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MODELING MULTIYEAR SURFACE EVAPOTRANSPIRATION WITH REMOTE SENSING DATA

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1. INTRODUCTION

Key issues in meteorology, climatology, and resource management deal with water in its various forms in the global water cycle. To address the water cycle, the U.S. Department of Energy initiated a three-year pilot study at the Walnut River Watershed (WRW), which encompasses an area of about 5000 km^2 in southeastern Kansas. Work at Argonne National Laboratory, one of the five primary participants in the pilot study, includes simulation of evaporation and soil moisture content in the WRW with the Parameterized Subgrid-scale Surface (PASS) model. Recent studies with PASS, focusing on short-term simulations of land surface processes during intensive field campaigns and evaluation with field observations, have led to a better understanding of, and improvements in, simulations of the land surface processes (e.g., Song et al. 2000a, 2000b). Short-term field experiments, however, typically concentrate on the summer growing season and selected environmental conditions. Surface models that are verified with data obtained from intensive experiments might not perform as well in other seasons and during prolonged drought or wet conditions. One goal for long-term surface modeling of hydrological components at regional scales and/or a grid scale suitable for high-resolution global climate models is that seasonal variations in surface parameters are accurately described, even when the surface is spatially very heterogeneous. Another goal is that the subgrid-scale variability of precipitation, soil moisture, and vegetation are resolved to the extent that biases are not introduced by the scheme of aggregating to computationally manageable grid cell sizes. To address these goals and to aid in the study of the interannual variability of key surface hydrological components, research continues on the ability of the PASS model to simulate evapotranspiration. This paper focuses on modeling over the five-year period of 1996-2000 at the WRW. Weaknesses in the results are examined, with the purpose of improving model parameterizations.

The PASS model is observationally driven and makes use of extensive parameterizations of surface properties and processes (Gao 1995; Gao et al. 1998). One advantage of the PASS model in comparison with other land surface models is that it is computationally efficient for simulations over extended areas and periods of time. The PASS model uses routine, spatially sparse surface meteorological data and satellite remote sensing data to calculate surface evapotranspiration rates over extended areas. Heterogeneities in surface conditions are spatially resolved to an extent determined primarily by the satellite data pixel size. In this study, input data from satellites, radars, and meteorological stations were continually updated to apply the PASS model over the five-year period.

2. OBSERVATIONAL DATA

2.1 Satellite Data

Simulations of evapotranspiration require descriptions of the spatial and temporal variations in surface vegetative conditions, especially those affecting bulk canopy stomatal conductance. Satellite remote sensing data can provide portions of the detailed information needed to drive some of the surface model parameterizations used to describe the surface conditions. In particular, the normalized difference vegetation index (NDVI) derived from radiometers on environmental satellites is a commonly used measure of surface greenness and associated surface properties. This study used biweekly composite 1-km-resolution NDVI values processed by the U.S. Geological Survey (USGS); the values of NDVI had been adjusted with improved methods for compensating for atmospheric effects to produce estimates of surface NDVI values (DeFelice et al. 2002). Figure 1 shows an example, derived from one biweekly composite data set, of the summertime spatial variation of NDVI at the WRW. Associated work (unpublished) has shown that NDVI values derived from satellite data agreed well, on average over the course of a growing season, with occasional measurements made with a hand-held radiometer at the surface of the Whitewater site (Fig. 1). The spatial variability in NDVI, however, is large and occurs on spatial scales that are smaller than 1 km in the agricultural area encompassing the Whitewater hayfield site.

Long-term simulation of surface evapotranspiration requires continuous data on surface conditions, which can be supplied in the form of the biweekly composite

