–91 cm), and root zone (0–122 cm) soil moisture were generally well correlated with observed soil moisture. The correlations were poorest for the surface layer, where soil moisture values fluctuated sharply, and best for the root zone as a whole. Modeled annual estimates of evapotranspiration and drainage beneath the rooting zone showed large differences between sites and between years. Despite the Sandhills' relatively homogeneous vegetation and soils, the high spatiotemporal variability of major water balance components suggest an active interaction among various hydrological processes in response to precipitation in this semiarid region.

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Introduction

Soil moisture and evapotranspiration (*ET*) are intricately linked and quantifying them either through modeling or measurement is important in understanding the processes responsible for land-atmosphere interaction (Delworth and Manabe 1988, 1989; Milly 1992; Iturbe 2000; Mahmood and Hubbard 2003). Often, soil moisture is arbitrarily prescribed in general circulation models and numerous studies report that model initialization with accurate soil wetness can improve predictions of precipitation and other atmospheric variables (e.g., Robock et al. 1998; Entin et al. 1999; Fennessy and Shukla 1999; Dirmeyer et al. 2000). Huang et al. (1996) reported that knowledge of soil moisture is needed to accurately forecast temperature. Various land surface hydrology and mesoscale models have been developed, implemented, and validated in order to improve the understanding of exchange processes between the land and the atmosphere (Anthes 1984; Mahfouf et al. 1987; Chen et al. 1996; 1997; Lohmann et al. 1998; LeMone et al. 2000; Sridhar et al. 2002).

Grasslands, in particular, are characterized by high inter- and intra-annual variability in soil moisture (e.g., Hollinger and Isard 1994). Understanding this variability may be critical when characterizing regional hydrological processes in semiarid grassland regions such as the Nebraska Sandhills. In this study, we use a well-tested hydrology model in conjunction with soil moisture observations from various sites to validate the simulation of soil moisture over the Sandhills region.

The Sandhills

The Sandhills region is the largest sand dune area in the Western Hemisphere covering about 58,000 km^2 of west-central Nebraska and a small portion of South Dakota (Fig. 1; Bleed and Flowerday 1998). The region's climate ranges from subhumid at its eastern edge (59 cm mean annual precipitation) to semiarid at its western edge (43 cm mean annual precipitation). Over 75% of this precipitation falls from April through September. Annual snowfall ranges from 55 cm in the southeast to 115 cm in the northwest. Upland dunes stabilized by native grassland comprise approximately 85% of the area, with wet interdunal valleys comprising most of the remaining area. Soil texture also varies across the landscape: upland soils are very sandy (92–98% sand in texture), whereas soils in interdunal valleys may have a higher silt and clay component. Land cover in the interdunal valleys depends on the depth-to-water table and surrounding geomorphology, and includes lakes, wetlands, naturally subirrigated meadows dominated by cool-season (C_3) grasses, tall grass prairie, and irrigated cropland. Both topography and the erodible nature of the Sandhills discourage irrigated agriculture, which comprises only 4% of the total land area. The water table under the Sandhills is considered part of the vast High Plains (Ogallalla) Aquifer (Bleed and Flowerday 1998; Gosselin et al. 1999). Considering that more than 30% of this aquifer lies under the Sandhills, groundwater recharge beneath the dunes and upland grasslands is a critical

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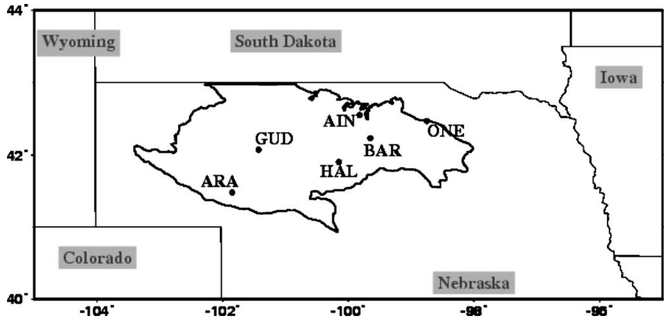

Fig. 1. Location map showing the Nebraska Sandhills boundary and six High Plains Regional Climate Center (HPRCC) Automated Weather Data Network (AWDN) sites used in this study

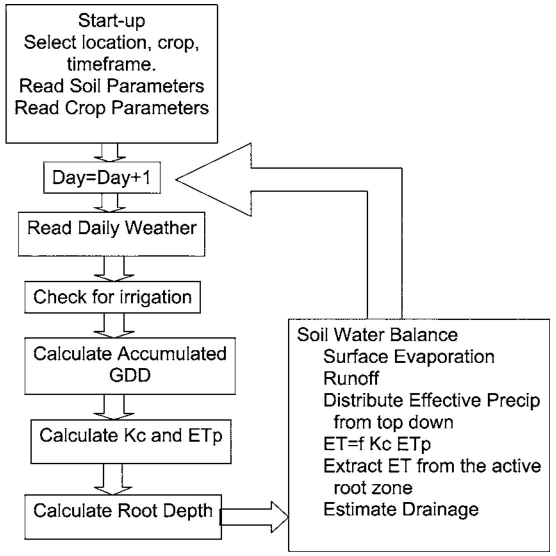

Fig. 2. Flow diagram illustrating the processes of the hydrology model

component of both local and regional hydrology.

Dune geomorphology varies considerably across the region. In some areas dunes may reach 120 m in height, stretching less than 20 km, whereas other areas are covered by extensive sand sheets with subtle (more than 30 m) topographic relief. Bare sand areas ("blowouts") are generally small (less than 2 ha) and scarce today. However, the dunes have lost their grass cover and mobilized multiple times in the recent geologic past. New research suggests that many of the dunes may have mobilized as recently as 900 years ago during a prolonged drought event (Mason et al. 2004). Root zone soil moisture presumably plays a key role in the stability, or loss, of Sandhills grasslands, because of its role in sustaining *ET* and local land surface-atmosphere interactions, as well as its impact on groundwater recharge beneath the dunes.

