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Application of multiscale water and energy balance models on a tallgrass prairie

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Abstract. The models presented in the previous paper (Famiglietti and Wood, this issue) are applied at their appropriate scales for evapotranspiration modeling at the First International Satellite Land Surface Climatology Project Field Experiment (FIFE) site. The local soil-vegetation-atmospheric transfer scheme is applied at five flux measurement stations in the northwest quadrant of the FIFE site. Simulations were performed for three of the four FIFE "golden (cloud-free) days" with good results. The spatially distributed model was applied at the 11.7-km² King's Creek catchment. also located in the northwest quadrant of the FIFE site, during FIFE Intensive Field Campaigns (IFCs) 1-4. Simulated catchment average evapotranspiration was compared to an average of observations made at the five aforementioned measurement stations with good results. The macroscale formulation was applied to both the King's Creek catchment and the entire 15-km FIFE site for evapotranspiration simulations. Macroscale model simulations for King's Creek were nearly identical to the spatially distributed results, implying that at this location and at this scale, the assumptions invoked in the development of the macroscale formulation are reasonable. The macroscale model was also employed to simulate evapotranspiration from the entire 15-km site for the four golden days. Simulated evapotranspiration rates show reasonably good agreement with the 22-station average of observations. However, it is suggested that at 15-km and larger scales, simulation error may arise as a result of the macroscale assumptions of areally averaged atmospheric forcing, vegetation parameters, soil parameters, and the methods by which these data and other flux observations are aggregated. A methodology to combat these problems at larger scales is reviewed.

1. Introduction

This paper presents the application component of a body of research which addresses aggregation and scaling issues in multiscale hydrological modeling. In the first paper [Famiglietti and Wood, this issue], a methodology was proposed to aggregate local process physics across scales. A spatially distributed modeling framework was proposed for use at the catchment scale, and at the macroscale, a statistical-dynamical framework was presented. The macroscale formulation is intended for use as a land parameterization in regional and global atmospheric models. The purpose of this study is to apply the models of the previous paper [Famiglietti and Wood, this issue] on a temperate grassland at their appropriate scales. A second goal of this work is to investigate some of the simplifying assumptions utilized in the development of the macroscale formulation using observed field data.

The site of these applications is the tallgrass prairie of eastern Kansas (United States). The area includes rolling hills and shallow soils, with roughly 50 m of elevation from

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stream bottoms to ridge tops, and is representative of the strip of native tallgrass prairie, 50-80 km wide, that extends from Kansas to Nebraska to Oklahoma. In the summers of 1987 and 1989, the First International Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) was conducted on a 15×15 km region of tallgrass prairie located near Manhattan, Kansas. FIFE was a large-scale field experiment whose purpose was to develop relationships between satellite measurements and hydrologic, climatic, and biophysical variables at the land surface [Sellers et al., 1992]. A second goal of the experiment was to collect ground-based data to validate these relationships, and to validate simulation models of land surface processes from the point scale to scales compatible with remotely sensed observations. During the summers of 1987 and 1989, multiscale ground-based and remotely sensed water and energy balance data were collected simultaneously. Thus the FIFE data set affords unique opportunities to observe the scaling behavior of hydrological processes and to test modeling strategies over a range of spatial scales.

In this paper, the local soil-vegetation-atmosphere transfer scheme (SVATS) is applied to model evapotranspiration at five flux measurement stations (stations 2, 8, 10, 12, and 14) in the northwest quadrant of the FIFE site (see Figure 1).



Figure 1. FIFE site showing approximate locations of King's Creek catchment (shaded area), flux measurement stations, and meteorological stations. Portable automated mesonet meteorological stations are abbreviated PAM. U.S. Army Corps of Engineers Data Control Platform meteorological stations are abbreviated DCP.

When possible, local meteorological data, soil parameters, and vegetation parameters are employed in the simulations. Next, the spatially distributed model is applied at the King's Creek catchment, an 11.7-km² watershed also located in the northwest quadrant of the FIFE site. Modeled evapotranspiration is compared to the average of observations at stations 2, 8, 10, 12, and 14. Spatially distributed fields of model inputs and parameters are utilized in the simulations when available. Streamflow was a negligible component of the catchment scale water balance, and although modeled, [see Famiglietti, 1992] is not reported on here. Validation of model simulated spatial soil moisture patterns is best accomplished by comparison to remotely sensed observations and is the subject of past and current research [e.g., Famiglietti and Wood, 1991; Wood et al., 1993; Lin et al., 1994]. The simulations at the King's Creek catchment are then repeated with the macroscale formulation. Although the macroscale formulation is intended for use at larger scales (O(100-10,000 km²)), comparison of the spatially distributed and macroscale model simulations should provide insight into the restrictiveness of the assumptions invoked in the macroscale model development, albeit at a relatively small scale. These include assumptions of areally averaged atmospheric forcing, soil parameters, vegetation parameters, and a statistical representation of spatial variability in the topographic-soil index, soil moisture, and the water and energy fluxes.

