A Growing Season Land Surface Process/Radiobrightness Model for Wheat-Stubble in the Southern Great Plains

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***Abstract*— Our point-scale Land Surface Process/Radiobrightness (LSP/R) model for a prairie grassland in the northern Great Plains was adapted to winter wheat-stubble within the region of the Southern Great Plains 1997 (SGP'97) Hydrology Experiment. The model maintains running estimates of near-surface soil moisture and stored water in soil and vegetation when forced by weather, and predicts the microwave brightness of the terrain. LSP/R model predictions were compared with the field observations recorded during SGP'97. The model captures canopy and soil temperatures very well, with the maximum mean and variance of the difference between the model and field temperatures being 1.06 K and 3.28 K^2, respectively. It yields reasonable predictions for the moisture in deeper layers of the soil, but its predictions for the moisture in the upper layers are low by ~ 2.3% by volume. These underpredictions of near-surface soil moisture result in higher H-pol brightnesses at 19 GHz than those observed.**

I. Introduction

PHYSICALLY-BASED modeling of near-surface energy and moisture fluxes is crucial for the accurate estimation of stored water by land surface process (LSP) models and the prediction of weather and near-term climate. However well the surface processes are simulated by the LSP models, current estimates of stored water will diverge from reality without the periodic incorporation of observational data that can be related to surface soil moisture. Microwave radiometry can provide those observations because of its sensitivity to soil moisture even when there is a relatively dense vegetation cover (i.e. wet biomass that can be as large as 6 kg/m^2 at 1.4 GHz) [15]–[17].

We have developed point-scale LSP/R models for northern Great Plains prairie in fall and winter [8], [24]. When forced by weather, the models maintain temporal estimates of soil moisture and temperature profiles, and these profiles are used to predict the microwave terrain brightness. Differences between the predicted and the observed brightnesses can be used to improve the models' estimates of stored water. Improvement of soil moisture estimates through the assimilation of remotely-sensed measurements, has been demonstrated [3], [9], [13], [19]. This work describes an adaptation of our LSP/R model, developed for prairie by Liou *et al*. [24], to winter wheat-stubble. We compare the moisture and temperature predictions

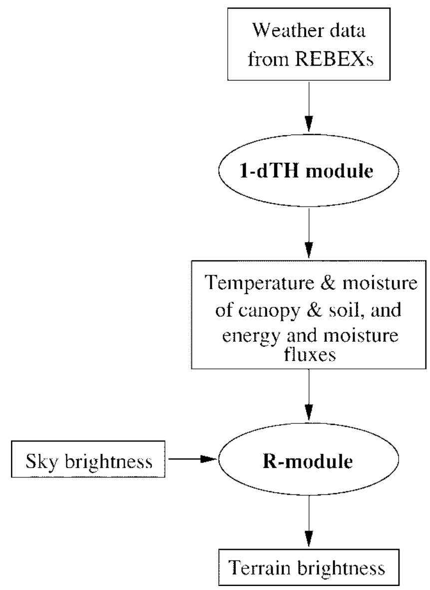

Fig. 1. Flow diagram of interactions between the 1-dTH and the R modules.

Fig. 2. Picture showing TMRS setup at the ARM-CART Central Facility near Lamont, OK. A truck-based microwave system with L-, S- and C-band radiometers from NASA Goddard Space Flight Center can be seen in the background.

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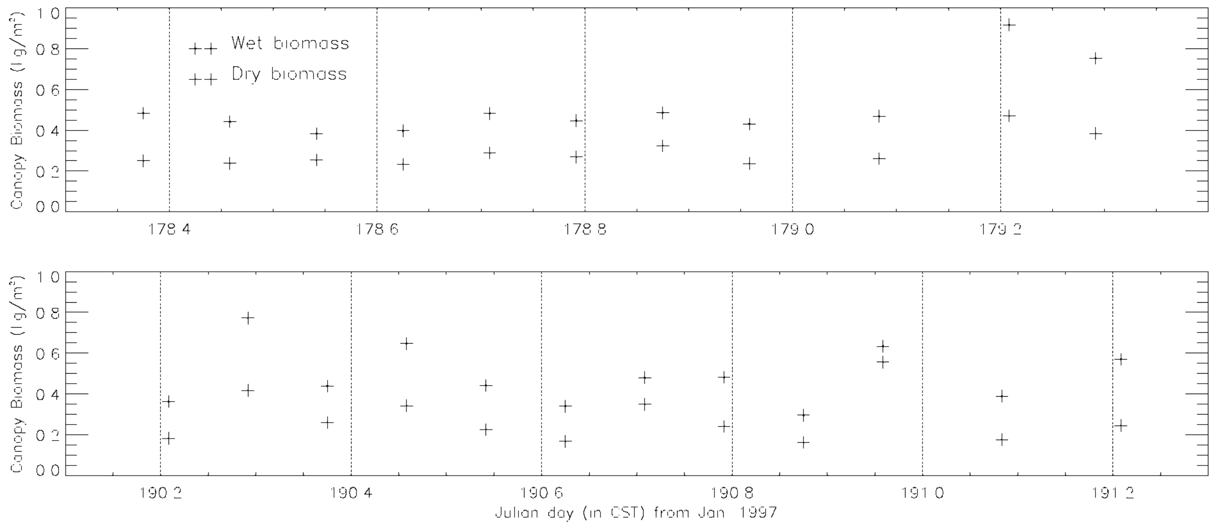

