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Radiobrightness of prairie soil and grassland during dry-down simulations

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Abstract. We present 60-day summer dry-down simulations for prairie grassland based upon a one-dimensional hydrology and radiobrightness models for northern prairie. Our objective is to examine the effect of scaling upon the interpretability of mixed pixel radiobrightnesses. Even for relatively homogeneous regions like North American prairie, there are significant variations in land cover within the relatively large footprints of satellite microwave radiometers. In this paper we specifically address 1.4- and 19-GHz brightness in the presence of subpixel variability in canopy density. Bare soil and a dense-canopy grassland can be viewed as extreme examples of prairie land cover. If land cover within any pixel is viewed as a mixture of these two extremes, then the terrain within that pixel can be modeled as some combination of the hydrology and radiobrightness models for bare soil and dense-canopy grassland. We examined two combination schemes: (1) a homogeneous combination where the dense-canopy grasses are simply spread uniformly over the pixel to achieve a desired vegetation column density between that of bare soil and dense-canopy grass, and (2) a tiled combination where the pixel is divided into a region of bare soil and a region of dense-canopy grassland. We examined H-polarized, 53° incidence angle, 19.35- and 1.4-GHz pixel brightnesses and found the 19-GHz brightness to be significantly greater for homogeneous pixels than for tiled pixels throughout the dry-down period. For example, a 19-GHz, 50% homogeneous pixel is 50 K brighter than a 50% tiled pixel at the beginning of the dry-down and 40 K brighter at 60 days. In contrast, the 1.4-GHz brightnesses are essentially identical for homogeneous and tiled pixels. Within the constraints of our simulation, subpixel variation in canopy density is a significant factor in the quantitative interpretation of the 19-GHz brightness of prairie grassland but is not a factor in the interpretation of the 1.4-GHz brightness.

1. Introduction

Water in soil and vegetation that is available to the atmosphere through evaporation or transpiration is often referred to as stored water. Stored water plays a significant role in the land-atmosphere exchanges of energy and moisture and becomes a critical parameter in atmospheric models for continental weather and climate [*Rowntree and Bolton*, 1983; *Cunnington and Rowntree*, 1986; *Rowell and Blondin*, 1990]. Embedded within each atmospheric model, a land-surface process (LSP) model acts as an accounting system for energy and water in soil and vegetation and manages the energy and moisture exchanges between the land and the atmosphere for each grid cell of the atmospheric model [*Dickinson et al.*, 1986; *Xue et al.*, 1991]. Because each cell, even for the larger-scale mesoscale models, may represent several hundred square kilometers, there have been many studies of the effects of subgrid variability upon model outcomes [*Blyth*, 1995; *van den Hurk and Beljaars*, 1996]. For example, a cell that is evenly divided into one region of forest and one region of grassland is likely to interact differently with the atmosphere than a cell where the same forest is dispersed into many smaller tree stands that are distributed uniformly over the grassland. These are "scaling" issues.

Scaling issues may also be a concern in the assimilation of microwave brightness data, as they will be used to improve soil moisture estimates within an

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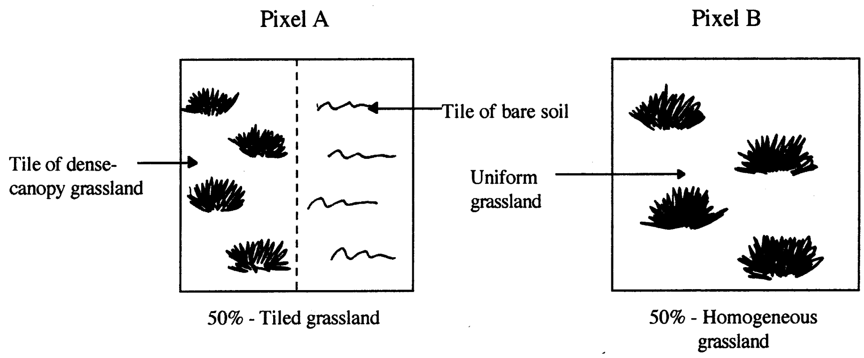

Figure 1. Mixed pixel schematic. Pixel A represents two regions of equal area: The left tile is a dense-canopy grassland, and the right tile is a bare soil. Pixel B represents a uniform distribution over the entire pixel of the grass found in the tile on the left in pixel A.