The scaling behavior of the various hydrologic fluxes over larger spatial regions and in different climatic regimes is the subject of ongoing research. Finally, the macroscale formulation is used to model evapotranspiration from the entire 225-km² FIFE site. Modeled evapotranspiration is compared to the 22-station average of observations made on the four "golden (cloud-free) days" during the summer of 1987.

2. Application to a Tallgrass Prairie

2.1. Data

The data required to run the models are described in the previous paper [Famiglietti and Wood, this issue]; model parameters are summarized in Table 1 of that paper. Local or areally averaged values of meteorological data (precipitation, shortwave and longwave radiation, pressure, air temperature, humidity, and wind speed), soil parameters, and vegetation parameters are required to drive the local and macroscale models, respectively. The spatially distributed model can accommodate spatially variable fields of these data by coregistering available fields using a geographic information system (GIS). The spatially distributed and macroscale model formulations require some description of spatial variability in the topographic-soil index, either in spatially distributed or histogram form. Initial conditions of various model states must be estimated.

In the present applications, all model forcing, parametric, and observed flux data were retrieved from the FIFE information system (FIS) which includes a 30-m gridded database of selected observations and land surface characteristics. When catchment-scale and site-wide simulations required areally averaged inputs, model parameters and forcing data were aggregated in one of two ways. Spatially distributed information, such as soil parameters, topographic variables, and rainfall (described below), were aggregated by averaging individual grid element values. Point data, such as meteorological and flux observations made at individual measurement stations, were extracted from the FIS and aggregated by simple linear averaging. Alternative methods for aggregating these data were not investigated in this study.

During FIFE 1987, most land surface flux observations were made at even numbered stations (see Figure 1) during four 2- to 3-week-long intensive field campaigns (IFCs 1-4). Therefore modeled evapotranspiration is compared to that observed during IFC 1 (May 26 to June 6, 1987), IFC 2 (June 25 to July 15, 1987), IFC 3 (August 6-21, 1987), and IFC 4 (October 5-16, 1987). Most flux and meteorological measurements were made at half-hourly intervals.

2.1.1. Meteorological data. During summer 1987 a network of 20 rain gages was used to measure rainfall over the King's Creek catchment and vicinity. A kriging algorithm was applied to the rain gage data to produce spatially distributed rainfall images at 15-min intervals during storm events. In this study, the 15-min rainfall data were converted to 30-min data for consistency with the FIFE data. These images were coregistered with the 30-m FIFE database for spatially distributed simulation of the catchment. Precipitation images were averaged for use in macroscale model simulations on King's Creek. Local model simulations and macroscale simulations for the entire FIFE site were conducted only on golden days, so that no rainfall data were required.

Net radiation and wind speed observed at individual

Soil Type	Parameter Value					
	K _s , mm/ h	θs	θη	$\psi_c,$ m	В	Fractional Cover
Alluvial land	6.1	0.49	0.04	0.27	0.18	0.08
Benfield-Florence complex	6.4	0.47	0.04	0.30	0.16	0.52
Clime-Sogn complex	6.4	0.47	0.04	0.30	0.16	0.30
Dwight-Irwin complex	5.4	0.48	0.05	0.33	0.14	0.04
Irwin silty clay loam	11.0	0.48	0.05	0.34	0.13	0.01
Irwin silty clay loam (eroded)	3.4	0.48	0.05	0.34	0.13	0.01
Ivan and Kennebec silt loams	11.0	0.48	0.04	0.30	0.16	0.01
Reading silt loam	11.0	0.48	0.04	0.30	0.16	0.01
Stony steep land	3.4	0.47	0.04	0.33	0.15	0.01
Tully silty clay loam	3.4	0.48	0.05	0.34	0.13	0.01

Table 1. Soil Types and Properties

stations were used in local model simulations. Other local meteorological data were not readily obtainable from the FIS for individual stations, so that areally averaged data for the King's Creek catchment were used instead. For both spatially distributed and macroscale model simulations of King's Creek, areally averaged radiation, humidity, pressure, and wind data were employed. Downward longwave and downward shortwave radiation were only collected at FIFE meteorological stations 5 and 21. An average of these data was used to drive simulations. Wet and dry bulb temperatures, pressure, and wind speed were averaged from observations at meteorological stations 3, 5, and 7. Macroscale simulations for the entire FIFE site were driven with the same shortwave and longwave radiation data, but with precipitation, humidity, air temperature, pressure, and wind speed averaged over all operating meteorological stations.

