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Evaluating the Simulation of a Simple Hydrology Model Using Long-Term Soil Moisture Measurements in the Nebraska Sand Hills

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Abstract. *In this paper, we investigate soil moisture, evapotranspiration and other major water balance components over six sites in the Sand Hills of Nebraska during a 6-year period (1998-2003) using a hydrological model. We simulate water budget components including root zone soil moisture and found that model predictions of soil moisture compare reasonably well with observations for these sites. In the precipitation-limited Sand Hills, a moderate change in precipitation pattern from year to year is found to have profound effects on the fast response components of the hydrological cycle. Despite the homogeneity in terms of soil (sandy) and vegetation (grass), both the spatial and temporal variability in the estimated soil moisture, evapotranspiration, runoff and drainage suggests an active interaction among various hydrological processes in response to precipitation over this semi-arid region.*

Keywords. *Soil Moisture, Water Balance, modeling, Nebraska Sand Hills*

Introduction

Soil moisture and evapotranspiration are intricately linked and quantifying them either through modeling or measurement is important to understanding the processes responsible for land-atmosphere interaction (Mahmood and Hubbard, 2003; Milly, 1992; Iturbe, 2000). Many times, soil moisture is arbitrarily prescribed in general circulation models (GCM) and numerous studies (e.g., Fennessy and Shukla, 1998; Dirmeyer, 1999) found that model initialization with accurate soil wetness has potential to improve predictions of precipitation and other atmospheric variables. The seasonal variation of environment in grassland areas can be significant as opposed to non-grassland areas (e.g. Hollinger and Isard, 1994). Huang et al., (1996) reported that knowledge on 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 the exchange processes between the land and the atmosphere (e.g., Anthes, 1984; Chen et al., 1997; Sridhar et al., 2002). The Sand Hills of Nebraska is predominantly covered by grasslands and the seasonal variation of soil moisture is therefore a crucial element to quantify in order to characterize the regional hydrological processes. Thus, by encompassing the science issues raised above, 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 Sand Hills region. This is aimed at understanding the linkages between soil water characteristics and the water budget but, is also beneficial to our long-term plan of studying the vulnerability of the Sand Hills to extreme conditions.

The Sand Hills

The Sand Hills region is the largest sand dune area in the Western Hemisphere and it covers about 58,000 km^2 of sand dunes stretching 424 km across north-central Nebraska and south central South Dakota. As seen in Figure 1, most of this Sand Hills ecoregion lies within the State of Nebraska. The sand dunes and sandy soils of this region have a unique distinction by supporting a fragile and vulnerable grassland prairie ecosystem above them. The dunes are typically 122 m high and 32 km long and have steep slopes of even up to 25 percent. These sand dunes were supposedly barren (without any grass) as late as 900 years ago and were exposed to vulnerability such as destabilization and the resulting movement would today be a serious potential economic loss to the inhabitants of the region. The Sand Hills have sharp contrasts in their topography and thus differ in their hydrological characteristics. It is quite common not only to encounter dry and wet regions adjacent to each other, but also to observe a simple and homogeneous landscape which is the most complex and abundantly varied desert ecosystem in the western Hemisphere region with species from adjacent areas to the east, north and south. (Bleed and Flowerday, 1998). There are numerous lakes and wetlands in the western part of the Sand Hills and they are critical for the wildlife habitat in the region including swans, duck and grebes. While the eastern Sand Hills region receives an annual average rainfall of 58.4 cm, the western edge receives only an average of 43 cm. The variability in soil texture, although minimal, is present in the Sand Hills and in general, the region dominantly contains sandy soil. 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 (spatio-temporal) weather station data for a six-year period, between 1998 and 2004 to simulate the Sand Hills hydrological processes. This is expected to aid our understanding of the variability in the land surface processes, in particular, when this investigation will be extended to a regional level study focusing on the interaction between the Sand Hills and the atmosphere. The location map of the Sand Hills Region and the sites considered for this study are shown in Figure 1. The Regional Automated Weather Data Network (AWDN) stations used in this study are spread across the entire Sand Hills region evenly and they are: Ainsworth (AIN), Arapahoe (ARA), Barta (BAR), Gudmundsens (GUD), Halsey (HAL) and O'Neil (ONE).