LSP model. The pixel area of a satellite microwave radiometer is often nearly the cell size of a mesoscale atmospheric model; that is, one brightness temperature represents the contributions of several hundred square kilometers. Even for relatively homogeneous regions like North American prairie, there are significant variations in land cover within such a large pixel. Our objective is to examine the effect of scaling upon the interpretability of the mixed pixel radiobrightness of North American prairie. Specifically, we compare 1.4- and 19-GHz brightnesses in the presence of a subpixel variability in canopy density.

Bare soils and dense-canopy grasslands are extremes of prairie land cover. To establish a scaling situation, we define a "homogeneous" pixel as a uniform grassland whose canopy column density is some percentage of a dense-canopy grassland. We assign the vegetation column density of the dense-canopy grassland to be 3.7 kg/m^2, the maximum we have observed in field studies at a short-grass prairie site near Sioux Falls, South Dakota. In contrast, we define a "tiled" pixel as being divided into two regions: a region of bare soil and a region of dense-canopy grassland. Schematics of homogeneous and tiled pixels are shown in Figure 1.

The terrain within these mixed pixels can be modeled as some combination of the LSP models for bare soil and prairie grassland. Early LSP models were quasi-physical in that physical processes were cartoons, or extreme parameterizations, of actual processes [*Sellers*, 1992]. Although LSP models have improved, the excessive computational demands of higher physical fidelity have meant that most parameterizations remain relatively coarse approximations to physical processes. In contrast, the one-dimensional, coupled heat and moisture transport models used in surface hydrology [*Mahfouf*, 1991] do emulate the essential physical processes relatively well and would serve as excellent LSP models except for their high computational burden. However, they are ideal for topical studies like this examination of scaling.

Our hydrology model is the product of several iterations [*Liou and England*, 1998a, b; *Liou et al.*, 1998]. It is composed of two modules: an energy and moisture flux module and a radiobrightness module. Both modules are for a specified soil with a quasi-specular surface and a grass canopy whose vegetation column density varies from 0 to 3.7 kg/m^2. The energy and moisture flux module includes energy and moisture transport in unsaturated soils, radiative transport in a thatch and grass canopy, and energy and moisture exchanges between the canopy and the atmosphere. The energy and moisture flux module includes coupled temperature and moisture transport [*Philip and de Vries*, 1957]. The model was forced with winds and diurnal air temperature, humidity, and downwelling short- and long-wavelength radiation from summer climatic data (i.e., expected weather and radiation for time of day and day of year) near Sioux Falls, South Dakota.

Our radiobrightness model manages emission from soil and canopy and absorption within the canopy. The soil is modeled as a moist half-space with temperature and moisture gradients obtained from the hydrology model. The canopy is modeled as an "atmosphere" whose complex index of refraction is the sum of the indices for air and moist grass weighted by their volume fractions with height above the ground

[*England and Galantowicz*, 1995]. Their experimental data showed that scatter darkening at 19 GHz in short grasses was not a factor to less than 2-K rms over a 22-day period. Scatter darkening will not be a significant factor at 1.4 GHz. Even though the dielectric contrast between a moist blade of grass and air would be greater, the cross sections of grass blades become very small with respect to wavelength at 1.4 GHz.

We use data from a series of Radiobrightness Energy Balance Experiments (REBEX) to develop and validate the hydrology and radiobrightness models. Our hardware consists of a tower mounted radiometer system (TMRS), a micro-meteorological station (MMS), and a command and data management system (CDMS) [*Galantowicz and England*, 1992]. TMRS includes radiometers at the special sensor microwave imager (SSM/I) frequencies of 19.35, 37.0, and 85.5 GHz, a thermal infrared radiometer, and a "scene grabber" video system, all on a 10-m tower. The 19- and 37-GHz radiometers are dual polarized. The 85-GHz radiometer is single polarization but can be rotated within its cabinet to operate in either polarization. The MMS includes wind direction and speed; air temperature and humidity; Bowen ratio; precipitation; downwelling and upwelling short wave radiation; net radiation; temperature, heat flow, and moisture at several depths in the soil; and temperature at several heights in the canopy or snowpack. Data are multiplexed and sent to the CDMS trailer over cables or an optical fiber. The system is designed to work autonomously for months at a time. An occasional telephone link allows the slaving of the remote CDMS computer to a computer in our laboratory for data dumps, system management, and instrument calibration.