2.1.2. Soil data. A map of soil types for the entire FIFE site is coregistered with the FIFE database. For each of the soil types in the region, soil texture classifications are available from the local U.S. Department of Agriculture Soil Conservation Service soil survey [Jantz et al., 1975]. The Brooks and Corey [1964] soil parameters were determined for each soil texture from Rawls et al. [1982] and incorporated into the database. Table 1 lists the soil parameters for each soil type in the King's Creek catchment. The soil type

Table 2. Additional Model Parameters

Parameter	Value
	Soil
α	0.15
<i>D</i> . m	0.50
z_0, m	0.001
z_{rz} , m	0.5
	Vegetation
a (wet canopy)	0.25
α (drv canopy)	0.20
rarmine s/m	110.0
ψ_{orit} m	-210.0
F	10 ⁴
<i>L</i> . m/m	2.0
R_{μ} , s/m	109
	Topography
λ (King's Creek)	3.73
λ (entire site)	5.03

at stations 2 and 10 is the Irwin silty clay loam, at stations 8 and 12 the Benfield-Florence complex, and at station 14, the Clime-Sogn complex. Simulations using the local model at these locations used the corresponding soil parameters. Actual patterns of the soil parameters were extracted from the database for spatially distributed simulations of the King's Creek catchment. Macroscale model simulations for the King's Creek catchment and for the entire FIFE site utilized areally averaged soil parameters from the database. The remaining soil parameters were considered spatially constant in this study. These include the bare-soil albedo (α) , the penetration depth of the diurnal heating wave (D), the bare-soil roughness length (z_0) , and the root zone depth (z_{rz}) . These values were determined from the FIS and are listed in Table 2.

2.1.3. Vegetation data. Since most of the region is covered by native tallgrass, vegetation parameters were considered spatially constant in all simulations. Values of leaf area index (LAI) and canopy height were extracted from the FIS for evapotranspiration simulations at individual stations. The fractions of bare and vegetated soil (f_{hs}, f_{y}) were determined for each IFC by the method of Smith et al. [1993] in terms of LAI and canopy height. Canopy roughness length and zero plane displacement were assumed equal to 15 and 67% of canopy height, respectively. For larger-scale simulations, catchment and entire site average values of canopy height and LAI were computed from the FIS for each IFC. Table 3 summarizes these vegetation parameters. Note that the LAI was treated as a tuning parameter in some of the local SVATS simulations and macroscale model simulations of the entire site. Therefore some of the LAI values shown in Table 3 for local and entire site simulations are the tuned, not FIS, values. The value of minimum stomatal resistance (r_{stmin}) shown in Table 2 is close to that of Smith et al. [1993], who calibrated a biosphereatmosphere transfer model to observations at FIFE flux measurement station 2. The critical leaf water potential (ψ_{crit}) , root activity factor (F), root density (L), and root resistance (R_{μ}) shown in Table 2 were chosen so that the relationship between transpiration capacity and root zone moisture content was consistent with observations [Smith et al., 1992, Figure 9].

2.1.4. Topographic data. A 30-m U.S. Geological Survey digital elevation model (DEM) is coregistered in the FIFE 30-m database. The topographic-soil index was com-

	Canopy		
Parameter	m	LAI	f_v
	IFC 1		
2	0.34	1.39	0.86
8	0.38	1.55	0.90
10	0.48	1.50	0.94
12	0.57	1.65	0.88
14	0.46	0.80	0.79
King's Creek	0.42	1.41	0.88
Entire site	0.34	1.14	0.81
	IFC 2		
2	0.42	1.20	0.78
8	0.48	2.17	0.89
10	0.79	1.00	0.98
12	0.70	1.80	0.94
14	0.63	1.39	0.90
King's Creek	0.66	1.71	0.94
Entire site	0.47	1.60	0.89
	IFC 3		
2	0.30	0.44	0.45
8	0.47	1.00	0.74
10	0.73	1.55	0.96
12	0.91	0.80	0.79
14	0.49	0.90	0.85
King's Creek	0.59	0.98	0.80
Entire site	0.43	1.00	0.68
	IFC 4		
2	0.27	1.15	0.79
8	0.35	0.42	0.45
10	0.40	0.18	0.24
12	0.19	0.07	0.08
14	0.35	0.38	0.50
King's Creek	0.34	0.34	0.39
Entire site	0.28	0.25	0.29

Table	3.	٧	egetation	Parameters
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puted for each grid element in the region by analysis of both the digital elevation and soil survey information. Actual patterns of the index were extracted from the database for spatially distributed simulations, while histograms of the topographic-soil index were created for macroscale model simulations of the King's Creek catchment and the entire FIFE site. Areally averaged values of the topographic-soil index λ for the King's Creek catchment and the entire site are shown in Table 2.

