Diurnal Variation of Vertical Temperature Gradients Within a Field of Maize: Implications for Satellite Microwave Radiometry

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***Abstract*—We present the diurnal variation of vertical temperature differences measured within and beneath a maize canopy over the course of a growing season, and we analyze the implied temperature gradients in the context of microwave radiometry and soil moisture retrieval in particular. We find that the temperature differences can be as large as 9 K in magnitude within the vegetation canopy and as large as 10 K between the soil surface and a depth of 4.5 cm. Satellite overpass times at 1:30 A.M. and 1:30 P.M. occur close to when the magnitude of the temperature differences are largest. For 6 A.M. and 6 P.M. overpass times, temperature differences were smaller in magnitude at 6 P.M. This contradicts the widely held assumption that surface temperature gradients are more uniform at 6 A.M. than at 6 P.M.**

***Index Terms*—Microwave radiometry, soil moisture, soil temperature, vegetation temperature.**

I. INTRODUCTION

VEGETATION and soil temperatures vary diurnally in response to atmospheric forcings. An example of this variation (for a field of maize, but representative of other canopies) is shown in Fig. 1. Although temperature variations generally have the same period, their amplitude and phase depend on their relative vertical position and constitutive properties such as thermal conductivity, heat capacity, and density [1]. The vertical temperature profile is often not uniform, and gradients within the canopy and soil normally exist. The impact of temperature gradients within the soil and vegetation on remote sensing depends on the wavelength of observation.

In microwave radiometry of the land surface, the emitting depth can be significant. Consider a nonscattering layer of vegetation over a soil half-space. The radiative transfer equation can be written [2]

$$T_B(z,\mu) = T_B(0,\mu)e^{-\frac{\tau(0,z)}{\mu}} + \int_0^z \frac{1}{\mu}\kappa_a(z')T(z')e^{-\frac{\tau(z',z)}{\mu}}dz'. \tag{1}$$

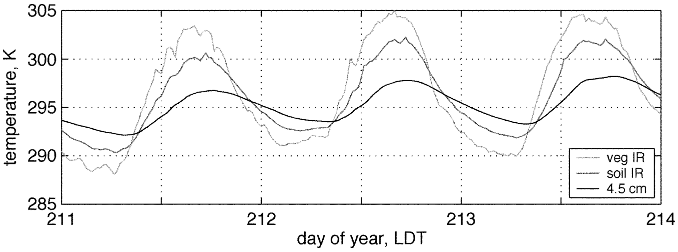

Fig. 1. Vegetation and soil temperatures for a maize canopy from day of year 211 (July 30) to 214 (August 2). Vegetation temperature measured at the top of the canopy (veg IR). Soil temperatures measured at the soil surface (soil IR) and at 4.5 cm below the surface. LDT is local daylight saving time.

Here $\mu = cos\theta$, where θ is the angle relative to the surface normal. The brightness temperature at the top of the vegetation canopy $T_B(z,\mu)$ has two components: radiation emitted by the soil beneath the canopy $T_B(0,\mu)$ and thermal emission from the vegetation $\kappa_a(z')T(z')$, where κ_a is the absorption coefficient and T the temperature. Both components are attenuated according to the optical depth of the vegetation, $\tau(z',z)$. When the optical depth is small, microwave emission depends on the temperature profile $T(z')$ within the vegetation, as shown in (1). Similarly, the soil temperature profile can also be important. For example, at L-band, the absorptive properties of vegetation and soil are such that modest canopies are semitransparent, and the first several centimeters of soil contribute to the emission from the land surface.

We present the diurnal variation of vertical temperature differences within a field of maize over the course of a growing season. We then analyze the temperature gradients implied by these temperature differences in the context of satellite microwave radiometry and soil moisture retrieval in particular.