REBEX 0 was a 2-week experiment in the summer of 1992 on short grass at the University of Michigan's Matthaei Botanical Garden in Ann Arbor. The soil at the site was a sandy loam, and the grass column density was 3 kg/m^2. REBEX 1 was a 7-month fall and winter experiment in grassland near Sioux Falls, South Dakota, during 1992–1993 [*Galantowicz and England*, 1997]. The soil at the REBEX 1 site was a silty clay loam, and the grass column density was 3.7 kg/m^2. Data from this experiment were used to validate the hydrology and radiobrightness models for prairie grassland that were used in this simulation [*Liou et al.*, 1998]. Over the 22-day period of the validation, observed and predicted soil moisture agreed to within a few volume percent moisture, and observed and predicted 19-GHz radiobrightness agreed to within 2-K rms. REBEX 3 was a 1-year experiment in tussock tundra on the Alaskan North Slope during 1994–1995. REBEX 4, a joint project with the Atmospheric Environment Service of Canada, was a 4-month growing season experiment in grass and bare soil at the REBEX 1 site during the summer of 1996. Data from REBEX 4 were not yet available for model validation at the time of this study.

2. The Hydrology and Radiobrightness Models

The hydrology model requires solving the coupled equations

$$\frac{\partial X_h}{\partial t} = -\nabla \cdot \bar{Q}_h$$
$$\frac{\partial X_m}{\partial t} = -\nabla \cdot \bar{Q}_m \qquad (1)$$

where X_h and X_m are thermal energy and moisture content in the soil, respectively, and Q_h and Q_m are heat and moisture fluxes in the soil, respectively. The canopy of the biophysical grass model is comprised of leaf and thatch layers. Within the canopy we solve the one-dimensional coupled equations

$$\frac{\partial X_{hc}}{\partial t} = F_c$$
$$\frac{\partial X_{mc}}{\partial t} = \rho_l(P_c - D_c - E_c) \qquad (2)$$

where X_{hc} and X_{mc} are thermal energy and moisture in the canopy, respectively; F_c is the net energy flux; ρ_l is the density of liquid water; and P_c, D_c, and E_c are rate of precipitation, water drainage, and rate of vaporization, respectively. Many of the constitutive relations among the physical parameters are temperature or moisture content dependent so that (1) and (2) become nonlinear. The model is forced by downwelling short- and long-wavelength radiation, precipitation, wind speed, air temperature, and humidity. The constitutive relations, these boundary conditions, and the numerical solution to (1) and (2) are discussed extensively by *Liou et al.* [1998].

The combined soil and canopy radiobrightness is

$$T_b = T_{se}(1 - R_p(\mu))e^{-\tau_o/\mu} + T_c(1 - e^{-\tau_o/\mu})(1 + R_p(\mu)e^{-\tau_o/\mu}) \qquad (3)$$