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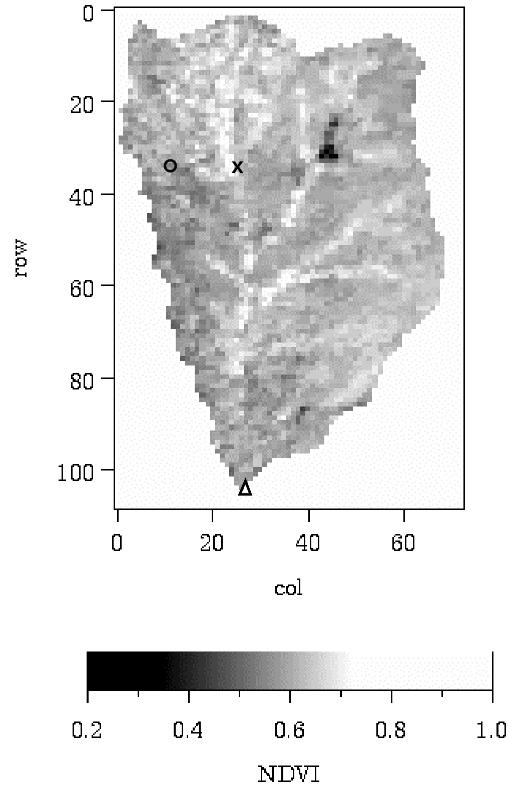

FIG. 1. Spatial distribution of NDVI in the WRW during the biweekly period of days 211-224 of year 2000. The circle indicates the surface flux measurement site south of the town of Whitewater, KS; the "X" shows the location of the ARM Program extended facility near Towanda, KS; and the triangle indicates the location of a stream gauge station operated by the USGS on the Walnut River near Winfield, KS.

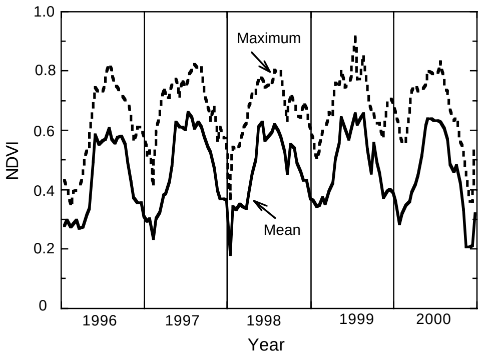

FIG. 2. Biweekly composite NDVI data averaged arithmetically over the entire WRW and the maximum values for each biweekly scene, for the five years of the present study.

NDVI data. Figure 2 shows the variations in NDVI for the WRW over the five-year period. As expected, the NDVI values in each year are smallest in the winter, increase rapidly in the spring, and decrease in the autumn. The maximum NDVI values in Fig. 2 indicate a broader growing season than do the mean values for some of the years, most likely because of the diversity of vegetation in the area.

2.2 Surface Data

Data on solar irradiance, air temperature, relative humidity, and wind speed were obtained as 30-min averages from surface stations operated by DOE's Atmospheric Radiation Measurement (ARM) Program and facilities operated by Argonne National Laboratory in the WRW. The five-year data set was constructed mostly from observations at the Whitewater site and the ARM extended facility near Towanda, KS (Fig. 1). Occasional gaps in the observational data were filled with data from nearby ARM extended facilities or by simple interpolation or rough extrapolation using data on days with similar environmental conditions. These meteorological measurements were treated as the regional-scale parameter estimates needed in the PASS model; values were assigned to each pixel according to the PASS distribution functions.

Data on surface precipitation in the WRW consisted of 4-km-resolution data based on Nexrad data that had been adjusted with rain gauge observations and supplied by the Arkansas-Red Basin River Forecast Center.

Daily discharge data at a stream gauge on the outlet of the WRW near Winfield, KS (Fig. 1), were obtained from the USGS. The discharge data do not constitute inputs to PASS modeling but can be compared to runoff estimates. In PASS, runoff estimates were found as a residual term in the water balance. Irrigation and industrial use of surface water in the WRW has been negligible compared to the other terms in the water balance, according to water use data provided by the Kansas Department of Agriculture's Division of Water Resources.

Estimates from PASS of surface energy fluxes (net radiation, latent heat, sensible heat, and ground heat) can be checked with measurements made with an energy balance Bowen ratio station in operation at the Whitewater site since the middle of 1999. Volumetric soil moisture in the surface layer (at depth of 0-5) cm was also measured at the Whitewater site.

