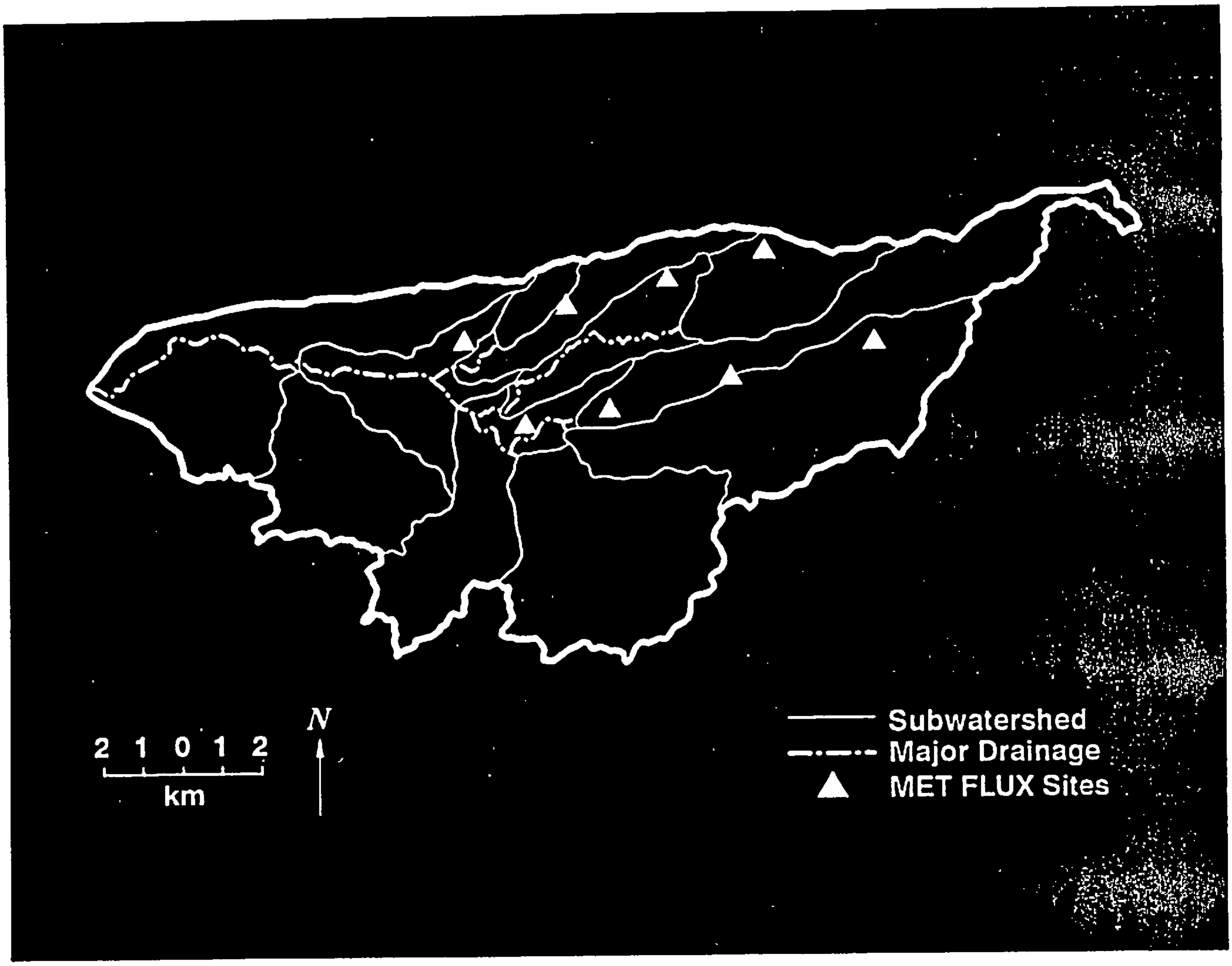
MONSOON'90 Multidisciplinary Experiment



USDA-ARS Walnut Gulch Watershed near Tombstone, Arizona

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Push broom microwave radiometer observations of surface soil moisture in Monsoon '90