Methodology for estimating ET

In this study we use the model developed by Robinson and Hubbard (1990) to simulate the hydrologic variables including evapotranspiration (ET) and soil moisture (S) for each site. This hydrology model was tested and validated for the Sand Hills region and the details of the model can be found elsewhere (Robinson and Hubbard, 1990; Mahmood and Hubbard, 2003). However, we provide some brief model description below. The main purpose of the model is to estimate the soil moisture storage at various depths in the plant root zone. The underlying equation for the soil water balance in the model is

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

where S is soil water in the root zone (mm), t is time, P is precipitation (mm), I is irrigation (mm), ET is actual evapotranspiration (mm), R is runoff and D is drainage below the root zone. A 24-hour time step is used with daily precipitation, and irrigation (if applied) as inputs to the model. Runoff is estimated from total precipitation, relative fraction of soil water present, and soil water retention factor (McCuen, 1982). 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 is performed by including a wind function developed by Kincaid and Heermann (1974). Actual evaporation is a function of potential ET and the number of days (d) since the last precipitation occurred. The relationship between actual evaporation and potential ET can be expressed as follows:

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

where, ET_p is potential evapotranspiration based on modified Penman method. Actual transpiration is a function of the crop in that 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 falls below 50 percent by volume, a soil water reduction factor is calculated in order to restrict crop-water use. 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:

$$T = (f)(K_c)(ET_p - E) \qquad (3)$$

Model implementation

The model simulations were performed at a daily time step for one year periods starting from April-March between 1998 and 2003. The crop 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 years of simulation available from either Vitel or Theta probes. The model output was analyzed at both daily and seasonal scales. The output variables are ET, runoff, drainage and soil moisture for four layers. The root zone (120 cm) soil moisture was computed subsequently by reconciling model and observation depths and compared with the observations. This period included both relatively dry and wet years and we found this is ideal to test the model and evaluate the surface hydrological conditions of the sites that represent the Sand Hills region. In order to verify the performance of the hydrology model, we had considered soil moisture as the only variable to compare with the observations.

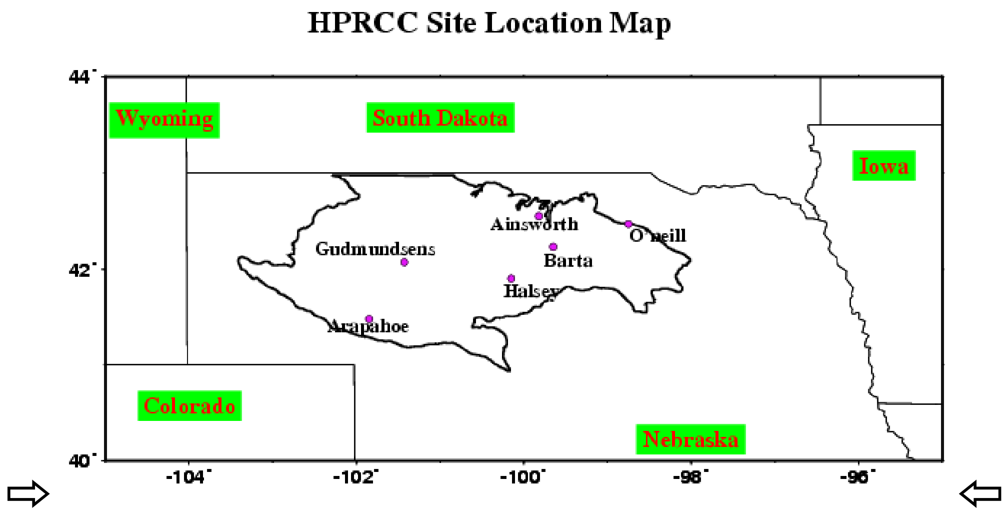

Figure 1. Location map showing the Nebraska Sand Hills boundary and six AWDN sites

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Results and Discussion

Figure 2 shows the six-year soil moisture comparisons for four sites, AIN, ARA, GUD and ONE. The modeled soil moisture is compared against the observed root zone soil moisture (approximately 120 cm depth). In general, good agreement can be seen between observed and model simulated soil water from Figure 2. There are some minor discrepancies seen in AIN for 1998-99 and 2001-02, in ARA for 1999-00 and in GUD for 1998-99. The reasons for the disagreements are due to abnormal functioning of soil moisture sensor thus creating a sudden spike or drop in the observations, assumptions about soil texture, initial soil moisture and growing degree days. For instance, we assumed an AGDD of 2700 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 crop growing season, April so that the soil moisture that is near the drained limit 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).

From the analysis of six different sites in the Sand Hills, 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 and for the other sites we found similar latitudinal variation in precipitation. While AIN and ONE received almost the same amount of total annual precipitation averaged over six years which is also the highest among other sites, their ET pattern was very different with 98% and 85% of their total annual precipitation being utilized for ET by the vegetation. GUD has the lowest annual ET when compared with all other sites. But notice that it has the highest drainage and reasonably high root zone soil moisture. The soil moisture is not apparently depleted by ET at this site.

The drainage is the smallest component of the estimated water budget components. Even though AIN received the highest precipitation and showed highest estimated ET, the root soil moisture remained quite high and closely agreed with the observed soil moisture. The precipitation regime varies from year to year so much that there are no two successive years that have the same amount of rain for any site that is studied. Precipitation, being the fundamental hydrologic source variable driving the hydrologic cycle, plays a critical role in modulating ET and soil moisture status for the Sand Hills ecosystem. The hydrology model used in the study captures the soil water, plant water use and interactions with atmosphere, despite significant differences exhibited both annually and geographically.