2.1.5. Initializing model states. Initial root and transmission zone moisture contents were determined for local, catchment-scale, and macroscale simulations during IFCs 1-3 by assuming gravitational equilibrium in the local soil profiles (by substituting $\psi = z$ in (6a) of Famiglietti and Wood [this issue]). This procedure resulted in initial conditions that were too wet for IFC4. In those simulations, a gamma distribution of root zone moisture content was assumed, with low moisture content values corresponding to steep, well-drained slopes (low values of the topographicsoil index), and wet soil moisture values corresponding to flat, poorly drained areas such those adjacent to stream channels (high values of the index). Average water table depth was initialized at 2.1, 2.4, 3.0, and 3.0 m for simulations at all scales during IFCs 1-4, respectively. Canopy water storages were assumed dry to initialize simulations.

2.2. Local-Scale Results

In this section, the results of SVATS applications at individual stations are presented. The local SVATS is applied at stations 2, 8, 10, 12, and 14. Simulations were performed using half-hourly time steps and the data described above. Modeled evapotranspiration was compared to that observed on three of the four FIFE golden (virtually cloud-free) days (June 6, July 11, and August 15, 1987). Observed flux data for stations 4 and 6, also located in the vicinity of the King's Creek catchment, were either unavailable or of questionable quality. Observed flux data were also unavailable for stations 8, 10, 12, and 14 for October 11, 1987, the final golden day of the 1987 FIFE campaign.

When analyzing the local-scale results, it is important to remember the following points. First, as was discussed above, some meteorological data (e.g., air temperature and pressure) were not readily available for individual stations from the FIS. Thus unavoidable bias results from driving local simulations with nonlocal data. The situation becomes more complicated when measurement errors in meteorological data and observed fluxes are considered. Errors induced by averaging air temperature, pressure, and humidity data further compound the problem. Second, the structure of the local SVATS is greatly simplified relative to others in current use so that it can be aggregated in space. Therefore our local SVATS is designed to capture the essential dynamics of land-atmosphere interaction: there are likely more detailed SVATS in operation that can better reproduce evapotranspiration observed at individual stations. Most errors in the local simulations are attributable to these two sources and are not discussed in depth below.

The results of local simulations at station 2 are shown in Figure 2a. Station 2 was located on flat-lying, unburned, bottomland prairie, close to the outlet of the King's Creek catchment. Simulated evapotranspiration shows good agreement with observations, with root-mean-square errors (rmse's) of 0.03 mm/h for each of the golden day simulations. The rmse's for all simulation results presented in this report were computed between the daylight hours of 1215 and 2345 UT. The model slightly underpredicts evapotranspiration during midmorning hours on June 6 and July 11. This is most likely a result of using nonlocal air temperature and humidity data to drive the local simulation.

Results of local simulations at station 8 are presented in Figure 2b. Station 8 was located within the one-dimensional subwatershed on the Konza Prairie, on the southeast side of the King's Creek catchment. It was a moderately sloping, northeast-facing site, which was burned before the 1987 FIFE campaign as part of routine prairie management. Evapotranspiration is overpredicted on the afternoon of June 6 and slightly underpredicted at the peak of the diurnal cycle on all three golden days. Daytime rmse's for the three simulations are 0.06, 0.06, and 0.03 mm/h.

Local simulations at station 10 are shown in Figure 2c. Simulations at station 10 were not as successful as those at stations 2 and 8. Daytime rmse's for the three golden day simulations are all roughly 0.06 mm/h. The computed diurnal cycle of evapotranspiration lags behind the observed cycle by nearly 1 hour in each simulation. The reasons for this are again related to the meteorological forcing data used. The air temperature and humidity data were averaged over three unburned topland or sloping sites, two of which face north.



Figure 2. Local SVATS simulated evapotranspiration rates versus observations for FIFE Golden Days June 6, July 11, and August 15, 1987, at (a) flux measurement station 2, (b) station 8, (c) station 10, (d) station 12, and (e) station 14.

Station 10 was located on burned, west-facing, bottomland prairie. Thus the actual air temperature and vapor pressure deficit at station 10 may have differed significantly from those given by the averaged forcing data.

Figure 2d shows the results of golden day simulations at station 12. Station 12 was an unburned, steeply sloping, north-facing site. The simulated diurnal cycle of evapotranspiration for June 6, as above, was biased low in the morning and high in the afternoon, resulting in a daytime rmse of 0.07 mm/h. Simulated evapotranspiration for July 11 agreed well with observations (rmse, 0.02 mm/h). Evapotranspiration was overpredicted during midday hours for August 15 (rmse, 0.07 mm/h).

Simulated evapotranspiration at station 14 agreed well with observations (see Figure 2e). Station 14 was located on an unburned, moderately sloping, east-facing site. Computed evapotranspiration rates were slightly lower than those observed at midday on June 6 (rmse 0.02 mm/h). Observed flux data were unavailable for July 11 at station 14. Computed evapotranspiration rates for August 15 agreed well with observations (rmse 0.03 mm/h).