The objective of this study is to evaluate the hydrology model over various sites located in the Sandhills region. The hydrology model developed by Robinson and Hubbard (1990) has been extensively used for consumptive water use purposes and soil-moisture based climate analysis in the study region. This investigation will utilize relatively high resolution (spatiotemporal) weather station data for a six-year period, between 1998 and 2004 to simulate the Sandhills hydrological processes.

Weather and Soil Moisture Monitoring

The Regional Automated Weather Data Network (AWDN) operated by the High Plains Regional Climate Center (HPRCC) collects hydrometeorological data in support of region-wide soil moisture and drought research while maintaining seamless connections between HPRCC and other climate centers to disseminate climate data. There are 181 automated weather stations in a ten state region, including 60 Nebraska stations that also measure soil water variables.

Six AWDN stations fall within the Sandhills Regions and were used in this study: Ainsworth (AIN), Arapahoe (ARA), Barta (BAR), Gudmundsens (GUD), Halsey (HAL), and O'Neil (ONE). (Fig. 1). Three of these stations (ARA, BAR, HAL) are located in native, upland grassland, one (GUD) near an interdunal hay meadow, and two (AIN, ONE) in pastures dominated by nonnative grasses on the northeastern edge of the Sandhills. Typical weather variables that are measured at the site include air and soil temperature, precipitation, relative humidity, solar radiation, wind speed, and direction. Measured variables are archived in both hourly and daily formats. Soil moisture sensors are permanently buried in the rooting zone at four depths: 10, 25, 50, and 100 cm beneath the surface. In analyses of replicated 300 cm deep cores from upland Sandhills grasslands, 91% of root biomass and 96% of root length were found on average in the top 100 cm. The top 150 cm contained 94% root mass and 98% of root length (D. Wedin and N. Dobesh, unpublished data, University of Nebraska, Lincoln, 2004). Soil moisture profiles to 300 cm depth, also support the conclusion that minimal soil moisture uptake occurs for the dominant grasses beneath 150 cm (D. Wedin, unpublished data, University of Nebraska, Lincoln, 2004). For this study, we assumed the rooting zone reached a depth of 120 cm. Among the six stations, AIN, ARA, GUD, and ONE are equipped with Vitel soil moisture probes, whereas BAR and HAL use Theta probes. Both Vitel probes (Stevens Water Monitoring Systems, Inc.) and Theta probes (Dynamax, Inc.) estimate volumetric soil moisture using a low voltage signal to measure the soil's dielectric constant.

Methodology for Estimating *ET*

In this study we use the model developed by Robinson and Hubbard (1990) to simulate the hydrologic variables including *ET* and soil moisture (S) for each site. This hydrology model was tested and validated for the Sandhills region; details of the model can be found elsewhere (Robinson and Hubbard 1990; Mahmood and Hubbard 2003). A brief model description is provided in the following. The main purpose of the model is to estimate soil moisture at various depths in the plant root zone. The schematic flow diagram of the model is shown in Fig. 2. The underlying equation for the soil water balance in the model is

$$\frac{\partial S}{\partial t} = P + I - ET - R - D \tag{1}$$

where S=soil water in the root zone (mm); t=time (day); P=precipitation (mm/day); I=irrigation (mm/day); ET=actual evapotranspiration (mm/day); R=runoff (mm/day); and D=drainage below the root zone (mm/day). A 24 h time step is used with daily precipitation, and irrigation (not considered here) as inputs to the model. The Natural Resources Conservation Service, formerly known as Soil Conservation Service runoff curve

Table 1. Soil Profile and Study-Site Characteristics for the Six Sandhills Locations

Station	Latitude (deg)	Latitude (min)	Longitude (deg)	Longitude (min)	Elevation (m)	Soil 10 cm	 25 cm	 50 cm	 100 cm
Ainsworth (AIN)	42	33	99	49	765	Silt	Silt	Silt	Clay
Arapahoe (ARA)	41	29	101	51	1097	Sand	Sand	Sand	Sand
Gudmundsens (GUD)	42	4	101	26	1049	Sand	Sand	Sand	Sand
O'Neill (ONE)	42	28	98	45	625	Sand	Sand	Sand	Sand
Barta (BAR)	42	14	99	39	777	Sand	Sand	Sand	Sand
Halsey (HAL)	41	54	100	9	824	Sand	Sand	Sand	Sand

number, total precipitation, relative fraction of soil water present, and a soil water retention factor (McCuen 1982) are adopted in the model to estimate runoff. Although, the model does not simulate runoff for time intervals shorter than a day, the daily runoff estimates are relative to the soil type in the present parameterization. Campbell's equation is used in this model to calculate drainage (Campbell 1985).

The model calculates actual evaporation (E) and transpiration (T) separately and the summation of the two is ET. A modified Penman (Penman 1948) combination method of potential ET estimation is used to derive actual E and T. This modification of the Penman method incorporates a wind function developed by Kincaid and Heerman (1974). Actual evaporation is a function of potential ET and the number of days (d) as precipitation last occurred. The relationship between actual evaporation and potential ET can be expressed as follows:

$$E = ET_p(1/d)^{1/2} \tag{2}$$

where ET_p=potential evapotranspiration based on modified Penman method and d=number of days. Actual transpiration is a function of the vegetation. The ET of a particular vegetation type or crop (ET_c) is related to the reference ET through the crop coefficient (K_c). A phenology specific crop coefficient (K_c) is multiplied by ET_p and a soil water reduction factor (f). In the model, when soil moisture content approaches the wilting point, a soil water reduction factor is calculated in order to restrict transpiration. This reduction factor is a function of available soil water and water holding capacity of the soil and changes in response to the ratio of available water to potential available water. Thus, actual transpiration is as follows:

$$T = (f)(K_c)(ET_p - E) \tag{3}$$

Soil and Vegetation Parameters

The soil-related parameters in the model are the number and depth of each soil layer, water content, percent clay, sand, silt as well as bulk density and wetting length. Also, based on the established soil textures of the soil profile, we establish water content at saturation, field capacity, and wilting point to ultimately estimate the saturated hydraulic conductivity. With respect to vegetation parameters, the model requires the number of growth stages, base and upper limit temperatures for growing degree days (GDD), accumulated GDD, crop coefficient by vegetation growth stage, and maximum root depth of the vegetation. The site characteristics with the land-cover details are shown in Table 1. ARA and GUD have relatively higher elevations of approximately 1,050 m and the other sites have uniform elevation of approximately 600–800 m. The soil texture information shows that all the sites have sandy soils except AIN which has increased silt and clay in the upper 85 cm, which might explain the higher soil moisture contents usually observed at AIN. The crop coefficients and the GDD for grass are given in Table 2. We used an estimated total GDD of 2,700 which was derived based on the temperature limits. As an example, Table 3 illustrates the model soil parameters used for BAR site and the model soil profile is divided into five layers of 2.54, 27.94, 30.5, 30.5, and 30.5 cm depths. Based on the observations from the AWDN sites, we provided the initial soil moisture content for each layer in order to bring the model into equilibrium in a relatively short time for each year. The other soil-related parameters are provided as described in Table 3. The soil properties including percent clay, sand and silt, bulk density and wetness length are assumed to be uniform for the entire soil column. This assumption is valid for the Sandhills as the soil layers are sandy and quite homogeneous.

Model Implementation

The model simulations were performed at a daily time step for 1 year periods starting from April between 1998 and 2004. The April to March modeling year is chosen in order to have a saturated soil condition after snow melt and early spring precipitation and the model is reset with updated soil moisture based on the observations at the beginning of the subsequent modeling year. The model output was analyzed both daily and seasonally. The output variables are ET, runoff, drainage beneath 120 cm, and soil moisture for five layers. The upper layer of 30 cm (0–30 cm), lower layer of 61 cm (30–91 cm), and root zone layer of 122 cm (0–122 cm) soil moisture was computed subsequently by reconciling model and observation depths and compared with the observations. Note that these three soil layers discussed in the results are aggregated soil layers derived from the model-based original five soil layers.

Table 2. Crop Coefficients for Grass in the Nebraska Sandhills Region

Stage	Crop coefficient (Kc)	Group[a] I	 II	 III
Green-up	0.1	0	0	0
Regrowth	1	125	125	125
Near full cover	1	1,077.5	1,140	1,202.5
Full cover	1	2,447.7	2,600	2,752.3
Dormant	0.6	4,700	5,000	5,300

Note: Temperature limits for growing degree day estimates: Upper limit =77.0°F and lower limit =40.0°F.

[a] Growing degree day accumulation at the beginning of each growth stage for three maturity groups (I, II, and III). Group I was used for this study.

Table 3. Typical Model Soil Parameters for BAR Site Showing Five Soil Layers and Other Soil Properties

Model soil parameters						Description
5						Number of soil layers
2.54	27.94	30.5	30.5	30.5		Soil layer depth from the surface (cm)
0.12	0.11	0.12	0.10	0.14		Volumetric soil moisture (%)
1.1	0.017	259.7	23			Penman wind function constants (1 and 2), limit on daily wind run, vapor pressure deficit
0.40	150					FTRAN[a], RLIM[b]
0.20	0.70	0.10	1.49	0.05		%(Cl,Sa,Si), bulk density, wet, length
0.31	0.31	0.26	0.25	0.25	0.25	Saturated particle % for holdrege soil series
0.26	0.26	0.21	0.20	0.20	0.20	Field capacity
0.05	0.05	0.05	0.05	0.07	0.07	Wilting point

[a] FTRAN is transpiration factor and formulated as $[T/\mathrm{PET}]/[\theta-\theta_{\mathrm{wp}}/\theta_{\mathrm{whc}}-\theta_{\mathrm{wp}}]$ where T=transpiration; PET=potential evapotranspiration; θ=actual soil moisture; θ_{wp}=moisture at the wilting point; and θ_{whc}=moisture at the field capacity. A value of 0.4 indicates that *ET* is equivalent to PET above this limit.

[b] RLIM=runoff curve number.

We carried out this investigation for the period of record from AWDN stations between 1998 and 2004. As shown in Table 4, this period included both relatively dry and wet years, ideal for testing the model and evaluating the surface hydrological conditions of representative Sandhills sites.

To evaluate the performance of the hydrology model, we emphasized comparisons with observed soil moisture. Figs. 3(a), 4(a), and 5(a) show the time series comparison of soil moisture prediction for three different layers from four sites (AIN, ARA, GUD, and ONE). Figs. 3(b), 4(b), and 5(b) show similar results for BAR and HAL for 2 years, 2002 and 2003. In Fig. 6, cumulative precipitation and the model simulated cumulative *ET* are shown for the site BAR and it indicates that in the year 2002–2003, precipitation was relatively lower than it was in 2003–2004. A corresponding decrease in the annual *ET* is observable for these two years from the right-hand panel. The other simulated variables of the water budget components are discussed in later sections.

Results

Fig. 3(a) shows the 6 year comparisons of modeled and observed upper 30 cm (0–30 cm) soil moisture for four sites: AIN, ARA, GUD, and ONE. Of the sites with long term data, ARA, an upland grassland site in the southwestern Sandhills, had on average the lowest soil moisture. The model adequately predicted average soil moisture contents in the upper soil layer, but overestimated peak soil moisture events during the first 4 years of the study. These modeled soil moisture peaks attenuated within weeks, as *ET* demands for soil moisture during the growing season were high. The observed soil moisture data from the 10 and 25 cm deep sensors showed frequent fluctuations during the growing season at all sites. Annual precipitation in the region is dominated by growing season thunderstorms, which recharge upper soil horizons. However, these peaks rapidly attenuate because of high *ET* and relatively fast soil drainage. As discussed in the following, the model did a much better job estimating total rooting zone (122 cm) soil moisture, than it did capturing the short-term dynamics of the near-surface soil moisture.