II. MEASUREMENTS

The experimental site, an 800 m (east–west) × 400 m (north–south) corn field in southeastern Michigan, was unusually flat and uniform in terms of soil properties and vegetation. The soil at the site was a silty clay loam of the Lenawee series (16.1% sand, 55.0% silt, 28.9% clay). Average row spacing was 0.77 m. Plant density was 7.49 m^{-2}. Rows were planted east–west. The field was planted on April 29 and 30 (day of year 119 and 120) and harvested on October 17 and 18 (day of year 290 and 291). After June 25 (day of year 176), the fraction of vegetation cover was unity. The evolution of leaf-area index, vegetation column density, and water column density is shown in Fig. 2. We measured near-surface soil temperature, soil surface infrared temperature, vegetation infrared temperature,

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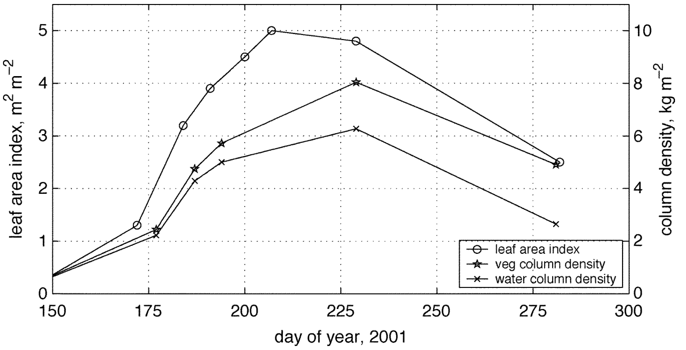

Fig. 2. Maize canopy leaf area index, mass of vegetation per unit area (vegetation column density), and mass of water within the vegetation per unit area (water column density) during the growing season of 2001.

air temperature, relative humidity, and downwelling solar and atmospheric radiation with instruments mounted on or near a tower-based micrometeorological station located at the approximate center of the field. A datalogger system sampled each instrument once every 10 s and recorded 20-min averages. Only data from day of year 177 (June 26) until 283 (October 10) are presented in this letter.

We buried six thermistors in the soil at 4.5 cm. The thermistors were distributed between several adjacent rows, three in row spaces and three in the rows. Each thermistor had an accuracy of $< \pm 0.2$ K and a precision of <0.1 K. We measured top-of-the-canopy vegetation temperature with an infrared thermometer (IRT) pointed at nadir approximately 1 m above the canopy. We measured soil surface temperature with an identical IRT underneath the canopy approximately 20 cm above the ground, centered in the row space, and pointed at nadir. The field of view of each IRT is $1:1$ for 98% of the signal (at 1 m away from the target the field of view is 1 m).

Each IRT consists of two thermocouples, one for the detector and another for the sensor body. The only significant thermocouple measurement error was an uncertainty in the reference junction temperature of $< \pm 0.3$ K. The manufacturer's estimate of error for each IRT is ± 0.4 K with sensor body temperature correction and ± 0.1 K when detector and sensor body temperatures are equal. For the IRT at the soil surface, its detector and sensor body temperatures will be nearly equal. We estimate the soil surface IRT to have an accuracy of better than ± 0.4 K. We estimate the total accuracy of the canopy temperature gradient measurement to be ± 0.5 K (reference junction temperature errors cancel). IRT precision is <0.1 K.

The canopy space at the soil surface is nearly a blackbody cavity. At the top of the canopy, emission from the sky at infrared wavelengths is considerably different than emission from the canopy, and reflected sky brightness should be considered. A vegetation canopy can be modeled as a Lambertian (perfectly rough) surface with an emissivity of 0.98 to 0.99 [1]. The radiant emittance at the top of the canopy I, is

$$I = eI_B(T_{\mathrm{can}}) + [1 - e]I_{\mathrm{sky}} \tag{2}$$

where e is the emissivity of the canopy, I_B is blackbody radiant emittance, T_{can} is the radiometric temperature of the canopy, and I_{sky} is sky irradiance. The units of irradiance are power per area [1]. An IRT reports a brightness temperature that corresponds to the radiance, R in its field of view. Since emission from a Lambertian surface is independent of angle, we have

$$R = \frac{I}{\pi}. \tag{3}$$

The units of radiance are power per area per solid angle. I, I_B, I_{sky}, R, and e are specific to the finite wavelength band of the IRT.