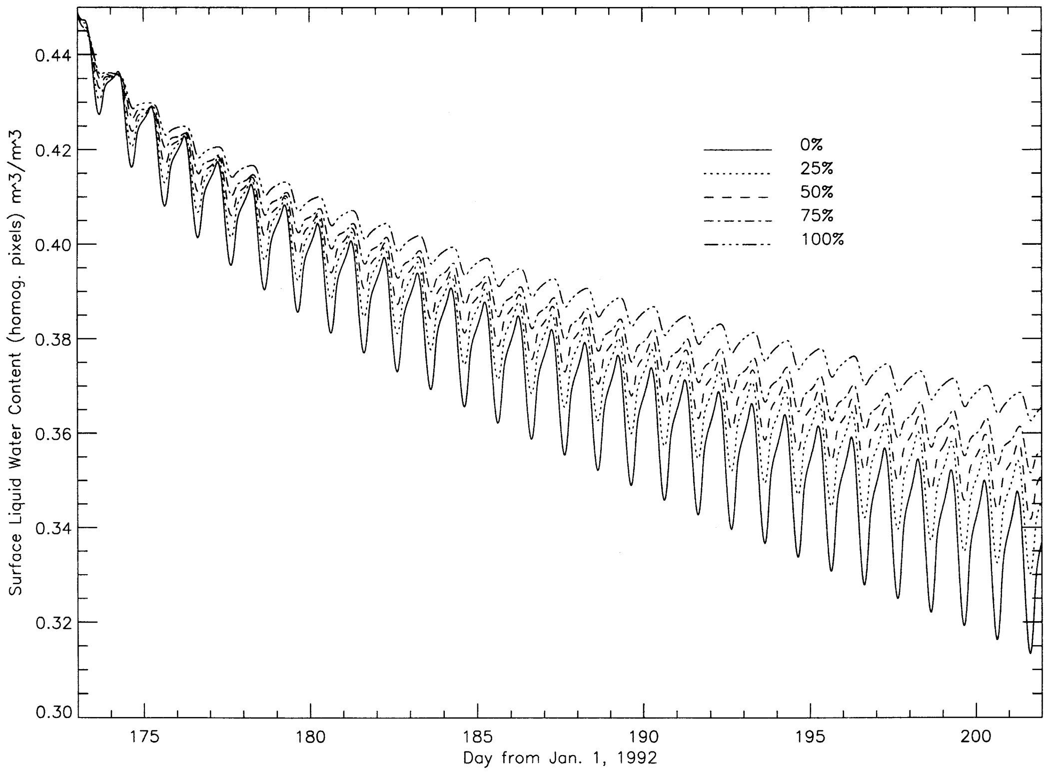

Figure 2. Surface soil moisture during a 60-day dry-down simulation. Volume fraction of soil moisture in the top 5 mm of soil is shown as a function of Julian day for 0, 25, 50, 75, and 100% of maximum canopy density for a homogeneous pixel.

where T_{se} is the effective thermal temperature of the soil, μ is the direction cosine with respect to zenith of the ray direction, p is polarization, $R_p(\mu)$ is the Fresnel reflectivity of the soil, T_c is the canopy temperature, and τ_o is the optical thickness of the canopy.

3. Simulations

Sixty-day dry-down simulations were performed for five homogeneous cases and five tiled cases representing pixels having 0, 25, 50, 75, and 100% of the grass that would be found in a pixel filled with dense-canopy grass. Soil and vegetation physical properties were assigned to be those of a typical prairie grass [*Liou et al.*, 1998]. Climatic initial conditions, radiation, and atmospheric forcing for mid-June through mid-August at Sioux Falls were used in the simulations except that the initial soil moisture was assigned to be a uniform and very wet 45% by volume, and precipitation events were omitted. Volumetric soil moisture for the top 5 mm of soil during the dry-down simulations are shown in Figure 2. The 19-GHz brightness of the bare soil is primarily dependent upon the moisture content and temperature of this soil layer. In contrast, the 1.4-GHz brightness of bare soil is more nearly a weighted average of the top 5 cm of soil. The 3.7 kg/m^2 grass canopy is essentially opaque at 19 GHz but significantly transmissive at 1.4 GHz.

The brightnesses for the homogeneous and tiled cases at 1.4 and 19 GHz are shown in Figure 3. To ease comparison between brightnesses at the two frequencies, the 1.4-GHz brightness was displaced upward 60, 100, or 120 K in all but Figure 3a. Note that the 1.4-GHz brightness is sensitive to the decrease in surface soil moisture in every case. At 19 GHz, sensitivity to surface soil moisture in the homogeneous case is less than the diurnal variation for a 50% canopy cover and decreases as canopy cover increases.