Fig. 3. Wet and dry biomass of wheat-stubble measured during two diurnal experiments from REBEX-5.

TABLE I
SOIL PROPERTIES USED IN THE MODEL

Properties	Values
Texture	20% sand, 60% silt, 20% clay [6]
Porosity	0.46 [6]
Sat. Hydr. Cond.	2x10^{-6} - 6x10^{-8} m/sec [1]
Therm. Cond.	1.6 - 2.75 $J/m.K.sec$ [4]
Field Capacity	0.20 % by volume [6]
Albedo	0.5 [*unconstrained parameter, best estimate*]

TABLE II
VEGETATION PROPERTIES USED IN THE MODEL

Properties	Values
LAI	0.7 [*unconstrained parameter, best estimate*]
TIR emissivity	0.98 [11]
Root depth	10 cm [10]
Wet Biomass	0.5 kg/m^2 [Figure 3, [10]]
Initial moisture	0.22 kg/m^2 [10]

TABLE III
MEAN DIFFERENCES AND VARIANCES BETWEEN LSP/R PREDICTIONS AND SGP'97 OBSERVATIONS FOR CANOPY AND SOIL TEMPERATURE

	Mean Difference (K)	Variance (K^2)
Canopy	-0.276	3.28
3 cm	0.270	2.41
10 cm	0.029	0.75
20 cm	-0.025	0.41
40 cm	1.016	0.12
60 cm	-0.177	0.21

for soil and canopy, and the 19-GHz brightness predictions with those observed during SGP'97.

II. THE LSP/R MODEL

The LSP/R model for wheat-stubble consists of two modules: a one-dimensional coupled thermal and hydrology module (1-dTH) and a radiobrightness module (R). When forced by observed weather, the 1-dTH module models moisture and energy exchanges between soil, canopy and atmosphere, and nonisothermal moisture transport in soil and through the canopy. The R-module predicts apparent terrain brightnesses based upon the estimated profiles of moisture and temperatures by the 1-dTH module. Fig. 1 shows the interactions between the two modules.

A. 1-dTH Module

The 1-dTH module consists of a multilayered soil with a bilayer canopy. The soil is modeled to a depth of 4 m to capture the diurnal and seasonal variations in moisture and temperature, and is divided into eleven standard layers with distinct physical, thermal, and hydraulic properties. The layers are discretized into 60 nodes, the thicknesses of which increase with depth. Soil properties used for the upper 10 cm are given in Table I. The canopy consists of a layer of wheat-stubble, grass, and weeds overlying a layer of wheat-straw from the harvest. The canopy properties used in the model are given in Table II.

The equations of conservation of energy and moisture govern heat and moisture transport in soil [(1) and (2)] and canopy [(3) and (4)] [5], [22], [24]. The module uses a forward finite-difference method to solve these equations for moisture and temperature in the soil and canopy [22].