3. RESULTS OF SURFACE HYDROLOGICAL MODELING

3.1 Comparison with Stream Gauge Measurement

The PASS model was applied for continuous simulation of evapotranspiration in the WRW from the

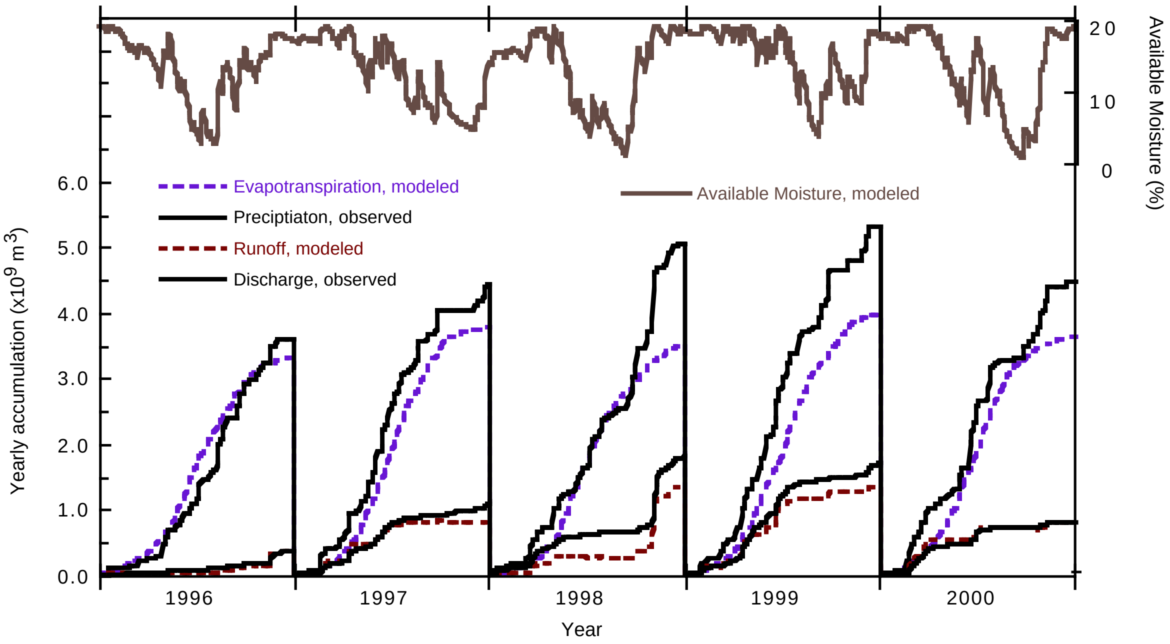

FIG. 3. Modeled and observed yearly accumulative values of surface hydrological components at the WRW and modeled root-zone available moisture during 1996-2000.

beginning of 1996 to the end of 2000, with data input from the sources noted above on NDVI from satellite observations, radar-based surface precipitation estimates, and observations from conventional surface meteorological stations. The initial value of the root-zone available moisture (RAM) for all pixels was assumed to be the maximum value allowed, specifically, the available moisture capacity for the dominant soil type in each pixel area. Surface runoff was assumed to occur when the PASS estimate of RAM exceeded the available moisture capacity. This water excess was assumed to be lost from the soil layers contributing to evapotranspiration, but the additions to local stream flow and groundwater recharge were not estimated as they would have been in a more complex hydrology model. The total runoff from the WRW could be estimated as the difference between precipitation and evapotranspiration, which is a reasonable approach if the root-zone storage of water (RAM) for the entire WRW is the same at the end of the computational period as it was at the beginning and water losses though the bedrock were negligible. Also, the amount of time for the water balance computations should be sufficiently long to relegate changes in soil and groundwater storage to small contributions relative to the precipitation and evaporation components of the water budget. Figure 3 shows the result of calculating runoff as sum of the water excessfor all pixels, relative to the discharge measured at the Winfield stream gauge station. The average RAM calculated for the WRW is lowest in the late summer, when rainfall is limited and evaporative demand is high, and is highest in the winter. Except for the transition between 1997 and 1998, the soil moisture storage appears to be consistently at very large values at the end of the yearly computational periods.

Over the five-year period addressed in Fig. 3, the modeled water loss from evapotranspiration accounts for 70%-90% of precipitation at the end of each year, percentages that are reasonable for southern Kansas. The differences between the observed discharge and modeled runoff are less than 25% and seem to depend on the precipitation amount and distributions. For example, the differences are smaller for 1996 and 2000, when precipitation was spread evenly across the year, than for 1998 and 1999, when large precipitation events occurred rather late in the year. Relatively large evapotranspiration rates beginning in the summer of 1997 led to the lower RAM at the end of the year, and the resulting deficit in the soil moisture in early 1998 led to reduced runoff until a large precipitation event occurred in October. Rather large evapotranspiration rates were also simulated for the summer of 1999, mostly driven by high precipitation rates that increased RAM. Overall, the modeled runoff is less than or equal to observed discharge amounts, which suggests that that modeled evapotranspiration estimates might be too large.