The difference between I and $I_B(T_{\mathrm{can}})$ will be largest on clear days. Sky irradiance can be related to near-surface air temperature T_{air}

$$I_{\mathrm{sky}} = e_{\mathrm{sky}} I_B(T_{\mathrm{air}}) \tag{4}$$

where e_{sky} is the emittance of the atmosphere in the wavelength band of the IRT. The emittance of the sky over all wavelengths $e_{\mathrm{sky},\infty}$ can be written

$$e_{\mathrm{sky},\infty} = \frac{I_{\mathrm{sky},\infty}}{\sigma T_{\mathrm{air}}^4} \tag{5}$$

where $I_{\mathrm{sky},\infty}$ is sky irradiance over all wavelengths, and σ is the Stefan–Boltzmann constant. For a clear sky

$$e_{\mathrm{sky},\infty} = 1.72 \left[\frac{w_{\mathrm{air}}}{T_{\mathrm{air}}}\right]^{\frac{1}{7}} \tag{6}$$

where w_{air} is the water vapor pressure near the surface [3]. We used measurements of w_{air} and T_{air} to find $e_{\mathrm{sky},\infty}$ in (6). Numerical calculations using [1, Fig. 10.6] produced $e_{\mathrm{sky}} = 0.383$. We then used calculated values of T_{air} (not site measurements), determined with ventilated pyrgeometer measurements of $I_{\mathrm{sky},\infty}$ in (5), to produce a better estimate of I_{sky} in (4). I_{sky} was calculated for the 13 clear-sky days during the experiment.

For a Lambertian surface of temperature $T_s = 300$ K, emissivity $e = 0.98$, and the smallest calculated I_{sky}, the brightness temperature would be 299.1 K. For a Lambertian surface of temperature $T_s = 300$ K, emissivity $e = 0.99$, and the largest calculated I_{sky}, the brightness temperature would be 299.7 K. Hence, the maximum difference between the radiometric temperature of the vegetation canopy and the brightness temperature reported by the IRT was about 0.9 K. This difference was always at least 0.3 K on clear-sky days. These errors are similar to those reported in another study [4] and small enough to be neglected when analyzing our data.

III. RESULTS

The diurnal variations of the soil temperature difference and vegetation canopy temperature difference are shown in Figs. 3 and 4, respectively. Many remote sensing satellites are in sun-synchronous (polar) orbits so that they pass over areas on the earth's surface at the same local solar time. Accordingly, solar time is used in each figure. Solar time is calculated by referencing time to solar noon, the time of day that the sun reaches its highest point in the sky (also the midpoint between sunrise and sunset). Solar noon for the experiment site varied from 12:38 Eastern Standard Time (EST) on day of year 177 (June 26) to 12:42 EST on day of year 207 (July 26) to 12:22 EST on day of year 283 (October 10). From day of year 177 to 188 and

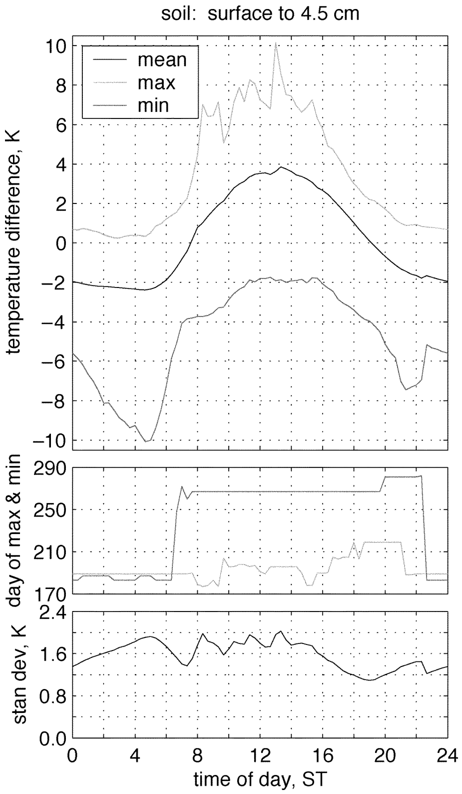

Fig. 3. Diurnal variation of the vertical temperature difference between the soil surface and a depth of 4.5 cm beneath a maize canopy. (Top) The mean, maximum, and minimum values. (Middle) Day of year when maximum and minimum values were observed. (Bottom) The standard deviation. ST is solar time.