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Abstract. The push broom microwave radiometer (PBMR) was flown on six flights of the NASA C-130 to map the surface soil moisture over the U.S. Department of Agriculture's Agricultural Research Service Walnut Gulch experimental watershed in southeastern Arizona. The PBMR operates at a wavelength of 21 cm and has four horizontally polarized beams which cover a swath of 1.2 times the aircraft altitude. By flying a series of parallel flight lines it was possible to map the microwave brightness temperature (T_B), and thus the soil moisture, over a large area. In this case the area was approximately 8 by 20 km. The moisture conditions ranged from very dry, <2% by volume, to quite wet, >15%, after a heavy rain. The rain amounts ranged from less than 10 mm to more than 50 mm over the area mapped with the PBMR. With the PBMR we were able to observe the spatial variations of the rain amounts and the temporal variation as the soil dried. The T_B values were registered to a Universal Transverse Mercator grid so that they could be compared to the rain gage readings and to the ground measurements of soil moisture in the 0- to 5-cm layer. The decreases in T_B were well correlated with the rainfall amounts, $R^2 = 0.9$, and the comparison of T_B with soil moisture was also good with an R^2 of about 0.8. For the latter, there was some dependence of the relation on location, which may be due to soil or vegetation variations over the area mapped. The application of these data to runoff forecasts and flux estimates will be discussed.

Introduction

A primary goal of the Monsoon '90 experiment was the evaluation of remotely sensed data for the estimation of surface fluxes in an arid environment [*Kustas et al.*, 1991]. The site chosen for the experiment is the well-instrumented Walnut Gulch experimental watershed operated by the Southwest Watershed Research Center of the U.S. Department of Agriculture's Agricultural Research Service. It is located in southwestern Arizona about 120 km southeast of Tucson. The region has 250–500 mm of annual precipitation with the majority falling during a "summer monsoon season" in July and August. This was the period chosen for the experiment.

One of the most important surface parameters affecting these fluxes is the moisture stored in the soil. It affects the thermal properties of the soil and serves as the reservoir for the evaporation process. This is seen in Figure 1 where the measured daily Bowen ratio (sensible heat/latent heat) from the meteorological and flux (METFLUX) network [*Kustas et al.*, this issue] is compared to the surface soil moisture expressed as a percent of the estimated field capacity for the soil. The smooth curve is a nonlinear regression fit to the data. It is seen that there is a strong dependence of the Bowen ratio on the moisture content of the surface soil, especially for moistures below about 25% of field capacity. This situation may be true only for the sparsely vegetated conditions considered in this experiment, but it indicates the importance of the bare soil evaporation for these conditions.

The remote sensing technique of interest in this paper is the passive microwave sensing of soil moisture [*Schmugge*, 1989; *Jackson and Schmugge*, 1986]. This approach uses measurements of the thermal emission from the soil at the longer microwave wavelengths ($\lambda \geq 10$ cm) to determine the moisture content in the surface layer of the soil. It relies on the fact that the emissivity (ε) at these wavelengths is a function of moisture content as a result of the large dielectric contrast between water and dry soil. For water the real part of dielectric constant is about 80 while for dry soil it is less than 5 and thus for soils it ranges from about 3.5 to 20. This produces a change in ε from 0.95 to less than 0.6 when wet. This decrease in ε is approximately linear with soil moisture and is affected by factors such as soil texture, surface roughness, and vegetation cover. The texture affects the slope of the relation between ε and soil moisture but not the range of variation. While both roughness and vegetation reduce the range of variation, vegetation is more significant because it can totally obscure the soil surface if it is present in sufficiently large amounts. This will occur for vegetation water contents in excess of 6 or 7 kg/m^2 at the 21-cm

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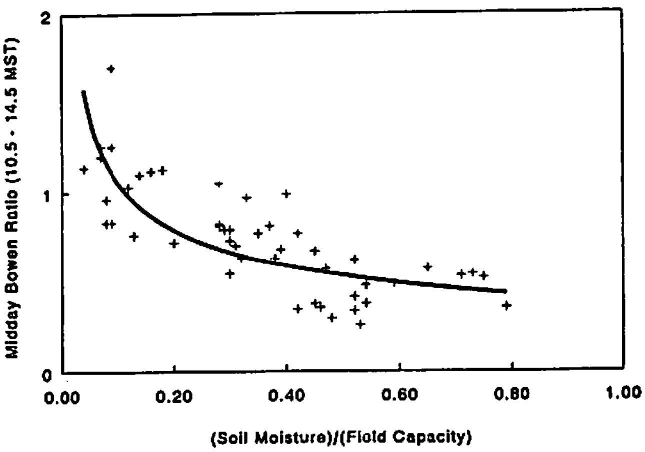