The AIN site generally had the highest observed soil moisture, presumably because of the higher soil water holding capacity associated with its higher silt and clay content. The model tended to underestimate shallow soil moisture at AIN, particularly in the spring. The model also tended to underestimate shallow soil moisture at ONE. Both ONE and AIN, located in the northeastern Sandhills, tended to have higher precipitation and this region included somewhat disturbed, nonnative pasture vegetation. The GUD site occurs in a lower topographic position than the other sites, and is a hay meadow dominated by cool season grasses growing on a sandy soil profile. Periodic peaks in shallow soil moisture associated with rainfall events tended to be higher in the observed data at GUD than ARA, and were more accurately captured by the model. BAR and HAL contained only two years of observed soil moisture data (2002–2003) as shown in Fig. 3(b). As both BAR and HAL sites are located in rolling prairie with sandy soils, precipitation of less than 400 mm, and low soil water

Table 4. Annual Total Precipitation and Perspective of Drought Condition in the Sandhills in April/May (Source: Adapted from Archives of National Drought Mitigation Center, UNL)

Year	Average precipitation (mm)	Drought condition
1998–1999[a]	579	No data
1999–2000	456	Abnormally dry in the west and drought in the east
2000–2001	449	Severe drought/drought first stage
2001–2002	555	Abnormally dry in the west/normal
2002–2003[b]	331	Abnormally dry in the east and severe drought in the west
2003–2004	398	Severe to extreme drought in the west and dry/moderate drought in the east

[a] 1998–1999 was the wettest year.

[b] 2002–2003 was the driest year in the six-year study period between 1998 and 2004.

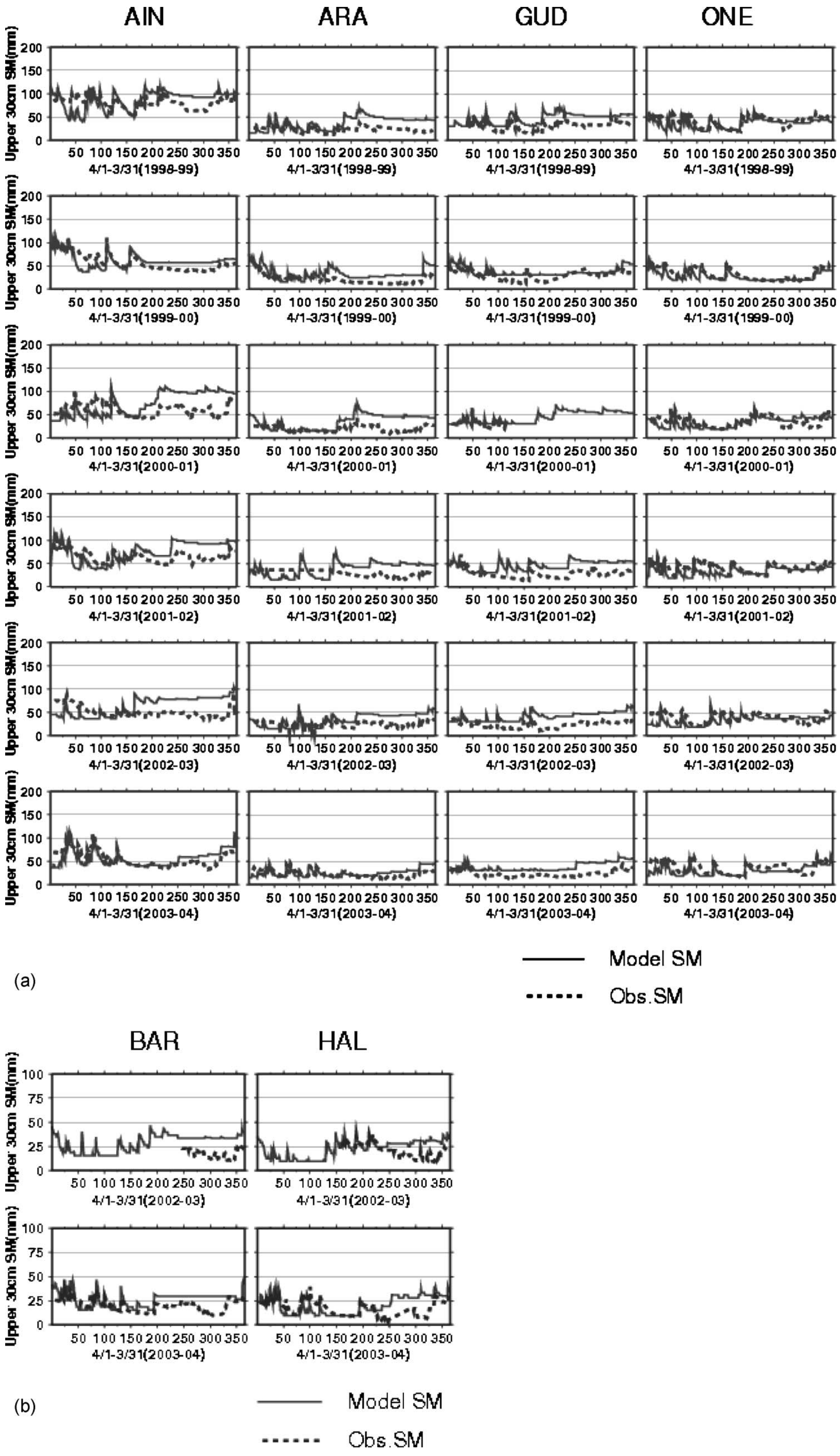

Fig. 3. Upper soil moisture (30 cm) comparisons between modeled and observed soil layers for (a) AIN, ARA, GUD, and ONE and (b) BAR and HAL sites

