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MAPPING THE BOUNDARY BETWEEN CONTINUOUS AND DISCONTINUOUS PERMAFROST IN ALASKA

Anthony W. England

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Attention:

Water Resources Research Grant Program Coordinator
Mail Stop 424
U. S. Geological Survey
12201 Sunrise Valley Drive
Reston, VA 22092

TITLE:

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Submitted by:

Anthony W. England
Professor
Department of Electrical Engineering
and Computer Science
University of Michigan
Ann Arbor, Michigan 48109-2122

Phone: (313) 936-1340
FAX: (313) 747-2106
Internet: england@eecs.umich.edu

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Short Title: **MAPPING PERMAFROST IN ALASKA**

Contents:

1. Summary

This U.S.G.S. project allowed us to begin interesting and, I believe, productive research toward linking energy and moisture exchanges between wetland tundra and the atmosphere to satellite radiobrightness. Our original objective was to use satellite radiobrightness to detect changes in the areal extent of permafrost in regions of discontinuous permafrost. As we expected, current satellite radiobrightness data could be used to detect onset of the thawing in the spring and the beginning of freeze-up in the fall. However, to determine whether or not the soil was perennially frozen at depth requires that the freeze/thaw observations be interpreted with a good thermal model for the soil and in the context of previous energy and moisture budgets at the land-atmosphere interface. However, the thermal model and the energy and moisture budgets are also essential to the models that are used to predict weather and short-term climate. It thus seemed prudent to expand our investigation to address the more general problem of assimilating satellite data - particularly radiobrightness data - in land-atmosphere models to improve there current estimate of state. Improved state estimates, i.e., temperature and moisture profiles, could then be used to infer whether soil at depth is perennially froze and, if so, the current thickness of the active layer, and as better initial conditions for an atmospheric model.

Our grant extended from September 1, 1991, through August 31, 1994, plus a no-cost extension. During that period we developed an annual thermal model for dry soil, an annual thermal model for moist soil with latent energy transfer between the soil and the atmosphere, and a diurnal thermal model with coupled moisture and heat transfer within the soil. The models were designed to apply to northern prairie and to arctic tundra. We are currently adding a grass layer to the prairie model and a tussock layer to the tundra model. For each of these models, we have developed a corresponding radiobrightness model that uses the thermal model's temperature and moisture profiles to predict radiobrightness at the frequencies of the Special Sensor Microwave Imager (SSM/I) - an imaging radiometer on a series of Defense Meteorological Satellites. We also modified our Tower Mounted Radiometer System (TMRS) and its associated Micrometeorology Station (MMS) to operate reliably in the arctic environment, and succeeded in obtaining a grant from NSF's Arctic System Science Program to install and collect data for a year in wetlands tundra north of the Brooks Range in Alaska. That field project will be completed in September, 1995. We will have collected one year of data at 20 minute intervals of V- and H-polarized 19.35 and 37.0 GHz radiobrightnesses, H-polarized 85.5 GHz radiobrightness, and thermal-infrared radiance of the sky and of a 10 m^2 patch of tundra; downwelling short-wave flux; net total flux; wind velocity; air temperature and humidity; temperature at several depths in the soil and the overlying snow; and moisture content and heat flow at several depths in the soil. These data will be analyzed and used to test thermal and radiobrightness models for tundra during the next year.

Funds from this grant were used to supplement funds from several NASA grants for modeling and field studies of northern prairie. The U.S.G.S. grant permitted us to prepare for the tundra field study and to successfully compete for the NSF grant to carry out the study. The list of products in Section 2 represent the combined efforts under all of these grants. There are at least five additional papers in various stages of preparation that will be published, to some extent, as a result of this grant.

2. Products

Refereed Journal and Proceedings Papers:

Zuerndorfer, B., and A.W. England, Radiobrightness decision criteria for freeze/thaw boundaries, IEEE Trans. Geosci. Remote Sensing, 30, pp. 89-102, 1992.

England, A.W., J.F. Galantowicz, and M.S. Schretter, The Radiobrightness Thermal Inertia measure of soil moisture, IEEE Trans. Geosci. Remote Sensing, 30, pp. 132-139, 1992.

Galantowicz, J. F. and A.W. England, An SSM/I radiometer simulator for studies of microwave emission from soil, Proc. of IGARSS'92, Houston, TX, May 26-29, 1992.