Figure 1. Comparison of the midday Bowen ratio (*H*/*LE*) as measured at the METFLUX sites with the 0- to 5-cm soil moisture expressed as a percent of the soil's field capacity also at these sites.

wavelength [*Jackson and Schmugge*, 1991]. The resulting sensitivity of ε to soil moisture can be expressed as [*Schmugge et al.*, 1992]:

$$\varepsilon = 1 + (\varepsilon_0 - 1) \exp(-h - 2\tau) \qquad (1)$$

where ε_0 is the bare smooth soil emissivity, h is the roughness parameter [*Choudhury et al.*, 1979] and τ is the optical depth of vegetative cover. The smooth surface emissivity, ε_0, can be calculated from the soil dielectric constant using the Fresnel equations of electromagnetic theory. At the 21-cm wavelength, τ is proportional to the plant water content (PWC) expressed in kilograms per square meter. For the Walnut Gulch site the vegetation consists of sparse grass and shrubs [*Kustas et al.*, 1991], and so we expect it to have a minimal effect on the microwave response at 21 cm.

The Push Broom Microwave Radiometer

The NASA push broom microwave radiometer (PBMR) operates at *L* band (frequency, 1.42 GHz; wavelength, 21 cm) and is flown on board the NASA C-130 aircraft. The PBMR has four horizontally polarized beams pointing at ±8° and ±24° from the nadir. Each of the beams has a full width at half maximum power of about 16°, which yields a footprint on the ground $0.3H$ for each beam and a total swath of about $1.2H$, where H is the aircraft flight altitude [*Harrington and Lawrence*, 1985].

Table 1. Dates and Times of PBMR Flights

Day	Date	Time, UT
212	July 31, 1990	1628–1807
214	Aug. 2, 1990	1612–1737
216	Aug. 4, 1990	1526–1641
217	Aug. 5, 1990	1658–1759
220*	Aug. 8, 1990	1602–1612
221	Aug. 9, 1990	1707–1815

*Northernmost and southernmost flight lines only.

The PBMR was flown on six flights of the C-130 during a 10-day period in July and August 1990 as part of the Monsoon '90 experiment. The objective was to map the surface brightness temperature (T_B) at a wavelength of 21 cm and to infer surface soil moisture from these data. For Monsoon '90 the PBMR flights were at an altitude of 600 m above the ground, which yielded an instantaneous field of view (IFOV) of 180 m for each beam and a 720-m swath for the four beams. To provide complete coverage of the study area, seven flight lines were set up separated by 500 m as shown in Figure 2. They were roughly in an E-W direction. On day 220 (August 8), only the outermost lines (lines 1 and 7) were flown; these lines provided coverage of the METFLUX sites. The flights were generally between 9 and 11 A.M. (MST) or 16 to 18 UT with the northernmost line (line 1) being flown first. The dates and times of coverage are given in Table 1.

The PBMR data were recorded on a floppy disk in a direct format which was subsequently converted to an ASCII format. The C-130 flight lines were plotted using the videotapes from a nadir-viewing camera onto copies of the high-altitude photos of the watershed. These flight lines were digitized at the Hydrology Lab directly into Universal Transverse Mercator coordinates using three easily identified landmarks.

Before creating the images with these data, the outer beams were corrected for incidence angle effects (limb darkening) by multiplying them by the ratio of the average of the center beam to the outer beam on each side. This darkening is due to the decrease in emissivity with angle for

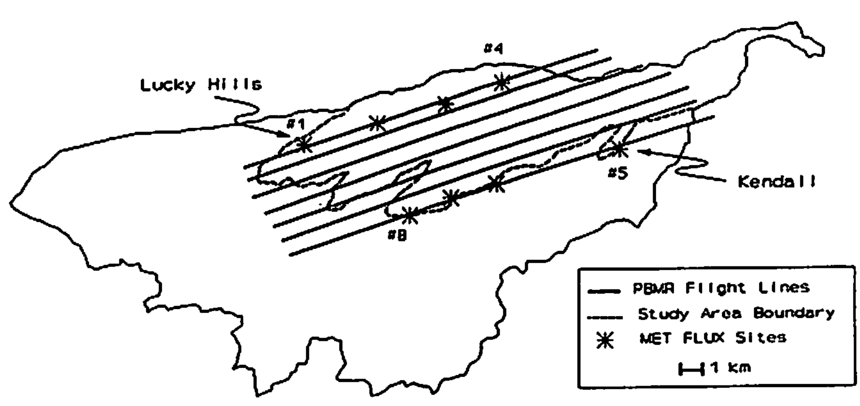

Figure 2. PBMR flight lines. The separation between the lines is approximately 500 m.