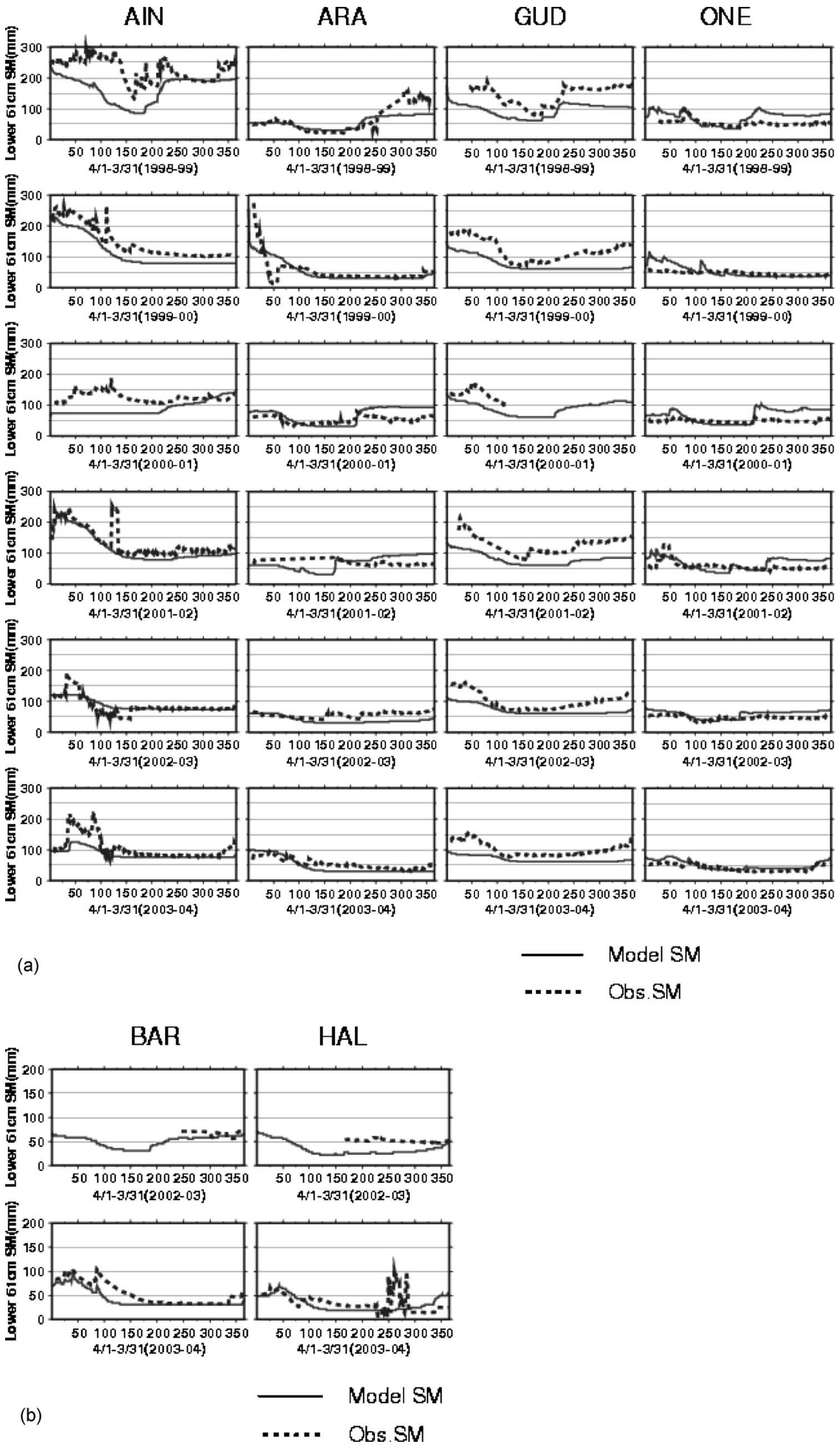

Fig. 4. Subsurface soil moisture (61 cm) comparisons between modeled and observed soil layers for (a) AIN, ARA, GUD, and ONE and (b) BAR and HAL sites