$$\frac{\partial X_m}{\partial t} = -\nabla \cdot \vec{q}_m \tag{1}$$

$$\frac{\partial X_h}{\partial t} = -\nabla \cdot \vec{q}_h \tag{2}$$

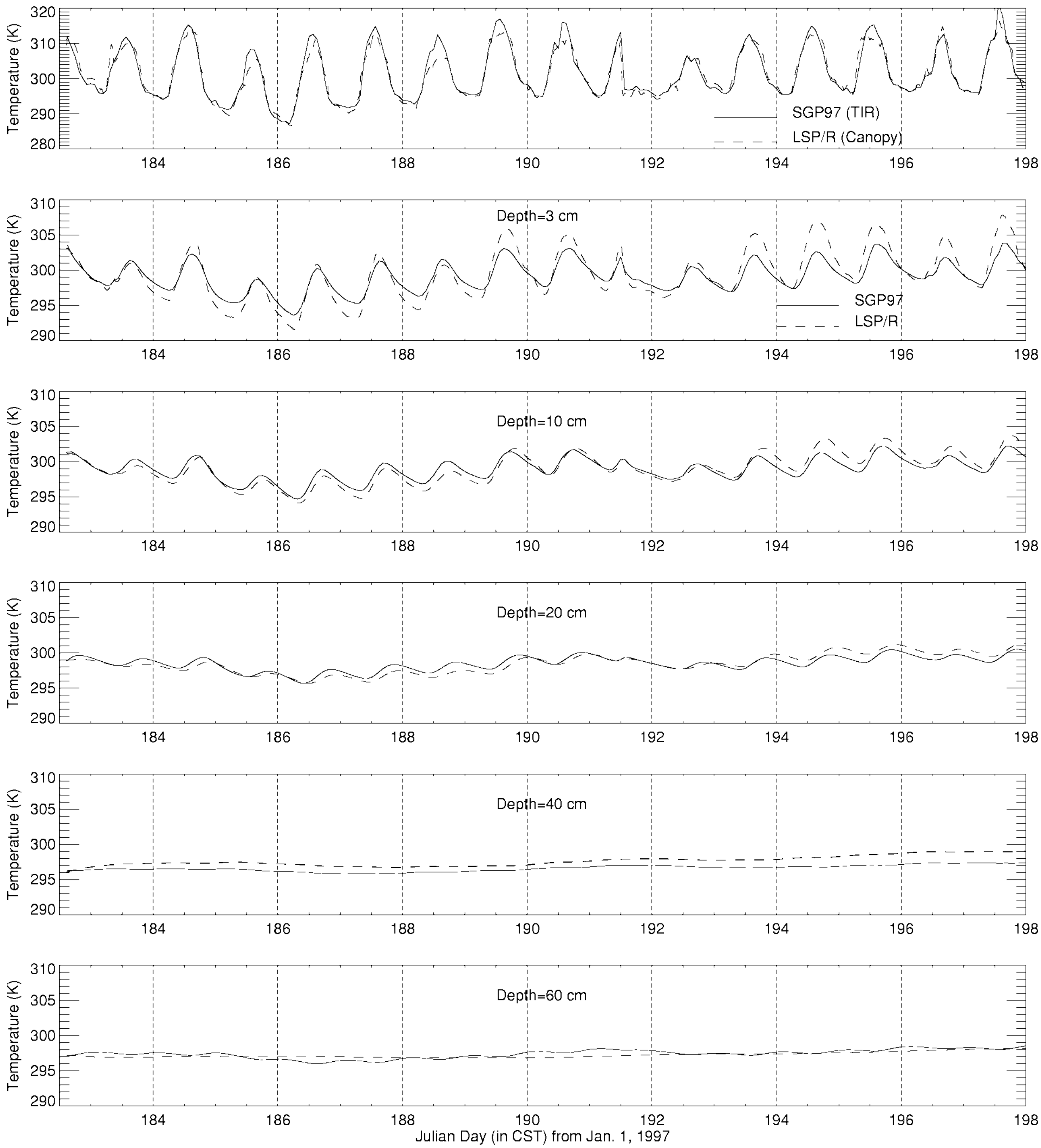

Fig. 4. Comparison of predicted and observed canopy temperatures, and soil temperatures at depths of 3, 10, 20, 40, and 60 cm.

$$\frac{\partial X_{hc}}{\partial t} = F_c \tag{3}$$

$$\frac{\partial X_{mc}}{\partial t} = \rho_l (P_c - D_c - E_c) \tag{4}$$

where

X_m total water content per unit volume (kg/m^3);
X_h total heat content per unit volume (J/m^3);
$\vec{q}_m$ moisture flux density (kg/m$^2 \cdot$ s);
$\vec{q}_h$ heat flux density (J/m$^2 \cdot$ s);
X_{hc} total heat content per unit area of the canopy layer (J/m^2);
F_c net heat flux into the canopy layer (W/m^2);
X_{mc} total moisture content per unit area of the canopy layer (kg/m^2);
ρ_l density of liquid water (kg/m^3);
P_c, D_c, E_c rates of precipitation, water drainage and evaporation from the wet fraction of canopy (m/sec), respectively.