2.3. Catchment-Scale Results

In this section, the spatially distributed model is applied at the King's Creek catchment (see Figure 1). Simulations were performed using half-hourly time steps and the data previously described. Example spatially distributed input data are shown in Plate 1. Modeled catchment-scale evapotranspiration (see equation (29) of *Famiglietti and Wood* [this issue]) is compared to the average of observations made at stations



Figure 2. (continued)

2, 8, 10, 12, and 14 for IFCs 1-4. As in the case of the local SVATS applications, the unavoidable problem arises of driving local (i.e., grid element) simulations with nonlocal data. Even in a field experiment such as FIFE, it is unreasonable to expect that high-resolution, spatially distributed fields of meteorological data (e.g., air temperature, pressure, wind speed) could be provided for continuous simulation during the IFCs. Thus available meteorological and flux data were linearly averaged as described above. With the exception of the King's Creek rainfall data, which was measured with a dense rain gage network, alternative methods of averaging or producing spatially distributed fields of input data were not considered. Probable errors induced by our approach were discussed under local-scale results. It is worth noting, however, that such high-resolution meteorological data can be provided by atmospheric models (e.g.,

large eddy simulation). This fact, combined with the widespread availability of GIS for representing spatially variable land surface characteristics, makes spatially distributed hydrological modeling a viable approach for detailed studies of land-atmosphere interaction.

Results of the catchment-scale simulations for IFCs 1-4 are shown in Figure 3. In each of Figures 3a to 3d, time step zero corresponds to 0515 UT (0015 locally), on June 1, June 25, August 6, and October 5, 1987, respectively. In general, computed evapotranspiration for all IFCs agrees well with the five-station average. Daytime rmse's were computed of 0.06 mm/h for IFC 1, 0.07 mm/h for IFC 2, 0.06 mm/h for IFC 3, and 0.05 mm/h for IFC 4. Observations made at the FIFE site indicated that during most of the field experiment (IFCs 1-3), evapotranspiration occurred at potential rates. An analysis of the simulated results showed that the model predicted evapotranspiration at atmospherically controlled rates for most of IFCs 1-3. Figures 3a to 3c show that model computed actual evapotranspiration agrees well with the five-station average for this time period. In addition to model error sources previously discussed, bias between simulated and observed results can also be attributed to overprediction or underprediction of potential evapotranspiration rates during this period. During IFC 4, drier root zone soil moisture conditions resulted in soil-controlled evaporation from bare soil and stomatal control of transpiration. The lack of soil water for evapotranspiration was evident at the field site, as the dry conditions resulted in senescence of the native tallgrass. Analysis of the simulated results and the agreement between computed and observed evapotranspiration in Figure 3d suggest that the mechanisms of soil and vegetation control are fairly well represented within the model. However, the model tends to overpredict evapotranspiration during and immediately after storm events. This suggests that potential evapotranspiration rates or soil- or vegetationcontrolled evapotranspiration rates are overpredicted during these brief periods.

Modeled root zone moisture content is shown in the top panels of Plate 2 in spatially distributed format. The top left panel of Plate 2 shows the spatial distribution of initial root zone moisture content employed in the IFC 4 simulation. The top right panel shows the simulated distribution at midday on October 9, 1987. The decrease in dark blue and green grid elements and the increase in red and yellow grid elements from October 5 to October 9 indicates that the modeled root zones are somewhat drier after 4 days, although not much owing to low evaporation rates at that time of year.

The bottom panels of Plate 2 show modeled midday evapotranspiration rates for the corresponding times in the top panels. Evapotranspiration rates vary from near 0 to 0.4 mm/h. These images give some indication of the degree of spatial variability in evapotranspiration rates within the catchment. Such high-frequency variability was not sampled by the flux measurement stations, since only one station was located within the catchment, and a total of 22 stations were located within the entire 15-km site. Furthermore, logistical considerations required that most stations be located on prairie toplands and moderate slopes, so that steep slopes and valley bottoms were undersampled. Thus spatial patterns such as those shown in the bottom panels of Plate 2 are difficult to verify. However, FIFE investigators Holwill and Stewart [1992] and Jedlovec and Atkinson [1992] showed that such high-frequency variation existed using highresolution remotely sensed imagery. The patterns shown in the bottom panels of Plate 2 are consistent with the microtopographic variation shown in the imagery produced in both of these studies.

Comparison of the top and bottom panels of Plate 2 shows a strong relationship between spatial patterns of root zone moisture content and evapotranspiration. Evapotranspiration rates decrease with decreasing root zone moisture content. Wetter grid elements located along the stream network evaporate at higher rates than drier locations, such as those located near ridge tops. As was described above, IFC 4 was drier than the previous IFCs, resulting in active soil and vegetation control of evapotranspiration, particularly at midday [see *Famiglietti and Wood*, this issue, Figure 4]. Since exfiltration and transpiration capacities are strongly



dependent on moisture content, the correspondence between the top and bottom of Plate 2 is understandable. The larger number of dark blue and green grid elements in the bottom of Plate 2 for October 5 indicates that evapotranspiration rates were higher than on October 9. The decrease in evapotranspiration rates during that period is due to the catchment-wide decrease in root zone moisture content, which resulted in decreased exfiltration and transpiration capacities locally.