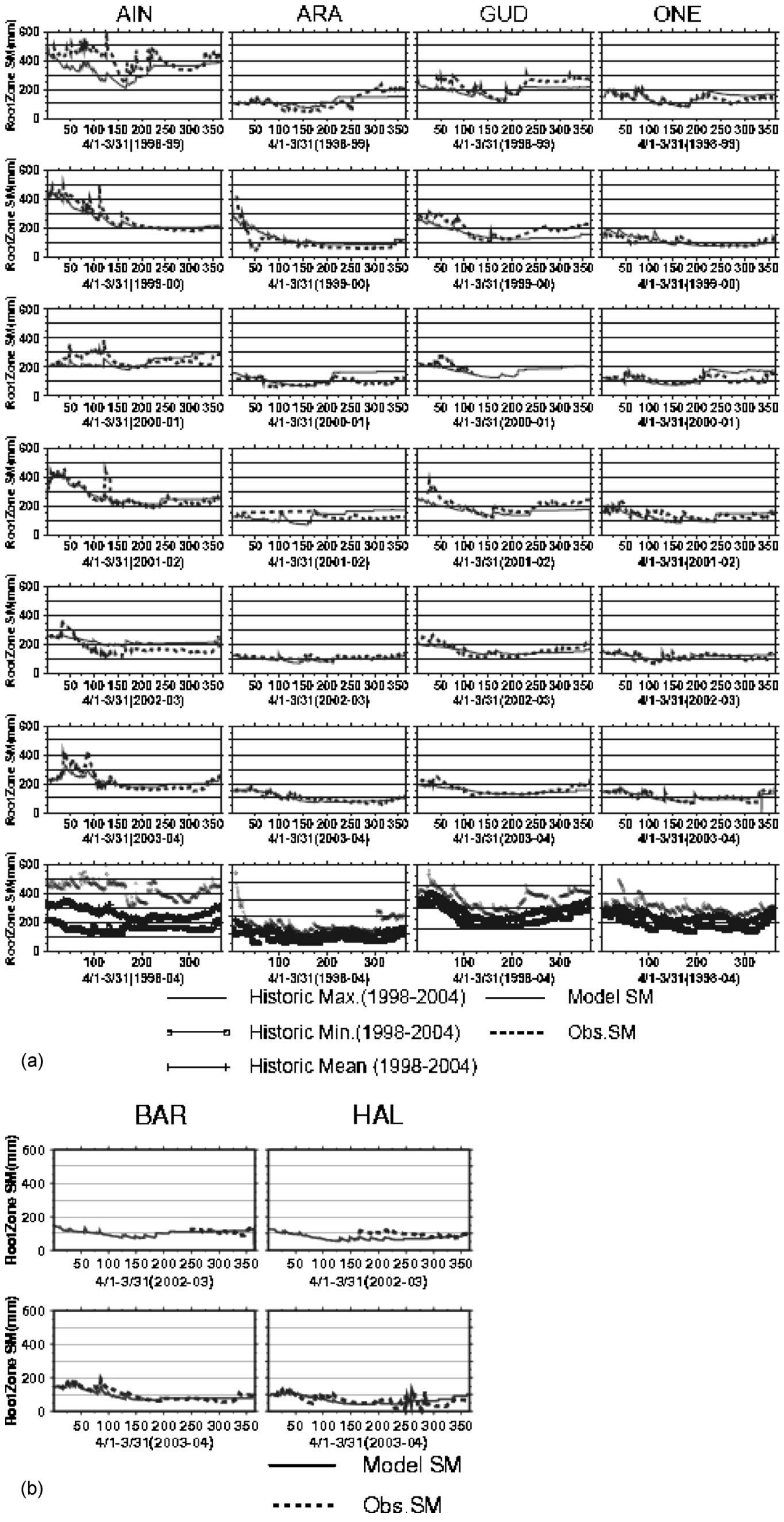

Fig. 5. Root zone soil moisture (122 cm) comparisons between modeled and observed soil layer (122 cm) for (a) AIN, ARA, GUD, and ONE and (b) BAR and HAL sites

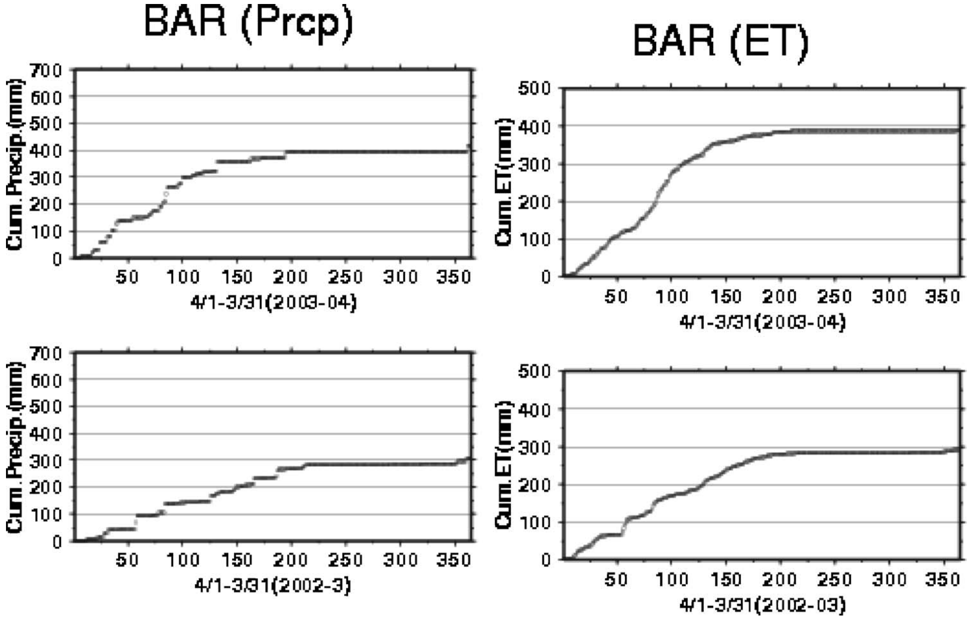

Fig. 6. Cumulative precipitation and modeled *ET* for BAR during 2002 and 2003

retention both contribute to low upper soil moisture much of the year.

Observed subsurface soil moisture showed considerably less intra- and interannual variability than the shallow soil layer. The model also generally did a better job of predicting subsurface soil moisture. The predicted soil moisture of lower 61 cm (30–91 cm) was obtained by aggregating Layer 3 and Layer 4 of the model soil profile and this was compared against the soil moisture at the corresponding depth from the observed soil profile. The 6 year comparison for ARA, GUD, and ONE, as shown in Fig. 4(a), gives a very close agreement between modeled and observed soil moisture. AIN, as was seen for shallow soil moisture, had higher observed soil moisture than the other sites, and the model tended to underestimate subsurface soil moisture at AIN, particularly in the spring. The seasonal pattern of deep soil moisture in the Sandhills is evident at the other three sites, although there is considerable interannual variability. Soil moisture is higher in April and May, decreases during the growing season, and depending on the year, it may increase again after mid-October [day 200 in Fig. 4(a)]. During the drought conditions of the last two years of the study, both spring and late fall deep soil moisture remained low at all sites except AIN. Soil moisture from lower 61 cm for BAR and HAL is higher in April–May as observed in other sites [Fig. 4(b)]. Except around day 250 both predicted and observed soil moisture storage for these two sites remained at about 50 mm for both 2002–2003 and 2003–2004.