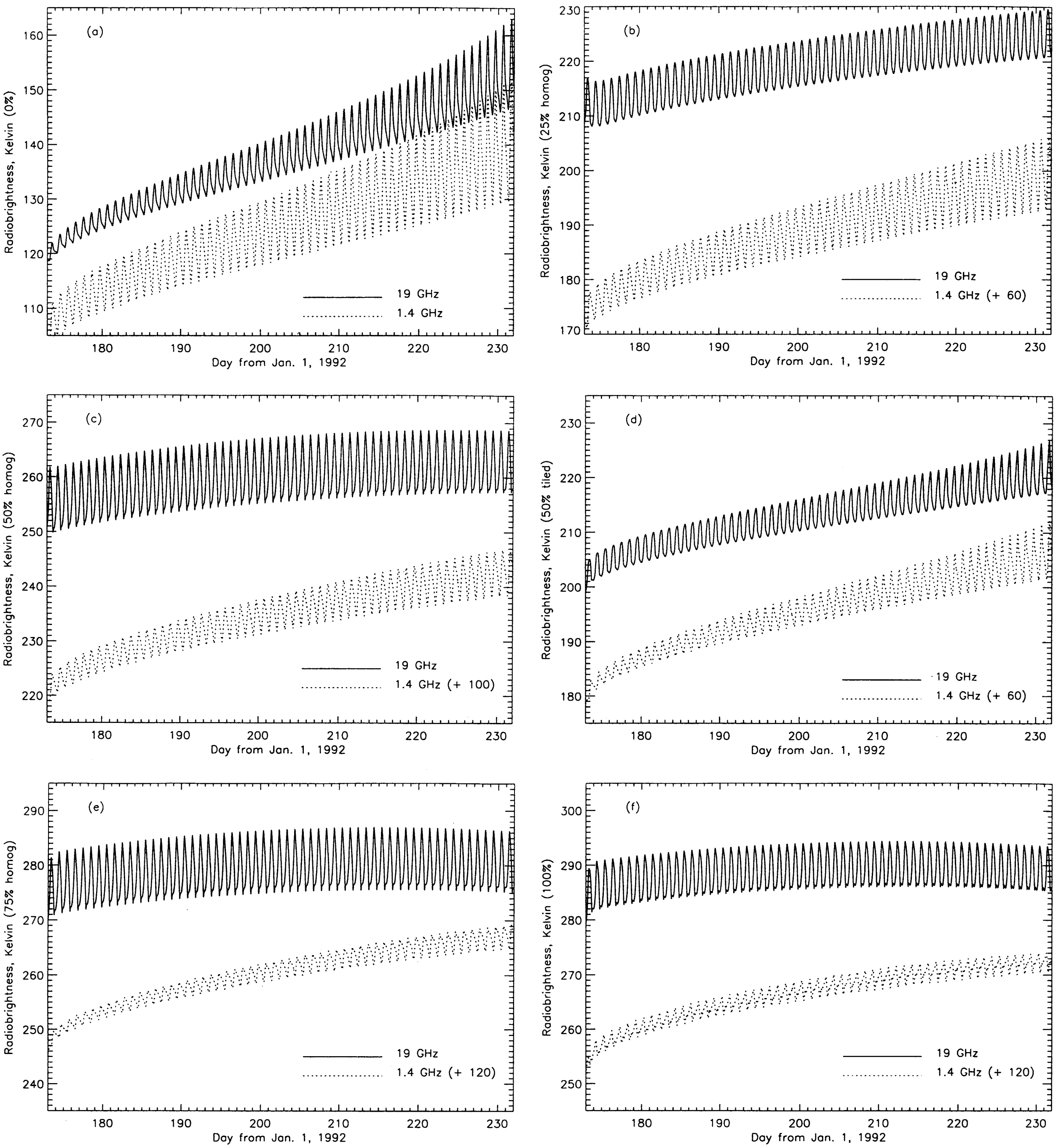

Figure 3. Examples of pixel radiobrightnesses during 60-day dry-down simulations. These represent (a) bare soil (or 0% tiled), (b) 25% homogeneous, (c) 50% homogeneous, (d) 50% tiled, (e) 75% homogeneous, and (f) 100% homogeneous (or 100% tiled). The 1.4-GHz curves are displaced upward in all but Figure 3a to ease the display of both 1.4-GHz and 19-GHz model data without compression of the vertical axis.