Liou, Y.A. and A.W. England, An annual model of SSM/I radiobrightness for dry soil, Proc. of IGARSS'92, Houston, TX, May 26-29, 1992.

England, A.W. and Y.A. Liou, Diurnal and annual radiobrightness thermal inertia of desert soils, Proc. URSI Microwave Signature Conf., Innsbruck, Austria, July 1-3, 1992.

England, A.W., J.F. Galantowicz, Y.A. Liou, E.J. Kim, and P.A. Dahl, A model for the radiobrightness of northern prairie, Proc. of ESA/NASA Workshop on Passive Microwave Remote Sensing Research Related to Land-Atmosphere Interactions, Saint-Lary, France, January 11-15, 1993.

England, A.W., and J.F. Galantowicz, The Tower Mounted Radiometer System (TMRS), Proc. of the ISTS Workshop on Ground Based Microwave Radiometry for Snow Cover and Soil Moisture, U. of Toronto Institute for Aerospace Studies, North York, Ontario, June 17, 1993.

Galantowicz, J.F., and A.W. England, An evolving radiobrightness model for northern prairie, Proc. of Pecora XII, Sioux Falls, S.D., Aug. 24-26, 1993.

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Liou, Y.A., and A.W. England, Effect of latent heat transfer on diurnal and annual prediction of temperature and radiobrightness of northern prairie, Proc. of IGARSS'94, Pasadena, CA, August 8-12, 1994.

Judge, J., J.F. Galantowicz, and A.W. England, An evaluation of BATS as a basis for a radiobrightness model for northern prairie, Proc. of IGARSS'94, Pasadena, CA, August 8-12, 1994.

Galantowicz, J.F., and A.W. England, Radiobrightness signatures of energy balance processes: Melt/freeze cycles in snow and prairie grass covered ground, Proc. of IGARSS'94, Pasadena, CA, August 8-12, 1994.

England, A.W., and J.F. Galantowicz, A volume emission model for the radiobrightness of prairie grass, Proc. of IGARSS'94, Pasadena, CA, August 8-12, 1994.

Kim, E.J., and A.W. England, Radiobrightness thermal inertia sensing of soil and canopy moistures for grassland areas, Proc. of Co-MEAS'95, Atlanta, GA, April 3-6, 1995.

England, A.W., and J.F. Galantowicz, Moisture in a grass canopy from SSM/I radiobrightness, Proc. of Co-MEAS'95, Atlanta, GA, April 3-6, 1995.

England, A.W., and J.F. Galantowicz, Observed and modeled radiobrightness of prairie grass in early fall, Proc. of IGARSS'95, Florence, Italy, July 10-12, 1995.

Galantowicz, J.F., and A.W. England, A dynamic radiobrightness snowpack model driven by land-atmosphere energy and moisture fluxes, Proc. of IGARSS'95, Florence, Italy, July 10-12, 1995.

Liou, Y.A., and A.W. England, A soil-vegetation-atmosphere-transfer model with associated SSM/I radiobrightness predictions for prairie grassland, Proc. of IGARSS'95, Florence, Italy, July 10-12, 1995.

Conference Abstracts:

England, A.W., Radiobrightness signature of land-atmosphere processes, Russian Institute for Control Sciences, Moscow, July 7, 1992.

England, A.W., Radiobrightness signature of land-atmosphere processes, Russian Institute for Space Research, Moscow, July 8, 1992.

Liou, Y.A. and A.W. England, Annual model of the energy flux and the radiobrightness of Northern Prairie soil, Am. Geophysical Union Fall Meeting, San Francisco, December 7-11, 1992.

Dahl, P.A., J.F. Galantowicz, and A.W. England, Frozen soil classification from SSM/I radiobrightness, Am. Geophysical Union Fall Meeting, San Francisco, December 7-11, 1992.

Galantowicz, J.F., and A.W. England, The first radiobrightness energy balance experiment, Am. Geophysical Union Spring Meeting, Baltimore, May 24-28, 1993.

England, A.W., Use of satellite remote sensing to improve biosphere models, GEWEX Global Soil Wetness Workshop, Longmont, CO, October 4-6, 1994.