Fig. 5(a) shows the 6 year comparisons of observed and modeled root zone (0–122 cm) soil moisture for four sites, AIN, ARA, GUD, and ONE. The correspondence of root zone layer soil moisture between observed and modeled data is distinctly superior to upper and subsurface comparisons. There are discrepancies between observed and model data in AIN for 1998–1999 and 2001–2002, in ARA for 1999–2000 and in GUD for 1998–1999. The reasons for the disagreements may include abnormal functioning of soil moisture sensor, assumptions about soil texture, initial soil moisture, and growing degree days. For instance, we assumed an AGDD of 2,700 for AIN for all years and this could vary in any particular year depending on radiation and air temperature.

The available soil moisture is generally recharged at the beginning of each growing season, April so that the soil moisture that is near the drained limit and starts slowly decreasing. However, due to brief periods of rainfall during the summer (the region's annual precipitation mostly comes from this season) the soil moisture is partially recharged, sufficient to meet the potential *ET* requirements during the mid-growing season. The senescence of the grasses starts the gradual reduction in *ET*, which is reflected in the increase of root zone soil moisture for all of the sites starting from about Day 200 (September/October).

Table 5 shows the computed statistics of Pearson correlation coefficient (r) between model-estimated and observed root zone

Table 5. Statistical Data Showing the Model's Root Zone Soil Moisture Prediction Performance for the Study Sites

	1998–1999		1999–2000		2000–2001		2001–2002		2002–2003		2003–2004	
Site	RMSE	r	RMSE	r	RMSE	r	RMSE	r	RMSE	r	RMSE	r
AIN	95.97	0.50	30.33	0.97	49.91	0.04	19.13	0.88	52.01	0.90	37.59	0.93
ARA	35.17	0.84	52.06	0.72	46.48	0.58	41.33	−0.07	14.95	0.75	15.86	0.86
BAR									13.43	0.03	17.19	0.90
GUD	46.60	0.94	51.95	0.81	35.45	0.63	48.63	0.93	27.29	0.87	23.25	0.87
HAL									45.53	−0.68	20.81	0.64
ONE	22.20	0.80	20.73	0.82	36.78	0.44	27.51	0.53	17.77	0.55	16.26	0.83

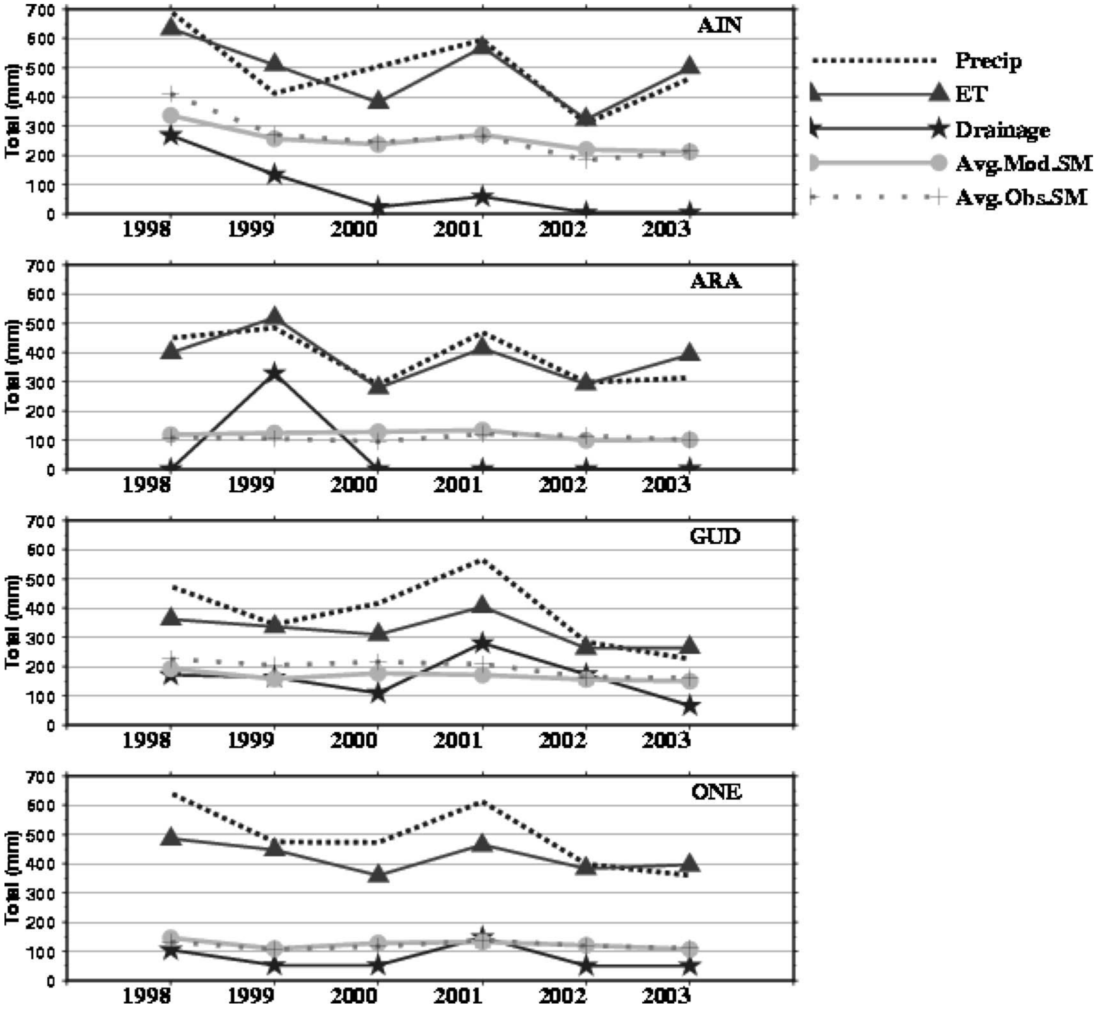

Fig. 7. Annual hydrologic budget showing total precipitation, *ET*, drainage, and average modeled and observed root zone soil moisture for AIN, ARA, GUD, and ONE during 1998–2003

soil moisture and root mean square error (RMSE). The Pearson product moment correlation coefficient, r, is

$$r=\frac{\sum (x-\bar{x})(y-\bar{y})}{\sqrt{\sum (x-\bar{x})^2 \sum (y-\bar{y})^2}}$$

where x and y=observed and modeled soil moisture and $\bar{x}$ and $\bar{y}$ are the observed and modeled soil moisture sample means.