To demonstrate the surface runoff capabilities of the model, the runoff-producing storm event of IFC 3 (August 13, 1987) was simulated independently of the work presented previously. In this simulation the model was tuned so that the volume of computed storm runoff matched that observed. All model parameters are given in Tables 1-3. As in the evapotranspiration simulation of IFC 4, a gamma distribution of initial root zone moisture content was assumed. Computed streamflow was tuned to that observed by increasing the root zone depth from 0.5 to 0.75 m and by increasing the saturated hydraulic conductivities of Table 1 by a factor of 5. Such independent tuning was required owing to a lack of runoff-producing storm events during the summer of 1987. To properly calibrate and verify runoffrelated model parameters, rainfall and streamflow data from a number of events would be required. Since these data were not available, no attempt was made to identify one optimal parameter set for continuous simulation.

Spatially distributed rainfall images for 0145 and 0215 UT, August 13, 1987, are shown in the top panels of Plate 3. The catchment-average precipitation intensities are 51 mm/h and



Plate 1. Example input data for the spatially-distributed model. Catchment area is 11.7 km^2 , and grid element resolution is 30 m; north is at top of page. Clockwise from upper left: precipitation, solar radiation, soil type, and topographic-soil index.

40 mm/h, respectively. The middle panels of Plate 3 show modeled root zone moisture content before the start of the simulation, at 0015 UT, August 13, 1987 (left), and after the peak precipitation intensity, at 0215 UT (right). The scale from blue to yellow represents volumetric moisture contents ranging from 0.48 to 0. Note the increase in modeled root zone moisture content after the storm. The bottom panels of Plate 3 show the locations and rates of runoff generation for the two time steps of peak precipitation intensity shown in the top panels. Since there were no saturated regions of land surface at this time, all surface runoff was produced by the infiltration excess mechanism. The scale red to blue/white represents runoff generation rates from 30 mm/h to near 0 mm/h. The dark blue background represents the remaining catchment grid elements where no surface runoff was generated. As the precipitation intensity reaches its peak at 0145 UT, runoff is generated where the intensity is highest and the soil wettest. The increase in the number of surface runoffproducing locations between 0145 and 0215 UT in the bottom panels of Plate 3 corresponds to the catchment-wide increase

in surface moisture content, which results in decreased infiltration capacities, so that runoff generation is more widespread. Comparison of the middle and bottom panels shows that in general, as in the case of evapotranspiration, higher magnitude fluxes are generated by the wetter catchment grid elements. These locations are found adjacent to the stream network and have relatively low infiltration capacities. Within both bottom images in Plate 3, the magnitude of surface runoff rates increases with increasing root zone moisture content, increasing precipitation intensity, and decreasing infiltration capacity.

2.4. Macroscale Results

2.4.1. King's Creek. In this section, the macroscale formulation is applied at the King's Creek catchment. Model parameters are listed in Tables 1–3, and atmospheric forcing data have been previously described. Computed, areally averaged evapotranspiration rates [see *Famiglietti and Wood*, this issue, equation (35)] are compared with the



Figure 3. Modeled and observed evapotranspiration for the King's Creek catchment using the spatially distributed formulation. Observations correspond to the five-station average described in the text: (a) FIFE IFC1; time 0 represents June 1, 1987, 0445 (UT); (b) IFC2; time 0 represents June 25, 1987, 0445 (UT); (c) IFC3; time 0 represents August 6, 1987, 0445 (UT); and (d) IFC4; time 0 represents October 5, 1987, 0445 (UT).

five-station average of observations made in and near the watershed.

Results of macroscale model simulations are shown in Figure 4 for IFCs 1-4. Modeled evapotranspiration agrees well with the five-station average for all IFCs. In addition to the sources of error already mentioned, other sources arise when the macroscale formulation is employed. Explicit patterns of land surface-atmosphere interaction are no longer represented by the model structure. Spatial variability in the topographic-soil index and the corresponding water and energy fluxes is represented statistically [see *Famiglietti* and Wood, this issue]. Meteorological forcing, vegetation, and soil parameters are represented as spatial averages. Therefore potential error sources include the loss of explicit pattern representation and the manner in which model parameters, model inputs, and field observations are aggregated to the scale of application. Comparison of Figure 4 and 3 shows that the macroscale and spatially distributed formu-