Table 2a. Soil Moisture Data for METFLUX Sites 1–4

METFLUX Site 1			METFLUX Site 2			METFLUX Site 3			METFLUX Site 4		
Time, decimal DOY†	VWC,* %		Time, decimal DOY	VWC, %		Time, decimal DOY	VWC, %		Time decimal DOY	VWC, %	
	Mean	s.d.‡		Mean	s.d.		Mean	s.d.		Mean	s.d.
204.434	9.80	1.84	204.467	9.02	1.70	204.479	9.99	0.71	204.494	9.43	1.75
205.372	8.37	1.36	205.392	8.34	1.82	205.401	8.86	0.18	205.410	8.21	1.25
206.396	7.45	1.57	206.414	11.42	1.49	206.424	7.71	1.80	206.431	9.26	0.32
207.333	5.58	1.32	207.397	8.60	0.37	207.413	4.39	0.15	207.426	5.59	1.21
208.340	3.70	1.37	208.383	4.60	0.31	208.394	3.24	0.35	208.404	4.25	1.45
209.401	2.65	0.22	209.422	4.24	0.50	209.432	2.42	0.41	209.439	2.99	0.79
210.396	2.56	0.65	210.393	2.38	0.44	210.403	2.67	0.57	210.410	3.35	0.34
211.389	2.26	0.06	211.404	2.27	0.41	211.416	2.14	0.07	211.423	2.41	0.44
212.379	2.18	0.40	212.389	2.01	0.19	212.403	1.84	0.11	212.413	2.13	0.18
213.396	1.94	0.38	213.393	2.40	0.35	213.403	1.62	0.04	213.410	2.94	0.27
214.375	11.45	3.29	214.408	14.81	2.42	214.421	16.25	1.71	214.431	18.72	1.16
215.396	8.56	1.44	215.415	13.87	0.75	215.429	13.61	0.88	215.437	16.76	1.76
216.385	12.11	2.60	216.391	13.10	1.05	216.405	11.18	1.27	216.416	13.02	1.24
217.375	9.61	0.72	217.398	10.60	0.47	217.408	7.36	0.50	217.415	9.77	0.80
218.403	6.48	1.30	218.386	7.07	0.80	218.401	5.68	0.54	218.404	7.41	3.49
219.000	M§	M	219.418	14.02	0.88	219.435	11.86	1.14	219.449	16.94	0.84
220.406	6.91	1.07	220.403	8.79	1.69	220.421	6.97	0.48	220.429	11.34	0.86
221.395	3.64	0.59	221.417	7.51	3.23	221.432	6.96	1.60	221.441	7.39	0.24
222.389	3.48	0.26	222.417	5.73	0.80	222.434	4.99	1.00	222.448	5.08	1.31
223.397	2.58	0.60	223.416	3.63	0.74	223.424	3.40	0.35	223.431	3.96	0.62
224.390	17.12	1.27	224.418	17.22	1.90	224.428	19.55	2.41	224.435	24.85	1.97
225.388	17.23	2.54	225.415	15.91	1.03	225.426	18.92	1.43	225.434	24.48	1.40
226.390	16.70	2.92	226.413	17.11	0.71	226.426	17.30	0.02	226.436	21.60	5.27
227.379	10.34	1.24	227.404	11.37	0.79	227.413	15.46	1.70	227.420	20.64	2.30

*VWC is volumetric soil water content (cm^3/cm^3).
†Decimal DOY is decimal fraction of day of year. For example, 204.434 corresponds to 1025 MST on July 23.
‡Here s.d. denotes standard deviation.
§M denotes missing.

the horizontal polarization predicted by the Fresnel equations of electromagnetic theory [*Schmugge*, 1989]. For the wetter days the ratio was about 1.03, and for the dry day the ratio was about 1.01.