Initial conditions for the upper 60 cm of soil moisture and temperature profiles are obtained from SGP'97 observations. The temperature profile for the deeper layers is estimated from an annual model [23]. Boundary forcings at the surface were obtained from micro-meteorological and downwelling sky radiance observations during SGP'97. The surface bound-

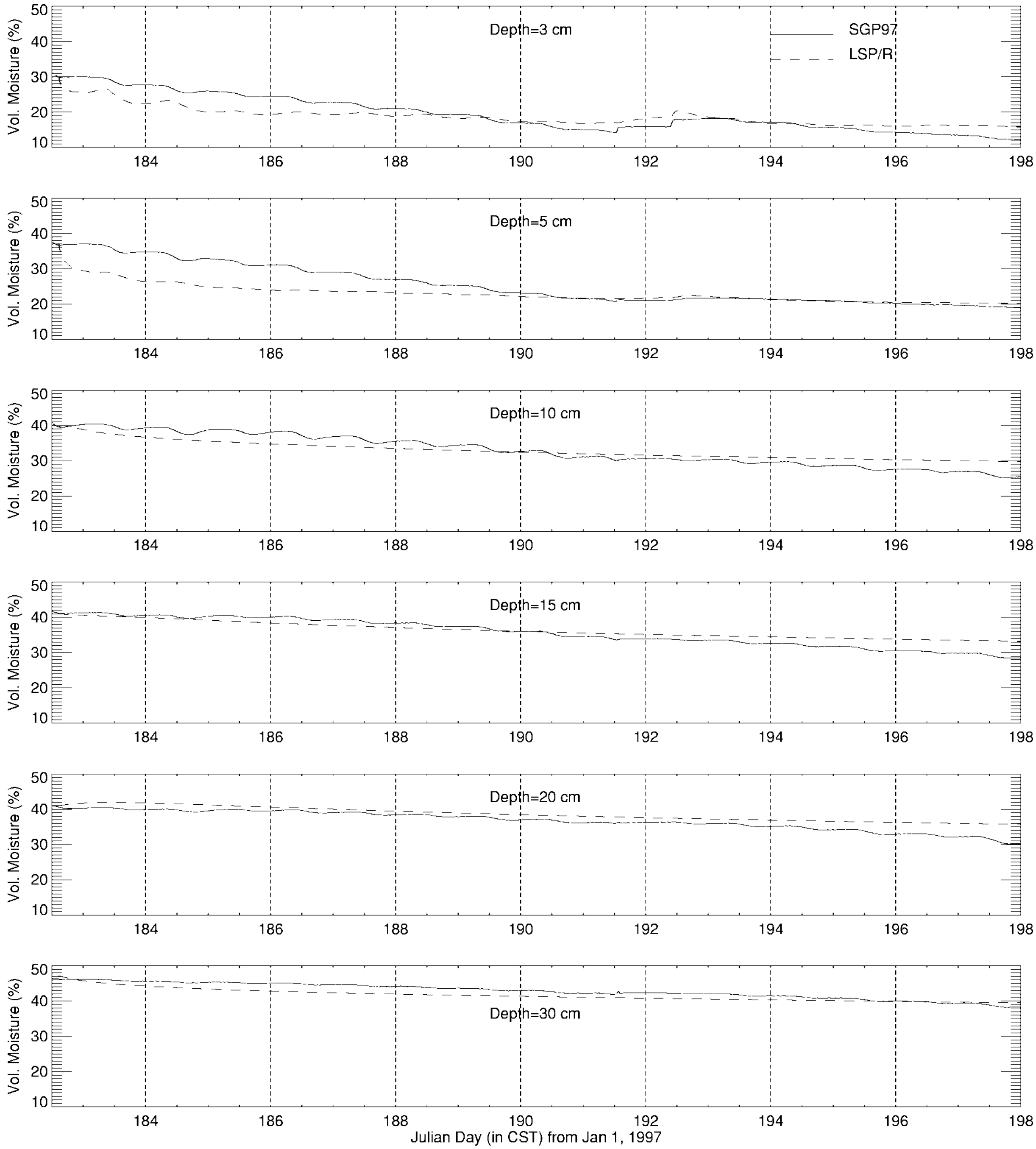

Fig. 5. Comparison of predicted and observed volumetric moisture in the soil at depths of 3, 5, 10, 15, 20, and 30 cm.

ary condition is from the energy balance among short and longwave radiation, and sensible and latent heat exchanges [24]. Soil retention curves are from the two-parameter junction model by Rossi and Nimmo [2], [18] and hydraulic conductivity is from the model by Mualem [21], [22]. Thermal conductivity, as a function of soil moisture and soil geometrical properties, follows the method used by DeVries [4].