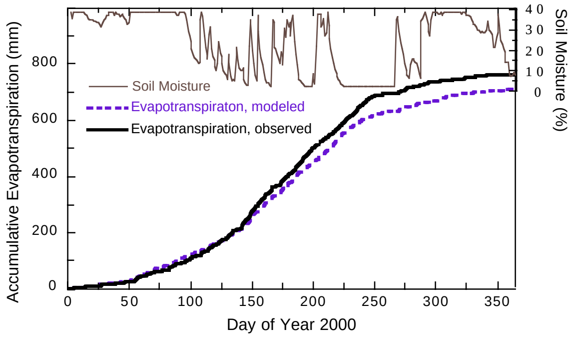

FIG. 4. Modeled and observed accumulative evapotranspiration and measured volumetric moisture content for the soil layer between the surface and a depth of 5 cm at the Whitewater hayfield site in year 2000. For soil moisture, analysis routines artificially limited the range from about 5% to 40%.

3.2 Comparison with *In Situ* Observation

Figure 4 shows modeled and measured accumulative evapotranspiration for year 2000 and the volumetric moisture content measured in the top 5 cm of soil. Evapotranspiration is slightly overestimated, by about 7%, at the Whitewater site, which suggests that parameters used to describe root-zone depth and canopy stomatal conductance might need to be improved. Additional comparison of latent heat fluxes during three 10-day periods in different seasons of year 2000 is shown in Fig. 5. Overestimation by the model occurred for the spring days 103-112, when modeled RAM was moderately high, while the observed near-surface moisture decreased rapidly. Comparisons between modeled versus observed net radiation and ground heat fluxes indicated reliable simulations except for some periods at night when cloudy conditions increased the net radiation considerably above the values modeled for clear-sky conditions.

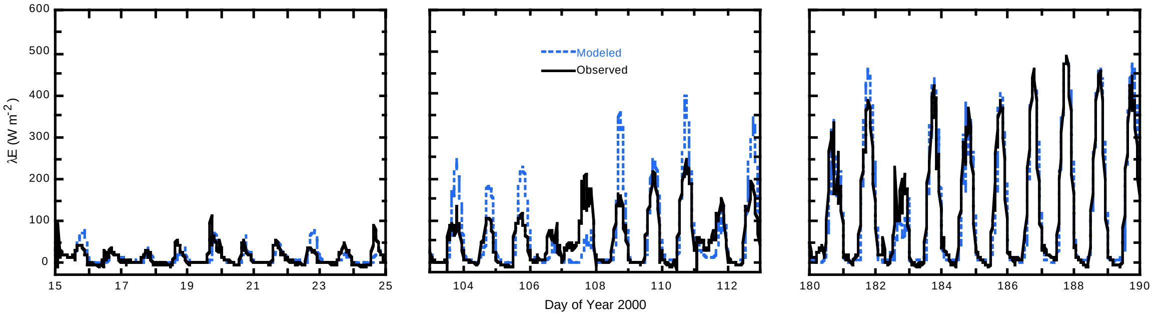

FIG. 5. Modeled and observed latent heat fluxes at the Whitewater site during three 10-day periods in year 2000, for winter (left), spring (center), and summer (right).

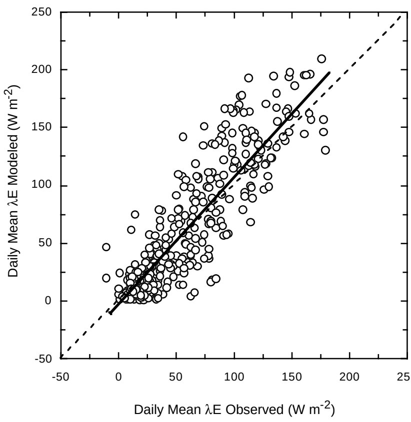

FIG. 6. Comparison of modeled versus observed daily mean latent heat fluxes in year 2000 at the Whitewater site. The solid line represents a linear regression fit.