Ground Measurements

In addition to microwave data just described, the ground or surface measurements of soil moisture are used in this paper. Daily gravimetric soil moisture samples were collected adjacent (within approximately 15 m) to each of the eight METFLUX sites from July 23 to August 15. Three replicates (roughly 30 cm apart) were collected from the surface 0- to 5-cm layer and converted to volumetric water content using in situ bulk density measurements from each site. This sampling was generally done during the 2-hour window in which the PBMR flights occurred. The soil moisture data are given in Tables 2a and 2b. The other properties of the soil, assumed constant over the period of the experiment, are given in Table 3. The quantity SSA is the specific surface area for the soil and is used in the prediction of the dielectric properties of the soils.

Results

The period was characterized as being very dry (SM < 3%) for the first flight on July 31 (day 212), followed by up to 5 cm of rain on August 1 over most of the study area. Thus there was a significant decrease (50–60 K) in T_B observed during the next flight oq August 2 (day 214) due to the increase in soil moisture, up to 20%. The succeeding flights on August 4, 5, 8, and 9 (days 216, 217, 220, and 221, respectively) showed the effects of some smaller rains and the subsequent dry down of the study area. On day 221 the values of T_B rose to almost their prerain values.

The effect of the first rain is shown in Figure 3, where we have contour plots of T_B on days 212 and 214 and the rain amounts on day 213. The top panel presents the T_B contours on the day before the rain; values are 280 K or greater with the exception of the cool spot near the southwest corner of the map. This is the town of Tombstone, Arizona, with its many metal-roofed buildings. The sites of the eight METFLUX stations are indicated by the triangles. The middle panel gives the rainfall contours for the rain events on August 1 (day 213). The pluses indicate the sites of the rain gages used to create this map. The rainfall amounts range from less than 10 mm at the west to more than 50 mm near site 4. The bottom panel presents the T_B contours for day 214, August 2. Here we can see that T_B has decreased to less than 230 K; the lowest areas roughly correspond to the peak rainfall. All of the area which received more that 10 mm of rain had T_B < 240 K. Note that the 240-K contour roughly corresponds to the 10-mm contour.

With the data in this format it was possible to compare the change in T_B to the rainfall amounts at each rain gage. The

Table 2b. Soil Moisture Data for METFLUX Sites 5–8

METFLUX Site 5			METFLUX Site 6			METFLUX Site 7			METFLUX Site 8		
Time, decimal DOY	VWC, % Mean	VWC, % s.d.	Time, decimal DOY	VWC, % Mean	VWC, % s.d.	Time, decimal DOY	VWC, % Mean	VWC, % s.d.	Time decimal DOY	VWC, % Mean	VWC, % s.d.
204.561	8.24	3.40	204.542	8.93	1.22	204.583	11.62	0.96	204.594	9.84	1.54
205.447	6.27	2.29	205.459	12.38	3.41	205.466	10.68	1.98	205.474	12.40	0.80
206.458	6.31	0.87	206.487	5.70	2.41	206.494	7.91	0.64	206.502	6.41	1.60
207.428	3.22	0.31	207.467	2.93	1.29	207.477	3.28	0.82	207.487	4.70	0.27
208.457	3.02	0.68	208.473	4.48	2.26	208.481	3.10	0.69	208.491	4.76	0.24
209.465	3.33	0.84	209.476	2.15	0.51	209.482	2.37	0.55	209.489	3.19	0.42
210.449	2.51	0.42	210.464	2.82	0.61	210.472	1.45	0.22	210.481	2.21	0.03
211.547	4.96	2.42	211.458	2.70	0.80	211.466	1.20	0.21	211.488	1.95	0.18
212.563	2.99	0.51	212.458	2.29	0.29	212.474	1.05	0.13	212.490	1.77	0.14
213.514	2.76	0.84	213.490	1.91	0.25	213.457	0.98	0.04	213.472	2.17	0.55
214.523	18.31	5.38	214.467	17.70	1.38	214.475	13.49	1.93	214.483	19.79	4.90
215.514	16.75	2.43	215.480	10.01	1.73	215.488	7.35	0.94	215.497	9.70	1.33
216.448	13.44	0.86	216.460	11.70	2.32	216.468	10.56	1.12	216.481	13.16	2.45
217.490	9.33	1.72	217.454	8.22	1.93	217.464	5.12	0.84	217.472	8.09	0.65
218.433	5.32	1.98	218.456	6.33	3.99	218.462	2.82	0.64	218.469	5.34	0.35
219.498	14.53	1.79	219.523	14.12	3.36	219.542	8.44	0.24	219.554	8.45	1.54
220.528	12.93	1.90	220.470	9.86	3.10	220.479	3.22	0.49	220.486	4.36	0.28
221.521	7.85	2.51	221.489	7.17	1.36	221.498	2.31	0.34	221.506	3.91	0.98
222.521	6.51	1.76	222.486	5.37	1.05	222.493	1.78	0.48	222.500	2.68	0.47
223.458	4.89	0.29	223.461	4.09	0.35	223.469	1.37	0.26	223.477	2.56	0.43
224.493	21.72	4.43	224.473	23.84	6.93	224.481	17.79	2.51	224.490	23.17	6.35
225.467	24.93	4.56	225.492	30.96	0.39	225.502	22.40	1.71	225.512	24.93	4.36
226.481	22.99	2.53	226.516	19.67	3.05	226.529	17.31	1.04	226.542	15.90	1.15
227.454	24.04	2.52	227.476	16.43	3.28	227.484	13.13	2.19	227.492	12.65	0.96