England, A.W., Use of satellite remote sensing to improve land-atmosphere models, Geophysical Institute, Fairbanks, AK, October 12, 1994.

England, A.W., J.F. Galantowicz, E.J. Kim, Y.A. Liou, and J. Judge, Development of SVAT/Radiobrightness Models, Remote Sensing Science Workshop, Goddard Space Flight Center, February 27 through March 1, 1995.

England, A.W., Development of SVAT models for arctic tundra, NSF LAII Program Review, Orcas Island, WA, March 2-5, 1995.

Technical Reports:

Galantowicz, J.F., and A.W. England, The Michigan Earth grid: Description, registration method for SSM/I data, and derivative map projections, UM Technical Report 027396-2-T, February, 1991.

England, A.W., Status of the remote measure of soil moisture: A report of the SSM/I Products Working Team (SPWT), UM Radiation Laboratory Technical Report 027396-3-T, June, 1992.

Rojas, T.H. (advised by A.W. England), TDR vs Gravimetric; a comparison of soil moisture determination methods, UM Radiation Laboratory Technical Report 030613-1-T, September, 1993.

Galantowicz, J.F., E.J. Kim, and A.W. England, Design and operating specifications of the Tower Mounted Radiometer System (TMRS), versions 1 and 2, UM Radiation Laboratory Technical Report RL-903, December, 1993.

Galantowicz, J.F. (A.W. England, Principal Investigator), Field data report for the First Radiobrightness Energy Balance Experiment (REBEX-1), October 1992-April 1993, Sioux Falls, South Dakota, UM Radiation Laboratory Technical Report RL-913, February, 1995.

3. A Review of the Project

Continental atmospheric circulation models are driven by radiant energy, sensible heat, latent energy, momentum, and moisture flux boundary forcing at the land-atmosphere interface (e.g., Bhumralkar, 1976; Wilson and Henderson-Sellers, 1985; Abramopoulis et al, 1988; Verstraete, 1989; Dickinson et al, 1989; Avissar and Verstraete, 1990; and Giorgi and Mearns, 1991). There is ample evidence that mesoscale and global atmospheric circulation are particularly sensitive to the hydrologic boundary forcing of moisture and latent energy flux (e.g., Namias, 1958 and 1963; Walker and Rowntree, 1977; Rind, 1982; Shukla and Mintz, 1982; Yeh et al, 1984; Oglesby and Erickson, 1989; and Delworth and Manabe, 1988 and 1989). Hydrologic parameters that are interactive with circulation models have evolved from the bucket model of Manabe (1969) and Budyko (1974) to complex parameterizations like the Biosphere-Atmosphere Transfer Scheme (BATS) (Dickinson, 1984; and Dickinson et al, 1986) and the Simple Biosphere Model (SiB) (Sellers et al, 1986). While BATS involves more than 80 parameters and SiB involves 44, many are predictable for large, relatively homogeneous regions like the northern prairie or the arctic tundra. For example, soil thermal conductivity, density, and specific heat are readily estimated for either environment.

However predictable many of the hydrologic parameters are, the dynamic hydrological variables must be obtained through observation. Of these variables, soil moisture is critical because it represents the integrated effects of rainfall, runoff, infiltration, and evapotranspiration. Because soil moisture tends to be relatively slowly varying with time at mid- and high-latitudes (e.g., Yeh et al, 1984; and Delworth and Manabe, 1988), its estimation is particularly suited to daily, or even to weekly, satellite observation. Given that some satellite observation might yield an estimate of soil moisture, producing such estimates on something like the 25 km spatial grid of a mesoscale atmospheric circulation model is relatively undemanding of sensor spatial resolution or of satellite data management systems.

A satellite-based estimate of soil moisture and state must always be in the context of a soil thermal/hydrology model that places the satellite observations in a temporal context. Current temperature profiles are the integrated effect of secular changes in climate, annual insolation, diurnal insolation, and recent weather; the drying period after a rainfall will extend over several days or weeks. As thermal models become more sophisticated, they must also include the dynamical effects of vegetation, of snow, and of the coupling between temperature and moisture flux in the soil.