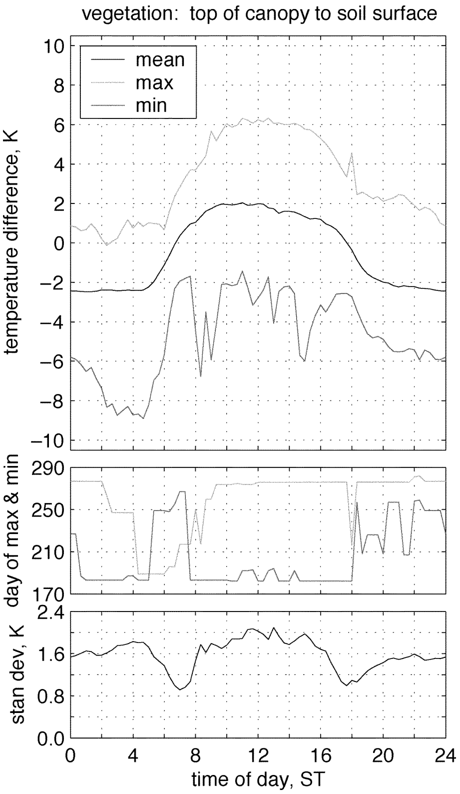

Fig. 4. Diurnal variation of the vertical temperature difference between the top of a maize canopy and the soil surface. (Top) The mean, maximum, and minimum values. (Middle) Day of year when maximum and minimum values were observed. (Bottom) The standard deviation. ST is solar time.

from day of year 222 to 283, solar noon fell within the 12:20 to 12:40 EST datalogger collection period. From day of year 189 to 221, solar noon fell within the 12:40 to 13:00 EST collection period. We converted the time reference of the data from EST to ST by shifting the data appropriately.

IV. ANALYSIS

The largest observed soil temperature difference was 10 K. The mean difference in the soil over the course of a day ranged from 4 to −2 K. Most extreme differences occurred early or late in the growing season, although the maximum observed differences from 6 P.M. to 9 P.M. occurred about day of year 210 during the period of maximum leaf-area index. The average difference was close to 0 K at approximately 7:30 A.M. and 7 P.M. The standard deviation of the temperature difference dips precisely at the points of zero average difference. In the vegetation canopy, the largest observed difference was nearly 9 K. The mean difference over the course of a day ranged from 2 to –2 K. Most extreme differences also occurred during the early or late growing season save for some notable exceptions between 6 P.M. and 10 P.M. The average difference was near 0 K about 6:40 A.M. and 5:40 P.M. The standard deviation of the canopy temperature difference dips even more sharply than the soil temperature difference when the average difference is near zero.

The National Aeronautics and Space Administration (NASA) Aqua satellite, which carries microwave radiometers that measure various surface variables including soil moisture, has 1:30 A.M./1:30 P.M. overpass times [5]. Several future satellite L-band radiometers will also provide surface soil moisture measurements. These include the European Space Agency's Soil Moisture and Ocean Salinity mission [6], NASA's Aquarius (http://aquarius.gsfc.nasa.gov/), and NASA's HYDROS (http://hydros.gsfc.nasa.gov/). All three will have overpass times of 6 A.M./6 P.M. Histograms of the soil and vegetation canopy temperature differences at overpass times of 1:30 A.M./1:30 P.M. and 6 A.M./6 P.M. are shown in Figs. 5 and 6.