Abbreviations and units are as defined in footnotes to Table 2a.

result is given in Figure 4, where a linear decrease in T_B with rain amounts up to about 25 or 30 mm of rain is seen. Above that level the soil is apparently saturated, and no further decrease in T_B is observed. We expect that the moisture in the surface 0- to 5-cm layer had stabilized by the time of the flight on day 214 to values between 15 and 20%.

The comparison between the gravimetrically determined soil moisture contents and T_B for the eight sites from the six flights are shown in Figure 5. The curves are plots of (1) and show the expected behavior for a soil with a texture similar to that found in Walnut Gulch with a range of surface parameters $\alpha = h + 2\tau$, where h is the roughness parameter and $\tau = (b)(\mathrm{PWC})$ is the vegetation optical depth. The factor b is a function of the plant water content expressed in units of kilograms per square meter and has been found to equal 0.1 ± 0.03 for a range of vegetation types [*Jackson and Schmugge*, 1991]. It is seen that the curves with $\alpha = 0$ and $\alpha = 0.2$ roughly bracket the data. The first curve ($\alpha = 0$) is the behavior expected for a bare smooth soil, and the second ($\alpha = 0.2$) is that for a slightly rough soil with a small amount of vegetation cover, PWC = 0.5 kg/m^2. The measured vegetation dry biomass is given in Table 3 for the eight sites. The water contents for the vegetation were between 40 and 50%, so that the maximum probably plant water content was about 1 kg/m^2, yielding a τ of 0.1 at most.

The results on a site-by-site basis show excellent correla-

Table 3. Soil Properties at METFLUX Sites

Site	Sand, %	Silt, %	Clay, %	SSA,* m^2/g	Density, g/cm^3	Rock, vol. %	Biomass, g/m^2	Slope, %/K	Intercept
1	66	24	10	26	1.64	29	228.7	−0.17	50.6
2	69	20	11	30	1.83	37	289.9	−0.20	60
3	71	20	9	20	1.58	28	228.3	−0.26	74
4	73	22	5	28	1.82	46	224.8	−0.31	91.8
5	69	20	11	54	1.61	39	102.3	−0.31	93.3
6	67	25	8	27	1.57	32	454.6	−0.28	81.8
7	80	14	6	10	1.74	10	140.2	−0.22	64.6
8	72	20	8	21	1.47	22	1033.7	−0.23	66.3

*SSA denotes specific surface area.

tions of T_B with soil moisture, $R^2 > 0.9$, except for sites 2 and 8. The plots are shown in Figure 6. The two curves for site 8 are for the regression with ($R^2 = 0.8$) and without ($R^2 = 0.9$) the outlier which had a moisture content of 20%, about 6% higher than expected on the basis of the other points for that site. Note that the standard deviation of the points for this day was 5%, indicating that one of the three samples for this day was significantly wetter than the others.

There is considerable variation in the slopes, with sites on the western end (sites 1 and 8) showing greater sensitivity to soil moisture than those on the eastern end (sites 4 and 5). The regression results for the eight sites are presented in Table 3. For the predicted curves in Figure 5 a value of SSA = 30 m^2/g was used and is seen to be appropriate for these soils. This difference would imply that the soils at the eastern end were heavier or that there was greater vegetation cover; however, this was not borne out by the data given in Table 3. In general, there does not appear to be any correlation of the variation of the slopes with any soil or vegetation parameters listed. Thus this variation is still under study.