Similarly, radiobrightness must be interpreted in the context of an emission model. While we expect L-band (1.4 GHz) radiobrightness to correlate well with soil moisture in the upper 5 centimeters of bare or sparsely vegetated soil (e.g., Schmugge, 1987) so that a simple halfspace emission model is appropriate, the radiobrightness at the SSM/I frequencies of 19.35, 37.0, and 85.5 GHz are very sensitive to surface roughness and to vegetation so that the models must be correspondingly more sophisticated.

3.1 An annual model of the radiobrightness of dry soils

There are three styles of remotely sensed data: (1) Spatial, (2) spectral, and (3) temporal data. Methods for interpreting temporal data are less mature than are methods for interpreting spatial and spectral data because reliable temporal data are more difficult to acquire and because the models needed for the interpretation are complex. The cost of prototype sensors needed to collect test data is generally spread over several projects so that few investigators have the luxury of dedicated use of the sensor for extensive temporal experiments.

The advent of operational thermal sensing satellite instruments like the Advanced Very High Resolution Radiometer (AVHRR), band 6 of the Thematic Mapper, and the SSM/I offer opportunities to use the temporal history of the land surface temperature to probe below the effective emitting depth. Essentially, the diurnal and annual insolation pulses probe soils to depths of decimeters and meters, respectively, and surface temperatures provide a record of the response. A temporal method that is based upon periodic insolation requires a minimum of two samples per period, and maximum sensitivity is achieved for observations at times near the extremes of the soil's thermal response. Sun synchronous satellites, if their orbits are appropriately phased, are ideal for diurnal methods because they pass over a given region twice each day at intervals of nearly 12 hours.

The interpretation of temporal data requires a dynamic model of thermal energy storage and exchange. Generally, such models are designed to capture the essence of thermal and emission processes while ignoring second order effects. The difference between diurnal extremes in surface temperatures of sparsely vegetated soils depends upon insolation, thermal exchanges with the atmosphere, and the thermal constitutive properties of the soils (e.g., Watson, 1975; Kahle, 1977; and England, 1990). This dependence is exploited in a satellite thermal infrared technique (Thermal Inertia Mapping) to discriminate among various rock and soil types (e.g., Watson et al, 1983), and to estimate soil moisture (e.g., Price, 1980; Idso et al, 1975b; Reginato et al, 1976; Vleck and King, 1983; and Heilman and Moore, 1980, 1981, and 1982). England et al (1992) have proposed a similar technique which uses the diurnal extremes in radiobrightness to estimate soil moisture. That technique, called Radiobrightness Thermal Inertia (RTI), is based upon the mutually enhancing signatures of increased thermal inertia and decreased emissivity with increasing moisture content. Unfortunately, the SSM/I's orbit is phased poorly for diurnal RTI. Overflight times of 6 a.m. and 6 p.m. correspond to thermal crossovers rather than to thermal extremes.

Though ill-suited for diurnal RTI, we thought that current SSM/I data might lend themselves to an annual adaptation of the RTI method. We found that the annual extremes in soil temperature were relatively insensitive to soil moisture. However, in the process of developing annual models we gained a much better appreciation for the contributions of antecedent weather and we developed some new, and more efficient algorithms for computing soil temperature. As a precursor to the wet-soil annual model, we examined the expected diurnal and annual RTI of dry soils. Through this model, we evaluated the sensitivity of diurnal and annual extremes in radiobrightness to soil thermal inertia -- and, indirectly, to soil density.

Thermal model. The analytical solution for periodic and uniform insolation of a homogeneous halfspace is well known (e.g., Carslaw and Jaeger, 1959), but, because of the dominantly radiative boundary condition, obtaining that solution for a combination of diurnal and annual processes is computationally intensive. The method requires that the radiative boundary condition be linearized and solved either through harmonic analysis or through a Laplace transform. We have examined the two methods for the annual problem, and find that the Laplace method provides greater insight about thermal processes, and greater flexibility with respect to parametric analyses. The Laplace method yields surface temperature and surface temperature gradient through a convolution of past solutions for surface temperature with the thermal response of the system. By introducing a variable time interval modification to the Laplace method, we compress workstation-class computation times from approximately 90 hours per annual model to 10 hours per model. The details of the variable time interval Laplace method were discussed by Liou and England (1992).