Plate 2. (top left) Spatial distribution of initial root zone moisture content used in simulation of IFC 4. Units are volume percent; scale is given in Plate 1. (top right) Simulated spatial distribution at midday on October 9, 1987. (bottom left) Spatial distribution of simulated evapotranspiration at midday on October 5. Units are millimeters per hour. (bottom right) Simulated spatial distribution at midday on October 9.

lations yield nearly identical results for the King's Creek catchment and, in fact, the rmse's are the same as those previously reported for the spatially distributed simulations. The implication of these results is reserved for the discussion section. Although the spatial scale studied is relatively small, the discussion should still provide initial insight into the impact of the assumptions utilized in developing the simpler, macroscale formulation. Note that *Famiglietti and Wood* [1994] (hereafter referred to as paper 3) also applied the local SVATS at the King's Creek catchment scale, with implications for the degree of spatial variability required to adequately model catchment-scale evapotranspiration. The reader is referred to that report for a detailed discussion of the scaling behavior of areally averaged evapotranspiration from the point to the catchment scale.

2.4.2. Entire site. Results of macroscale model evapotranspiration simulations for the entire 15×15 -km FIFE site

are shown in Figure 5 for the four golden days. All model parameters are given in Tables 1-3, and meteorological forcing data have been described previously. Figure 5 shows that modeled evapotranspiration agrees reasonably well with the 22-station average, with simulations of golden days 3 and 4 reproducing observations better than golden days 1 and 2. Rmse's for golden days 1-4 are 0.08, 0.06, 0.04, and 0.01 mm/h, respectively. Sources of error have been described in earlier sections. Although the simulation results shown in Figure 5 are reasonable given the simple model structure. simulations for the entire IFCs were not as good as those for the smaller King's Creek catchment. The reasons behind this are the subject of ongoing research. Initial analysis indicates that at the 15-km scale, the model results are rather sensitive to the manner in which meteorological and flux data are aggregated. No attempt was made to run the spatially distributed formulation at this large scale. However, in the



Plate 3. Spatially distributed rainfall images for (top left) 0145 and (top right) 0215 UT August 13, 1987, for the King's Creek catchment. Units are millimeters per hour. Scale is given in Plate 1. Initial root zone moisture content before the start of the simulation at (middle left) 0015 UT, August 13, 1987, and (middle right) simulated moisture content shortly after the peak precipitation intensity at 0215 UT. Units are volume percent. Locations and rates of runoff generation for the two time steps of peak precipitation intensity shown in Plate 3a. Units are millimeters per hour.



Figure 4. Modeled and observed evapotranspiration for the King's Creek catchment using the macroscale formulation. Observations correspond to the five-station average described in the text: (a) IFC 1, (b) IFC 2, (c) IFC 3, and (d) IFC 4. Times correspond to those in Figure 3.

next section, we speculate on possible differences between spatially distributed and macroscale simulations as spatial scale increases.

3. Discussion

This discussion focuses on the implications of the simulation results of the previous section. Specifically, we are interested in the implications of the agreement between macroscale model and spatially distributed simulations of evapotranspiration for the King's Creek catchment, and how these might change as spatial scale is increased. As a first step toward understanding the aggregation and scaling properties of land surface processes, we conducted a detailed investigation of the scaling behavior of evapotranspiration from local to catchment scales (paper 3). Simulation studies such as the present work and paper 3 are important because they provide insight into the role of naturally heterogeneous land surface properties and processes and how important spatial variability can be included in macroscale hydrological formulations. These types of studies provide a framework within which land hydrology parameterizations can be continually modified and our understanding of large-scale hydrological processes improved.

The assumptions invoked in the development of the macroscale formulation include an areally averaged representation of meteorological inputs, soil parameters, and vegetation parameters. Spatial variability in the topographic-soil index, soil moisture, surface runoff, and the energy fluxes is represented statistically, rather than explicitly, as in the spatially distributed formulation. Comparison of Figures 4 and 3 shows that for the 11.7-km² grassland King's Creek catchment these are reasonable assumptions, since macroscale model and spatially distributed results are nearly identical. Some discussion regarding why these results are similar and when they might differ should provide insight into the restrictiveness of the macroscale assumptions at larger spatial scales and in different geographic locations.

By comparing macroscale and spatially distributed evapotranspiration equations, Famiglietti and Wood [this issue] showed that the difference between evapotranspiration computed with the two formulations would depend upon two factors. The first is related to the degree of spatial variability in model parameters and inputs. The second factor is that the macroscale formulation represents spatial variability statistically rather than with explicit spatial patterns. At the King's Creek catchment, with the exception of topography and soil moisture, the degree of spatial variability in soil properties, vegetation properties, and meteorological inputs was not significant enough to yield differences in simulations with the two models. Table 1 shows that nearly 90% of the catchment has similar soil parameters. Most of the catchment is covered by native tallgrass, which showed minimal spatial variability in LAI on unburned prairie [Schimel et al., 1991]. Analysis of the precipitation data showed that many of the spatially distributed images exhibited minimal spatial variability. Comparison of Figures 4 and 3 further suggests that a statistical representation of spatially variable topography, soil moisture, and surface fluxes is adequate at the scale of the King's Creek catchment. This issue is discussed in more detail in paper 3.