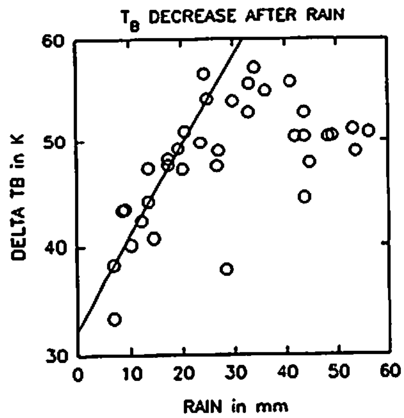

Figure 4. The decrease in T_B versus rain for the gages shown in Figure 3 (middle). The line is the regression for the data with less than 25 mm of rain, $R^2 = 0.8$.

Discussion

These PBMR data indicate that microwave radiometer data can be used to map rainfall patterns and the subsequent spatial and temporal variations of the surface soil moisture during the dry down process. The observed sensitivity of T_B to soil moisture was in approximate agreement with expectations, but variations in sensitivity from site to site remain to be explained and are currently under study. One of the factors we will consider in this analysis is that of rock fraction. The rock volume varies from 10% to almost 50% among the sites and can have a significant effect on the microwave response [*Jackson et al.*, 1992]. The use of these data for runoff forecasting is described in another paper in this issue [*Goodrich et al.*, this issue]. Presently we are analyzing the day-to-day differences in soil moisture as a means for estimating the direct soil evaporation. For example, the moisture differences around site 5 from day 216 to day 217 indicate soil evaporation of 3–4.4 mm, which is in reasonable agreement with the values determined from the METFLUX data. This application of the data will be studied further in the near future.

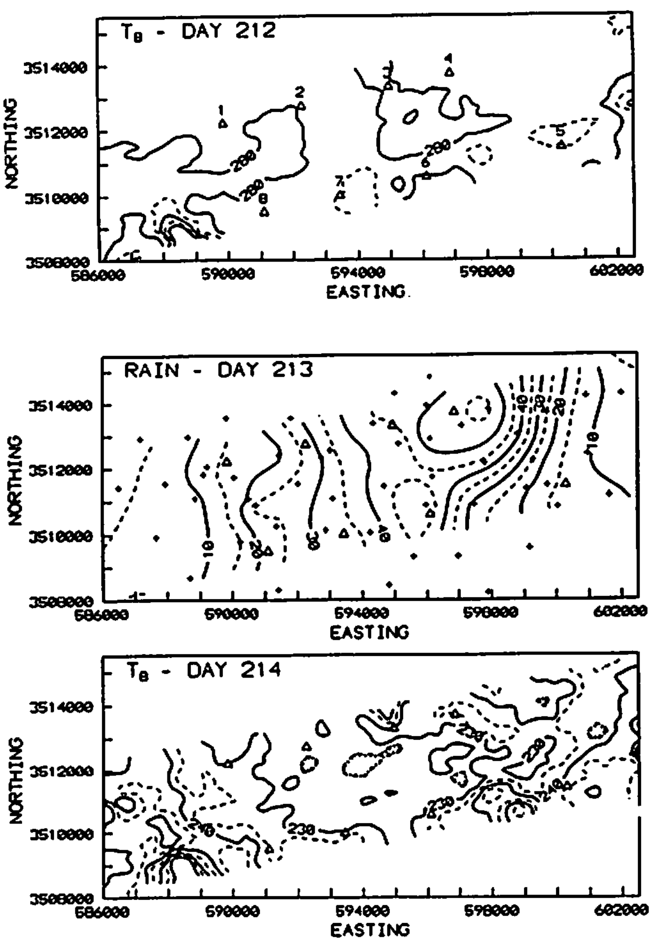

Figure 3. Contour maps of the PBMR brightness temperatures and rainfall for three days during Monsoon '90. (top) T_B is shown in degrees Kelvin for day 212; the triangles show the locations of the eight METFLUX sites. (middle) Rain amounts in millimeters on day 213 are shown; the pluses indicate the sites of the rain gages. (bottom) T_B is shown on day 214 after the rain.

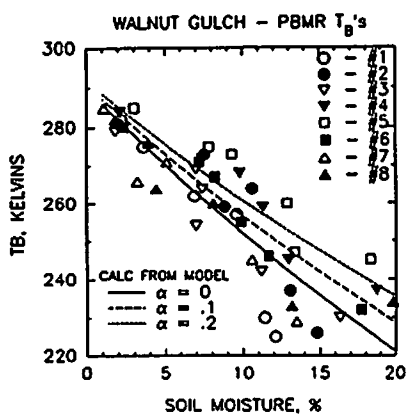

Figure 5. Comparison of T_B with ground measurements of soil moisture at the eight METFLUX sites. The curves are model predictions of the variation of emissivity with soil moisture for $\alpha = h + 2\tau = 0, 0.1$, and 0.2.