Consider a soil that is semi-infinite and homogeneous for $z<0$. If conduction is the dominant heat transfer mechanism,

$$\frac{\partial E(T_g(z,t))}{\partial t} = \frac{\partial}{\partial z}\left\{K(T_g(z,t))\frac{\partial T_g(z,t)}{\partial z}\right\} \tag{1}$$

where $E(T_g)$ is moist soil enthalpy, and $K(T_g)$ is moist soil thermal conductivity. Both are functions of ground temperature, $T_g(z,t)$, at depth z and time t. For dry soils, enthalpy is a linear function of temperature and thermal conductivity is essentially constant so that

$$\frac{\partial T_g(z,t)}{\partial t} = \kappa \frac{\partial^2 T_g(z,t)}{\partial z^2} \tag{2}$$

where κ is thermal diffusivity (m^2/s). The thermal constitutive property, κ, is constant in this formulation which precludes freezing or thawing soil moisture. Either (1) or (2) is solved subject to the energy flux boundary condition that

$$F_{soil}(0,t) = F_g(t) - F_{sun}(t) - F_{sky}(t) - F_{wind}(t) \tag{3}$$

where $F_{soil}(z,t)$ is upward flowing thermal energy flux in the soil, and $F_g(t)$ is Planck emission from the soil ($e\sigma T_g(0,t)^4$ for infrared emissivity, e, and Stefan-Boltzmann constant, σ). The forcing functions are radiant flux from the Sun, $F_{sun}(t)$, radiant flux from the atmosphere, $F_{sky}(t)$, and sensible heat transfer from the atmosphere, $F_{wind}(t)$ (whose form is $A[T_{air}(t) - T_g(0,t)]$ where A is a constant and $T_{air}(t)$ is a model of air temperature). These forcing functions are discussed in the literature (e.g., England, 1990; and Idso et al, 1975a). The thermal energy flux at the soil's surface is related to temperature in the soil through the thermal conductivity, K (W/m-K), i.e.,

$$F_{soil}(0,t) = - K \left(\frac{\partial T_g(z,t)}{\partial z} \right)_{z=0} . \tag{4}$$

Using the Laplace method (Jaeger, 1953), we find that the thermal flux at the surface appears as a convolution of past surface temperatures with the thermal response of the soil, i.e., if thermal inertia, $p = Kk^{-1/2}$ in units of J/kg-K-$s^{1/2}$, then

$$F_{soil}(0,t) = -p \left\{ \frac{\partial}{\partial z} \left(\frac{z}{2\sqrt{\pi}} \int_0^\infty T_g(0,t-t') \, \frac{e^{-z^2/4\kappa t'}}{t'^{3/2}} \, dt' \right) \right\}_{z=0} . \tag{5}$$

Equation (5) is solved by replacing the integral by a summation over time intervals of length $\tau = \tau_o/N$ where τ_o is the number of seconds in one year, and N is large enough that the surface temperature, $T_g(0,t)$, changes little in any time interval. For $\tau = 600$ s (10 minutes) which corresponds to N = 52,560, the numerical form of (5) is

$$F_n = \frac{p}{\sqrt{\pi \tau_o}} \sum_{s=0}^{N-1} Tg_{n-s} \, \phi_s \tag{6}$$

where $F_n = F_{soil}(0,nt)$, $Tg_{n-s} = T_g(0,(n-s)t)$, and weighting coefficients, ϕ_s, are independent of the thermal properties. In terms of Tg, the boundary condition becomes

$$\frac{p}{\sqrt{\pi \tau_o}} \sum_{s=0}^{N-1} Tg_{n-s} \, \phi_s = e\sigma Tg_n^4 - Fsun_n - Fsky_n - A(Tair_n - Tg_n) . \tag{7}$$

For iteration, r, a linear approximation for ground emission, and the approximation, $Tg_{n-s}^r \approx Tg_{n-s}^{r-1}$ for s>0, yields

$$Tg_n^r = \frac{\frac{p}{\sqrt{\pi\tau_o}} \sum_{s=1}^{N-1} Tg_{n-s}^{r-1}\,\phi_s + 3e\sigma\left(Tg_n^{r-1}\right)^4 + Fsun_n + Fsky_n + A\,Tair_n}{\frac{-p\phi_0}{\sqrt{\pi\tau_o}} + 4e\sigma\left(Tg_n^{r-1}\right)^3 + A} \tag{8}$$

For an initial $Tg_n^1 = Tair_n$ for all n, (8) converges in 5 iterations to $\left|Tg_n^5 - Tg_n^4\right| < 0.001$ K for all n.