To allow examination of some of the details of evapotranspiration simulation for 2000, modeled daily means of latent heat fluxes are plotted in Fig. 6 versus the observations made at Whitewater site for year 2000. While the variations appear to be well captured, the best-fit line is slightly steeper than the 1:1 line, indicating some overestimation by the model.

In Fig. 7, the modeled total evaporative water loss and runoff at each 1-km pixel within the WRW during 1996-2000 are presented together with cumulative radar-based precipitation amounts for each 4-km pixel. Large spatial variation exists in all three hydrological components, even for these five-year total accumulated values. The pattern of higher evapotranspiration corresponds to higher-precipitation pixels except in the southern part of the WRW, where an east-west belt of higher precipitation corresponds to higher runoff. Several strong precipitation events had occurred along this east-west belt in the southern WRW. On average, evaporative water loss accounts for nearly 80% of precipitation, and runoff accounts for 20%.

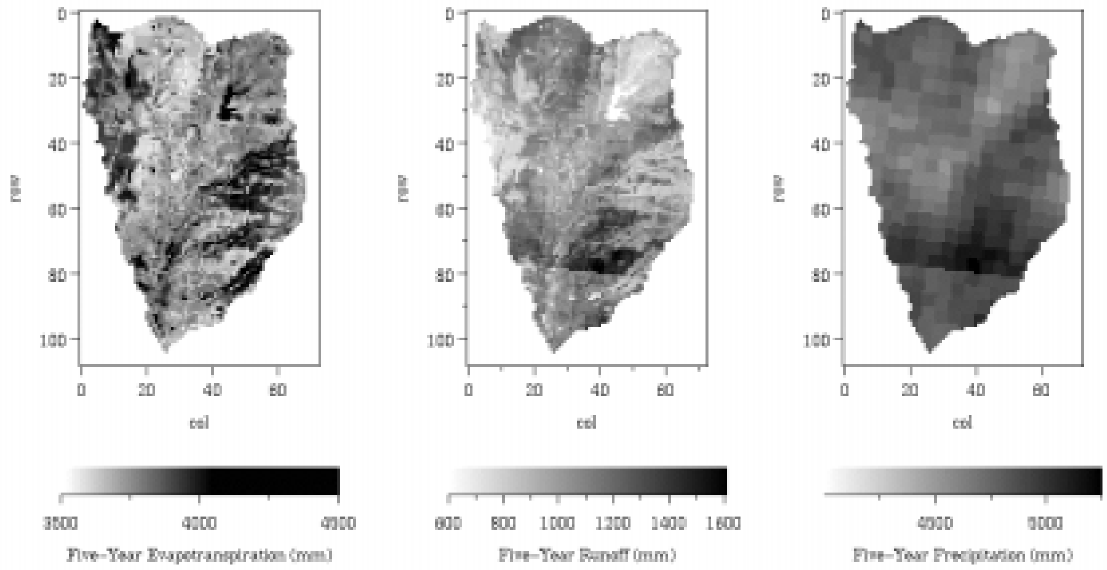

FIG. 7. Total modeled evapotranspiration (left), total modeled runoff (center), and observed precipitation (right) for the WRW during 1996-2000.

4. SUMMARY AND CONCLUSION

Estimates of the evaporative water loss from the WRW were made with the PASS model and applied in an evaluation of hydrological balance components for 1996-2000. The satellite remote sensing data were used to describe the surface vegetative conditions with biweekly, composite, 1-km-resolution NDVI data products. The 4-km-resolution, radar-based estimates of precipitation constituted a major input for the simulations. Surface radiation and basic meteorological data provided the driving force for the modeled evapotranspiration. Preliminary results indicate that accumulative surface evapotranspiration was slightly overestimated, which resulted in underestimates of cumulative runoff within the WRW as compared to observed discharge amounts at the outlet of the WRW; the maximum yearly underestimate was 25%, in year 1998. Diurnal and seasonal changes in modeled evapotranspiration in year 2000 matched fairly well with the *in situ* flux measurements; slight overestimates during certain periods resulted in the model estimates of cumulative evaporative water loss being about 7% larger than the discharge amount by the end of year. These results suggest that a highly parameterized but relatively simple surface model like the PASS model can be exercised efficiently to estimate the long-term surface hydrological components reasonably well. Work continues on selection of proper root-zone depths for various types of vegetation and parameterizations of stomata conductance.

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