$$\text{RMSE}=\sqrt{\frac{\left[\sum_{i=1}^{n}(P-O)^2\right]}{n}}$$

where P=predicted value; O=observed value; and n=sample size. Even though we recognized that a 6 year study period may not fully characterize regional seasonal patterns, the study captures general trends for surface hydrological processes as there are two extremes contained in this study period. For instance from Table 4, we found that 1998–1999 was the wettest year (based on precipitation alone as drought data was not available for this year) and 2002-03 was the driest year of this period and clearly the model performed well for both of these extremes in simulating root zone soil moisture. Except AIN for 1998, all other three sites showed a RMSE ranging between 22 and 46 cm with r between 0.80 and 0.97. Similarly, for 2002–2003 BAR showed a relatively low r of only 0.03 whereas all other sites ranged between 0.50 and 0.93 with the majority of the sites showing above 0.85. For 2002, BAR and HAL showed low or negative correlation coefficients, which can be attributed to the lack of variation through the season and a relatively small sample size. Also, one or more of these factors could be also directly pertinent to the negative correlation for ARA in 2001 as even the soil moisture data did not show any sensitivity to precipitation events around day 100 and 160.

Fig. 5(b) shows the results of BAR and HAL simulations starting in 2002, the year observation data became available. Also, both 2002–2003 and 2003–2004 were relatively dry as can be seen from the low root zone soil moisture. For BAR, the cumulative precipitation was about 300 and 400 mm for 2002–2003 and 2003–2004, respectively (Fig. 6). These values, although variable, are typical of the Sandhills region. Most of the precipitation was utilized by the grassland evapotranspiration, which was close to 300 and 400 mm, respectively, for 2002–2003 and 2003–2004 (Fig. 6).

Interannual Variability

Fig. 7 shows the annual total precipitation, model estimated annual totals of *ET* and drainage, and the annual averages of model and observed soil moisture for 6 years, 1998–2004. It should be noted that the Sandhills region is predominantly a precipitation-constrained region as opposed to energy-limited regions as evidenced by abundant sunshine (and hence energy) and an average annual of precipitation of 380 mm. Thus, precipitation may constrain total soil water, especially during the growing season. Mean annual precipitation total is generally between 400 and 600 mm with considerable intersite and interannual variability. For instance, AIN had high annual precipitation in 1998 followed by low precipitation in 1999 whereas ARA and ONE had relatively high precipitation in 1999. The variation in precipitation quantity is significant in terms of altering the other water budget components: *ET*, drainage, and soil moisture (Fig. 7). The estimated annual *ET* for any given year is less than or equal to precipitation, although it is possible that *ET* could exceed precipitation in some locations, given that many interdunal valleys of the Sandhills contain saturated areas and open waters. Root zone soil moisture is the third largest component of the water budget. Average annual soil moisture as estimated by the model matched observed values reasonably well.

Intersite Variability

From the analysis of six different sites in the Sandhills, it is clear that no two sites behave similarly. This is due to variations in the environmental conditions including precipitation and temperature and also variations in soil conditions such as texture and soil moisture. The latitudinal gradient in precipitation and hence soil moisture were obvious among the sites. AIN and ONE, being the northern-most sites in the region, clearly demonstrated a similarity in the amount of precipitation which was higher and ARA, being the southern-most site, presented a contrasting picture with low precipitation. Other sites showed a similar latitudinal variation in precipitation. Although AIN and ONE received almost the same amount of total annual precipitation averaged over 6 years their *ET* pattern was very different with 98 and 85% of their total annual precipitation being utilized for *ET* by the grasses. GUD has the lowest annual *ET* when compared with all other sites, the highest drainage, and reasonably high root zone soil moisture. The soil moisture is not apparently depleted by *ET* at this site.

Drainage is the smallest of the estimated water budget components. Even though AIN received the highest precipitation and showed the highest estimated *ET*, the root soil moisture remained quite high and closely agreed with the observed soil moisture. Precipitation, being the fundamental hydrologic source variable driving the hydrologic cycle, plays a critical role in modulating *ET* and soil moisture status for the Sandhills ecosystem. The hydrology model used in the study captures the soil water, plant water use, and interactions with atmosphere, despite significant differences exhibited both temporally and spatially.

Conclusions

Subsurface and surface hydrology are tightly coupled with the grassland vegetation of the Sandhills. Even though vegetation and soils are remarkably similar throughout the region, spatiotemporal variability in precipitation and topography drive considerable variability in hydrological processes. Using a hydrology model and AWDN station weather data, we performed simulations for six different Sandhills sites for the period 1998–2004. In these six years, the Sandhills region experienced both relatively wet and dry periods. The wettest year (1998–1999) and driest year (2002–2003) caused significant differences in *ET*, drainage, and soil moisture estimates. The modeled surface, subsurface, and root zone soil moisture was generally comparable to observed values. In particular, root zone (0–122 cm) soil moisture predictions were superior to those of upper and subsurface layers. Soil moisture availability is a primary factor controlling upland grasslands and hence the stability of the Sandhills landscape from wind erosion. The extraction of below root zone soil moisture was presumed to be minimal as *ET* estimated by the model never exceeded precipitation. However, our study sites were generally upland locations. In wet interdunal valleys, groundwater may significantly contribute to *ET* (Gosselin et al. 1999).

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