B. R-Module

The R-module approximates the canopy as a cloud with a distributed dielectric profile [24]. In our prairie model, we assign dielectic properties to a living canopy based upon the dual-dispersion model of Ulaby and El-Rayes [7]. In the dual-dispersion model, water is partitioned into bound-water (estimated by a sugar solution) and free water. It is unclear whether this is appropriate for inactive wheat-stubble. For simplicity, we have assumed that all water in the canopy is free water. Our canopy parameters are given in Table II. The soil is a smooth-surfaced, incoherent, multilayer emitter with dielectric properties from Dobson *et al.*'s four-component mixing model [12]. Total emission at each polarization from the wheat-stubble is

$$Tb_{\text{total}}\binom{v}{h} = Tb_{\text{soil}}\binom{v}{h} + Tb_{\text{canopy},d}\binom{v}{h} + Tb_{\text{canopy},u}\binom{v}{h} + Tb_{\text{sky}}\binom{v}{h} \tag{5}$$

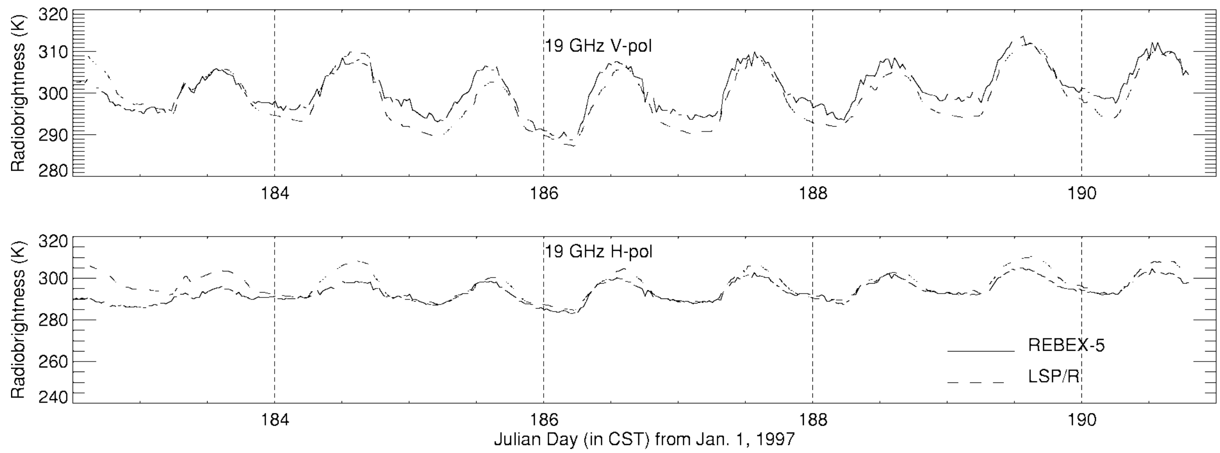

Fig. 6. Comparison of predicted and observed 19-GHz V- and H-pol terrain brightnesses.

where

Tb_{soil}	upwelling soil brightness;
$Tb_{\text{canopy},d}$	reflected downwelling canopy brightness,
$Tb_{\text{canopy},u}$	upwelling canopy brightness,
Tb_{sky}	reflected downwelling sky brightness [24].

III. Field Experiments

A. SGP'97

SGP'97 was an interdisciplinary investigation conducted from June 18 through July 17, 1997, that covered 11 000 km^2 of Oklahoma. One of its major objectives was to estimate soil moisture and temperature using remote sensing at different spatial scales [14]. Investigators collaborated to measure and map soil and vegetation properties; to monitor radiant fluxes, and soil temperature and moisture profiles; and to record weather. Microwave brightness and radar observations were made from the ground, aircraft and satellites.