The 6 A.M./6 P.M. overpass is typically chosen to minimize the effect of temperature gradients within the soil and vegetation on soil moisture retrieval. Temperature gradients are smallest in magnitude at the point of thermal crossover, near sunrise and sunset, as illustrated in Fig. 1. Temperature differences are clearly smaller, on average, at the 6 A.M./6 P.M. overpasses than at the 1:30 A.M./1:30 P.M. overpasses. The average soil temperature difference at 1:30 A.M. and 1:30 P.M., was about –2 and 4 K, respectively, while the average vegetation canopy temperature difference was about –2.5 and 1.5 K, respectively. The overpass times at 1:30 A.M./1:30 P.M. are close to the times of maximum differences. At 6 A.M. and 6 P.M., the average soil difference was about –2 and 1 K, respectively, and the canopy difference was about −1 and −0.5 K, respectively.

V. CONCLUSION

Of the common satellite overpass times, temperature differences in the soil and vegetation were smallest on average at 6 P.M. We expected differences to be smallest in the morning, at 6 A.M., rather than in the evening. Our expectation was based upon the widely held assumption in the microwave remote

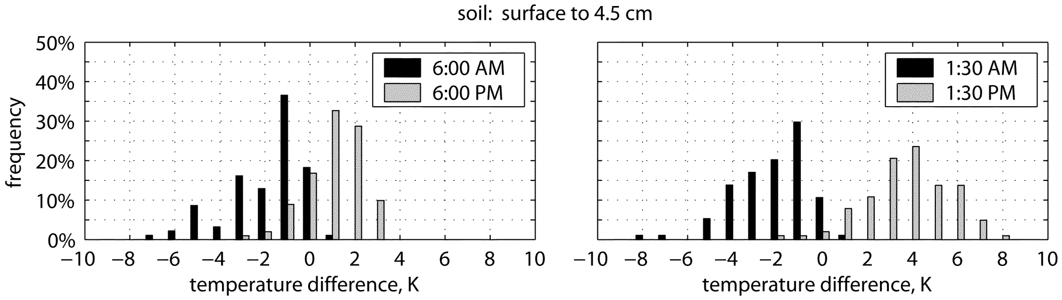

Fig. 5. Distribution of soil temperature differences at 6 A.M./6 P.M. and 1:30 A.M./1:30 P.M. satellite overpass times.

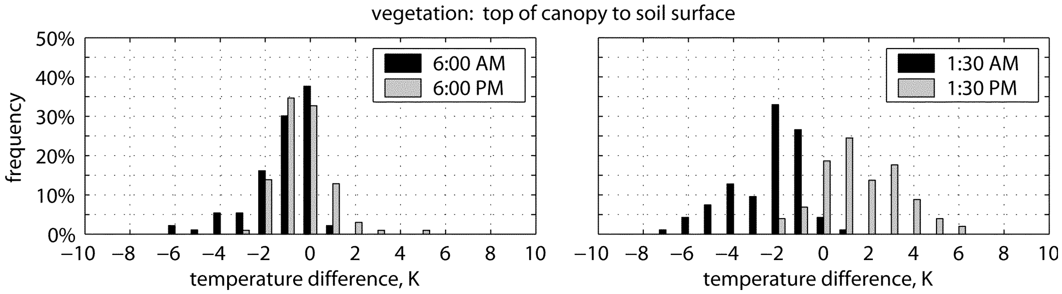

Fig. 6. Distribution of canopy temperature differences at 6 A.M./6 P.M. and 1:30 A.M./1:30 P.M. satellite overpass times.

sensing community that surface temperature gradients are more uniform at 6 A.M. than at 6 P.M. Our data indicate that the 6 P.M. overpass is at least as good, if not better than, the 6 A.M. overpass when considering the impact of temperature gradients upon soil moisture retrieval with microwave radiometry. Note that our findings cannot be translated directly to gradients of near-surface soil moisture, since soil water content does not change instantaneously in response to temperature gradients [7]. There also may be other effects that should be considered, such as the diurnal variation of electron density in the ionosphere and its effect on the rotation of the polarization vector (Faraday rotation) [8]. Finally, our observations are limited to a single field. Further experiments and modeling should be conducted to strengthen our conclusions.

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