Summary and Conclusion

The Sand Hills of Nebraska is a vibrant ecosystem where sub-surface, surface hydrology strongly interacts with the vegetation above ground. The precipitation pattern and the Sand Hills topography dominate the variations in hydrological processes. The soil moisture status in the Sand Hills, is primarily a controlling factor for the upland grasslands and hence the stability of the Sand dunes from wind erosion. However, the grass cover is not solely dependent on precipitation as a source. The extraction of below root zone soil moisture was presumed to be very limited as the ET estimated by the model never exceeded the precipitation. The interannual and inter-site variability for the simulated hydrological variables were found to be significant. Even though there can be homogeneity in terms of soil (sandy) and vegetation (grass), their role in altering the ET, runoff and drainage is quite remarkable.

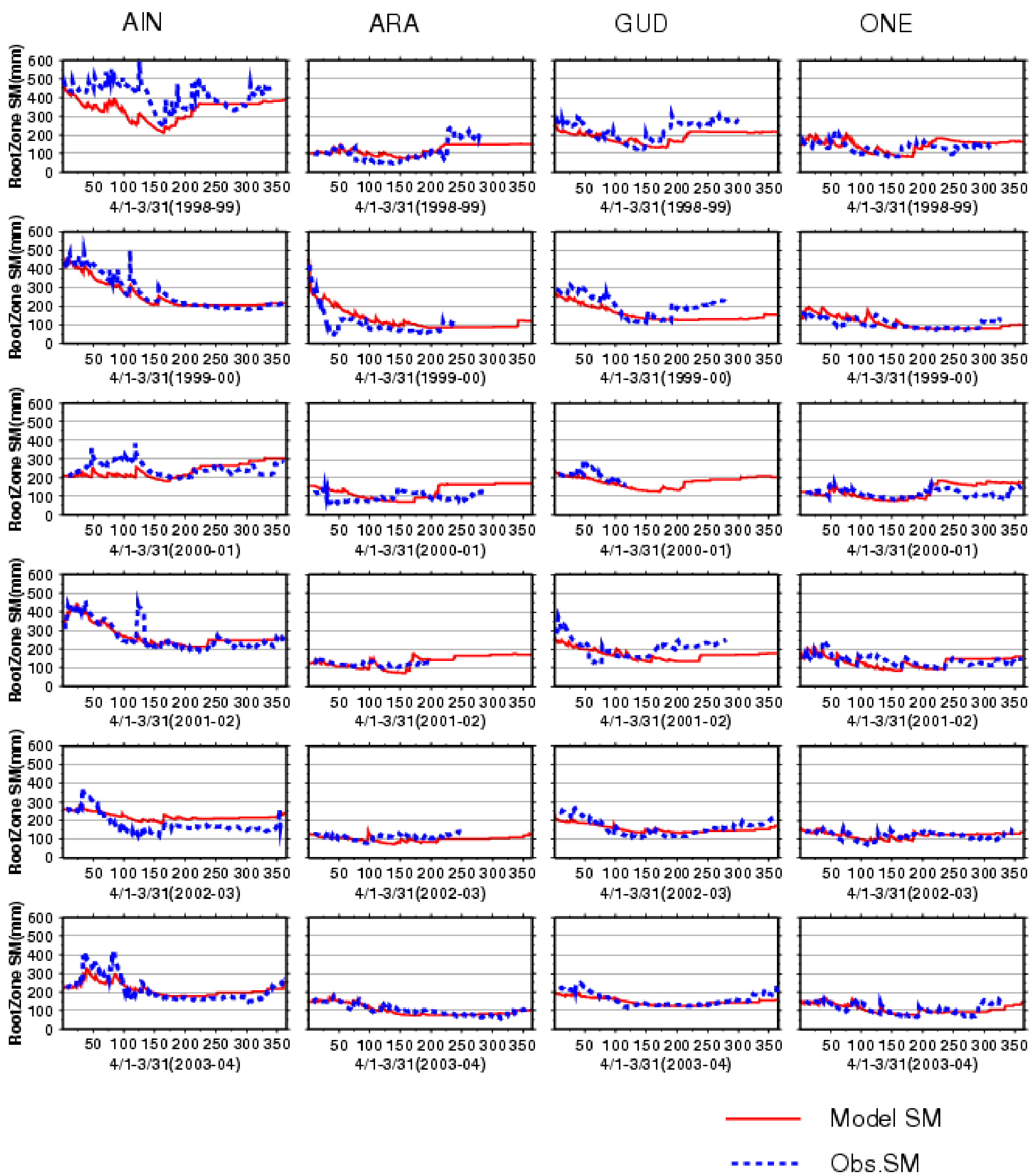

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Figure 2. Root zone soil moisture comparisons between modeled and observed soil layer (122 cm) for AIN, ARA, GUD and ONE site

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