B. REBEX-5

The University of Michigan's Microwave Geophysics group conducted its fifth Radiobrightness Energy Balance Experiment (REBEX-5) as its contribution to SGP'97. REBEX-5 provided a point temporal record of the microwave brightness of senescent winter wheat and, after harvest, wheat-stubble at DOE's Atmospheric Radiation Measurement—Cloud and Radiation Testbed (ARM-CART) Central Facility near Lamont, OK [10]. Michigan's Tower Mounted Radiometer System (TMRS) observed dual polarized 19.35- and 37.0-GHz brightnesses and H-polarized 85.5-GHz brightnesses every half-hour from a 10-m tower (Fig. 2). The radiometers duplicate the frequencies, polarizations, and incidence angle of the Special Sensor Microwave/Image (SSM/I). The group also measured canopy biomass during four diurnal experiments: two with senescent winter-wheat and two with wheat-stubble. Each experiment consisted of weighing the wet biomass of the canopy cut from a 900 cm^2 plot, every 2–3 h for a 24-h period during a precipitation-free day. Whenever there was water on the canopy due to condensation, it was included in the wet biomass measurement. The samples were dried at 70°F for 24 h in a laboratory and weighed again. Fig. 3 shows the wet and dry canopy biomass measurements during the two experiments with wheat-stubble. Because we had only one measurement every 2–3 h, we used an average of values in the two experiments to estimate the canopy biomass (see Table II).

IV. Results and Discussion

The 1-dTH module was run from Julian day 182 through 198. There was heavy precipitation five days before the run-period, 10 mm on day 177, and light precipitation, 3 mm, on day 192. The module predicts soil and canopy temperatures that match well with those observed during SGP'97 (Fig. 4). Mean differences and variances between the predicted and the observed temperatures are shown in Table III. The module captures the moisture profiles in deeper layers fairly well throughout the simulation period, but significantly underestimates moisture in the upper layers (0–5 cm depth) until day 190 (Fig. 5). After day 190, the moisture estimates differ from the SGP'97 measurements by as much as 3% by volume. This difference is within the accepted range of experimental error during SGP'97 moisture measurements [20]. The mean differences and variances between the predicted and the observed moisture values are given in Table IV.

The R-module was run from Julian day 182 through 191 (constrained by periods of missing brightness data after day 191). The results are shown in Fig. 6 and Table V. The sensitivity of the 19 GHz H-pol brightnesses to soil moisture for the given canopy biomass is approx. 2 K/% by volume, so that a mean difference of 3.1 K in the H-pol brightnesses translates to a 1.6% by volume error in the soil moisture. Differences between the observed and the predicted H-pol brightnesses may be largely due to error in the near-surface soil moisture prediction. V-pol brightnesses are less sensitive to soil moisture because their incidence angles are close to the brewster angle. Some of the differences may be a result of the smooth surface approximation in the R-module. Roughness causes an increase in emissivity.

V. Summary

We compared the predictions from our point-scale LSP/R model for winter wheat-stubble with temperature, moisture, and radiobrightness observations for a site within the region of SGP'97. The model soil and canopy temperatures match very well with the observed data, but the model soil moisture

TABLE IV
MEAN DIFFERENCES AND VARIANCES BETWEEN LSP/R PREDICTIONS AND SGP'97 OBSERVATIONS FOR VOLUMETRIC SOIL MOISTURE

Depth (cm)	Mean Difference (% by vol.)	Variance ($\%^2$ by vol)
3	-0.61	7.33
5	-2.30	10.37
10	-0.04	4.72
15	0.61	3.24
20	1.67	1.19
30 cm	-1.15	0.83

TABLE V
MEAN DIFFERENCES AND VARIANCES BETWEEN LSP/R PREDICTIONS AND REBEX-5 OBSERVATIONS FOR 19-GHz TERRAIN BRIGHNTESSES

Polarization	Mean Difference (K)	Variance (K^2)
V	-1.8	5.4
H	3.1	12.8

levels in the upper layers are lower than those measured in the field by ~2% by volume. These underpredictions resulted in 19 GHz H-pol brightnesses that were 3.1 K higher than the observed.

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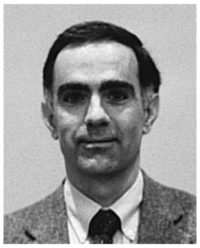

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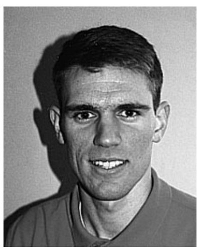

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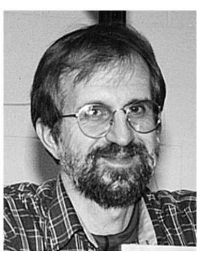

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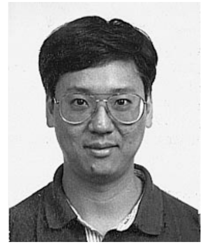

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