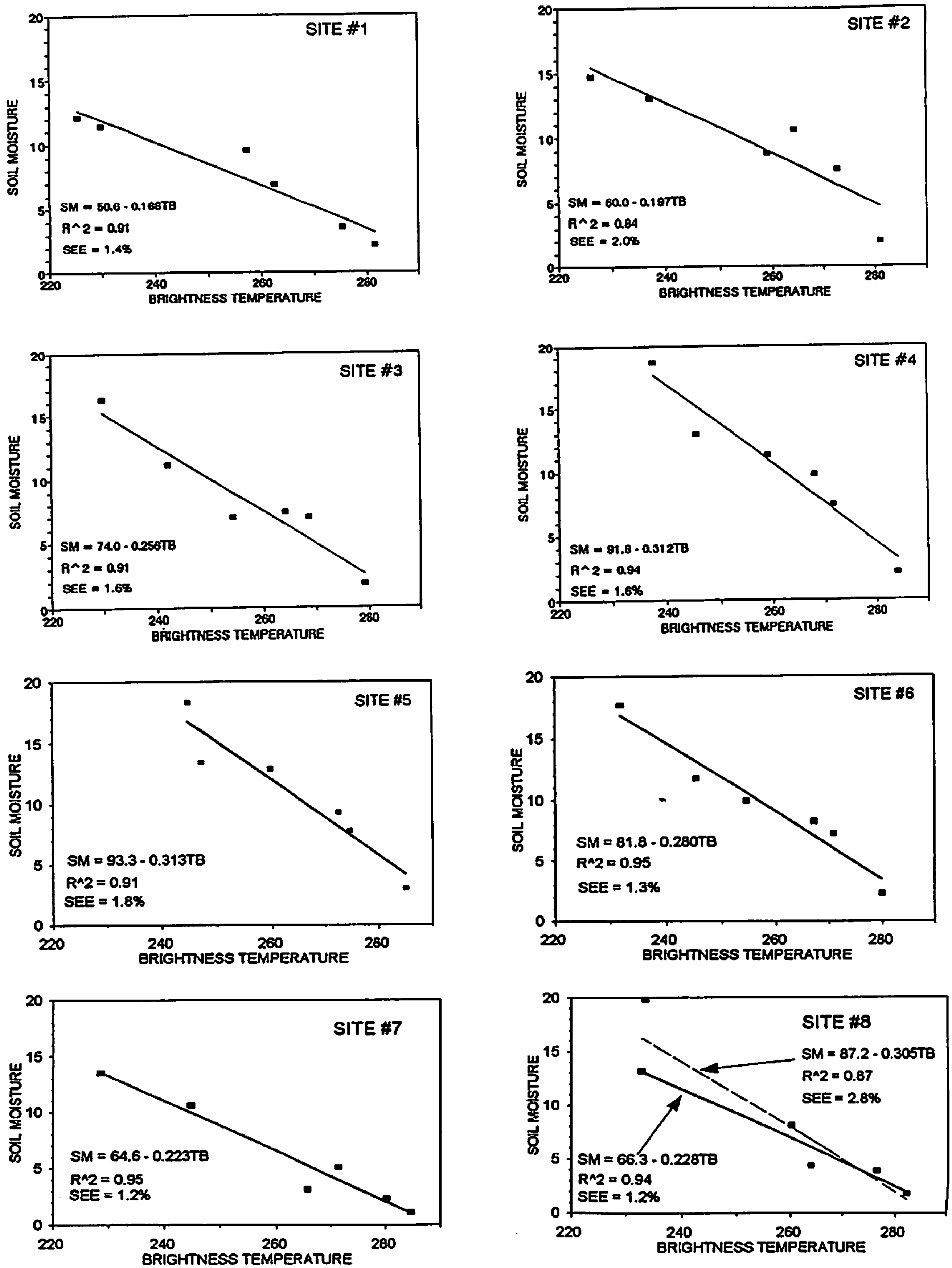

Figure 6. Plots of T_B versus volumetric soil moisture for the eight METFLUX sites with the regression lines shown.

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