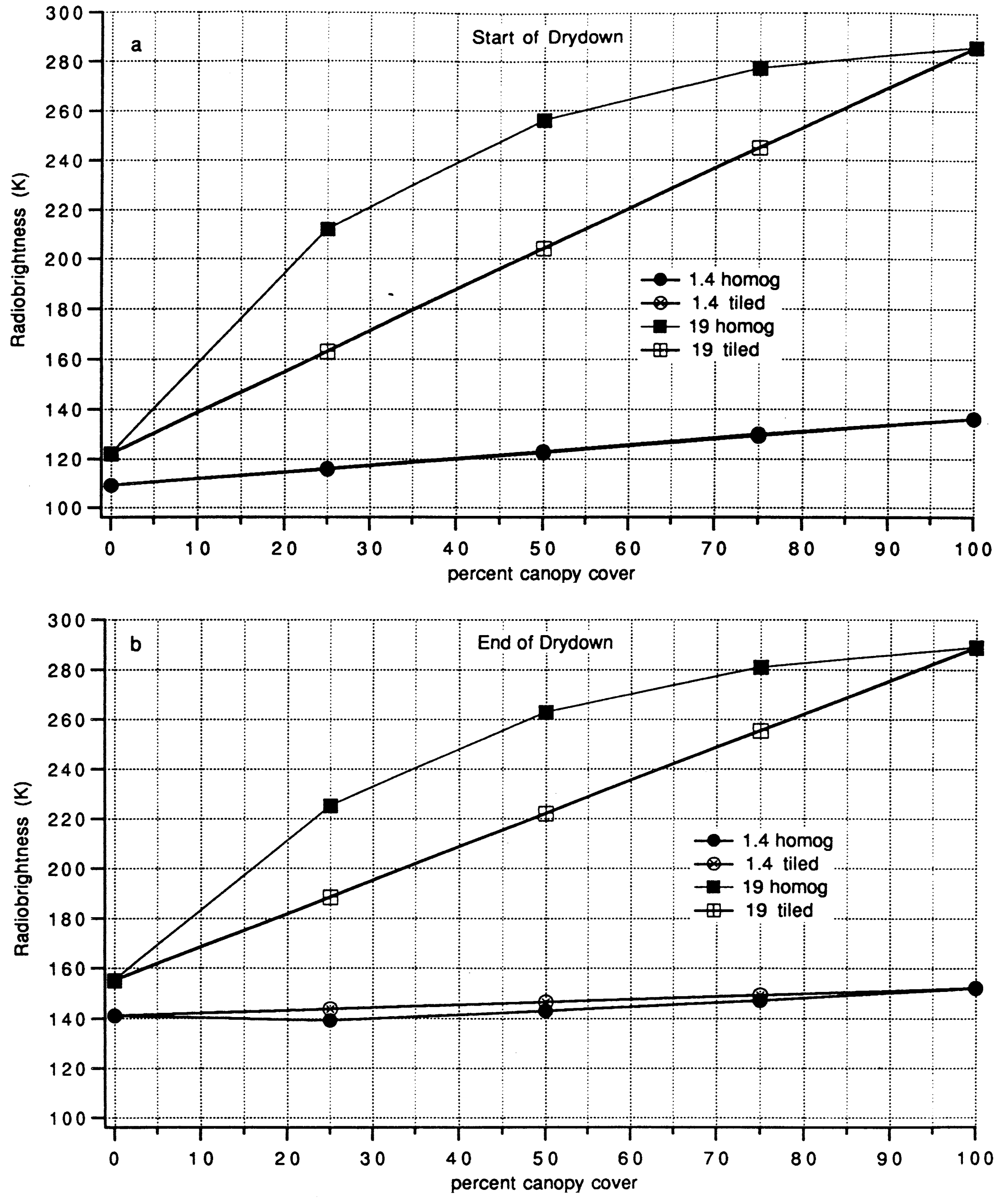

Figure 4. Radiobrightnesses of homogeneous and tiled pixels. Simulations were run for grass canopies filling 0, 25, 50, 75, and 100% of the pixel areas. Brightnesses at the start of the 60-day dry-down simulation are shown in Figure 4a, and those at the end of the simulation are shown in Figure 4b.

A comparison between the homogeneous and tiled cases appears in Figure 4. Only the beginnings and ends of each dry-down case are shown, but the relationships are essentially identical throughout the dry-down period. Note that there are significant differences between the homogeneous and tiled brightnesses at 19 GHz but that the homogeneous and tiled brightnesses are nearly identical at 1.4 GHz. The definition of tiling requires that the relationship between brightness and percent canopy cover be linear.

The fact that the homogeneous case brightnesses overlie the tiled case brightnesses suggests that the 1.4-GHz brightness is a linear function of mean canopy cover however the vegetation is distributed within a pixel.

4. Conclusions

The homogeneous and tiled pixel dry-down simulations for prairie grassland show significant differences in the scaling characteristics of 1.4-GHz and 19-GHz brightness. The nonlinear relationship between the 19-GHz brightness and the percentage canopy cover for the homogeneous case suggests that the 19-GHz brightness contains information about canopy column density. The differences between the 19-GHz brightness for the homogeneous case and the tiled case suggest that these brightnesses also contain information about the subpixel variability in canopy column density. Whether mean canopy column density or subpixel variability can be recovered from multifrequency brightness data is unclear.

The lack of sensitivity to subpixel variability at 1.4 GHz is a striking finding that needs further examination. If experimentally verified, it argues that with some knowledge of mean canopy column density, meaningful estimates of mean surface soil moisture in prairie grassland can be obtained from moderate spatial resolution, 1.4-GHz satellite radiometers even where there are significant subpixel variations in canopy cover.

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