In regions of similar scale but higher degrees of spatial variability, or in larger-scale applications where increased spatial variability is encountered, model results may well diverge. For example, although the spatially distributed model was not run at the scale of the entire 15-km FIFE site, spatially distributed and macroscale model results most likely would not show the same agreement displayed at the catchment scale. Differences in land use (agricultural versus nonagricultural), prairie management (burned versus unburned, grazed versus ungrazed), atmospheric forcing (rain versus no rain), and vegetation and soil type complicate the process of aggregating macroscale model input data. The problem is compounded by the fact that there are numerous methods for aggregating observed flux data, and that such areally averaged data do not necessarily represent a "true" areal average.

Famiglietti and Wood [this issue] propose a methodology for dealing with increased spatial variability in macroscale model applications. When soil and vegetation properties are correlated with topography (e.g., soil texture parameters, LAI) the appropriate parameters can vary jointly with each interval of the topographic-soil index. In larger-scale climate



Figure 5. Macroscale model golden day evapotranspiration simulations for the entire 15-km FIFE site. Observations represent a 22-station average: June 6, July 11, August 15, and October 11, 1987.

modeling applications, the model could be implemented in mosaic mode [Avissar and Pielke, 1989; Koster and Suarez, 1992; Seth et al., 1994] so that subgrid-scale variability in atmospheric forcing and major vegetation types could be represented between subgrid patches. Within each patch, spatial variability in topography, soils, vegetation, soil moisture, and the runoff and energy fluxes would be represented. Although such an approach is idealized, and there are certainly more detailed methods for modeling large-scale land-atmosphere interaction, it is important to remember the philosophy behind the macroscale formulation. The model simplifies the representation of vertical soil-vegetationatmosphere transfer so that lateral heterogeneity can be incorporated in the model structure without significantly increasing computational complexity relative to currently operational SVATS.

4. Summary

In this paper the models of Famiglietti and Wood [this issue] were applied at their appropriate scales for evapotranspiration modeling at the FIFE site. FIFE was a largescale field experiment held in the summers of 1987 and 1989, on a 15×15 km region of tallgrass prairie located near Manhattan, Kansas. During the experiment, multiscale ground-based and remotely sensed water and energy balance data were collected simultaneously, so that the data set provides unique opportunities to develop and test modeling strategies over a range of spatial scales. All model forcing, parametric, and observed flux data were retrieved from the FIFE information system.

The local SVATS was applied to model evapotranspiration at five flux measurement stations in the northwest quadrant of the FIFE site. When available, local atmospheric forcing, vegetation, and soil data were utilized. Simulations were performed for three of the four FIFE "golden (cloud-free) days" with good results. The simplified SVATS structure, the use of nonlocal forcing data, and observation errors were identified as sources of error in the simulations.

For catchment-scale and site-wide evapotranspiration simulations, model parameter and forcing data were aggregated in two ways. Spatially distributed information, such as soil parameters, topographic variables, and rainfall were aggregated by averaging individual grid element values. Point data such as flux data observed at individual measurement stations were aggregated by simple linear averaging. Alternative methods for aggregating these data were not investigated in this study.

The spatially distributed model was applied at the 11.7km² King's Creek catchment for evapotranspiration modeling during FIFE intensive field campaigns (IFCs) 1-4. The IFCs were roughly 2-week-long periods during which most flux observations were made. Catchment-average evapotranspiration was compared to an average of observations made at five measurement stations in and near the watershed. Simulation results were good and additional sources of error, beyond those listed above, were identified as periodic overprediction of potential evapotranspiration rates and soil or vegetation-controlled evapotranspiration rates. Model results were shown in spatially distributed format for selected times during the simulations and showed general agreement with patterns derived by other researchers using remotely sensed information.

The macroscale formulation was applied to both the King's Creek catchment and the entire 15-km FIFE site for evapotranspiration simulations. Macroscale model simulations for King's Creek were nearly identical to the spatially distributed results, implying that at this location and at this scale, the assumptions invoked in the development of the macroscale formulation are reasonable. The macroscale model was then employed to simulate evapotranspiration from the entire 15-km site for the four golden days. Simulated evapotranspiration rates showed reasonably good agreement with the 22-station average of observations. Results for the third and fourth golden days showed better agreement with observations than the first and second. It was suggested that at this and larger scales, additional error may arise as a result of the macroscale assumptions of areally averaged atmospheric forcing, vegetation parameters, soil parameters, and the methods by which these data and other flux observations are aggregated. A methodology to combat these problems at the grid scale of atmospheric models was reviewed.

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