Table 1 represents a realistic range of thermal constitutive properties for dry sandy to loamy soils [16]. Higher densities like those of very rocky soils were not included because they are rarely the target of SSM/I investigations. Latitude was 47^o, cloud cover was 20%, F_{sky} was based upon a typical Great Plains atmosphere, and winds were a constant 5 m/s.

Table 1. Thermal Constitutive Properties

Case	Density (kg/m^3)	Specific Heat (J/kg-K)	Thermal Cond. (W/m-K)	Thermal Inertia ($J/kg\text{-}K\text{-}s^{1/2}$)
1	1,000	1,000	0.17	412
2	1,400	1,000	0.17	490
3	1,800	1,000	0.17	550

Radiobrightness Model. To first order, the radiobrightness of a dry soil whose interface is quasi-specular to is

$$T_b(t) = e_m \left\{ T_g(0,t) + \frac{\cos\theta_g}{\kappa_m} \left(\frac{\partial T_b(t)}{\partial z} \right)_{z=0} \right\} \tag{9}$$

where $e_m = 1 - R(\theta)$ and $R(\theta)$ is the Fresnel reflectivity at $\theta = 53^o$ -- the SSM/I incidence angle, θ_g is direction with respect to vertical of a ray within the soil (θ_g is related to θ by Snell's law), and κ_m is microwave absorptivity in the soil. In terms of the thermal model and (3), this becomes

$$Tb_n = e_m \left(Tg_n - \frac{\cos\theta_g\, F_n}{\kappa_m\, K} \right). \tag{10}$$

The intrinsic dielectric properties for dry soil are not functions frequency. However, frequency appears in absorptivity, so we choose 19 GHz -- the lowest of the SSM/I frequencies (Table 2).

Figure 1 shows predicted soil surface temperatures and V- and H-polarization radiobrightness temperatures for the three soil models. The uppermost three plots are the diurnal temperatures for December 25 (the choice of date was arbitrary), and the lower four sets of plots are the annual temperatures for 2:00 am/pm and 6:00 am/pm local solar time. The 6:00 am/pm times are the current SSM/I overflight times, while the 2:00 am/pm times correspond very nearly to diurnal minima and maxima, respectively.

Table 2. Dielectric Properties at 19 GHz and $\theta = 53^{\circ}$

Case	Relative Permittivity	Loss Tangent	Microwave Absorptivity	V-Pol. Emissivity	H-Pol. Emissivity
1	3.3	0.23	166 m^{-1}	0.99	0.78
2	4.6	0.32	273 m^{-1}	0.96	0.70
3	5.9	0.41	396 m^{-1}	0.94	0.63

For this limited range of thermal inertia, there is very little difference among the surface temperature predictions, but there is considerable difference among the radiobrightness predictions. That is, the effect of density upon emissivity dominates the effect of density upon thermal response. While this might be read as a negative result, it means that the quantity and state of moisture, and processes associated with vegetation and evapotranspiration dominates the thermal response. Soil composition plays its role primarily through characteristic differences in stored moisture.

3.2 An annual model of the radiobrightness of wet soils

The annual thermal model for wet soils follows the approach of England (1990) for a periodically heated, moist soil halfspace that is subject to freezing and thawing. Permitting the moisture in soil to freeze and thaw means that the heat flow equation (1) cannot be linearized. The problem is particularly difficult because phase boundaries propagate in time, and because soils, particularly clay-rich soils, freeze over a range of temperatures rather than at 0° C. That is, their phase boundaries are diffuse (Hoekstra and Delaney, 1974). We employ a modified Chernous'ko method—a finite element method that tracks isotherms within the soil—to achieve an annual solution to equation (1). The annual model typically converges to within 0.01 K after 5 iterations for all 10 minute intervals of an annual cycle. Model predictions are tested by their reasonableness and, for non-freezing soils, by comparison with numerical solutions to the variable time interval form of the Laplace analytical method that was developed for dry soils.

Figures 2 and 3 show examples of solutions for prairie soils near Bismarck, North Dakota. The 7% moist soil is atypically dry while the 25% moist soil is atypically wet. We note that diurnal extremes in soil temperature are relatively

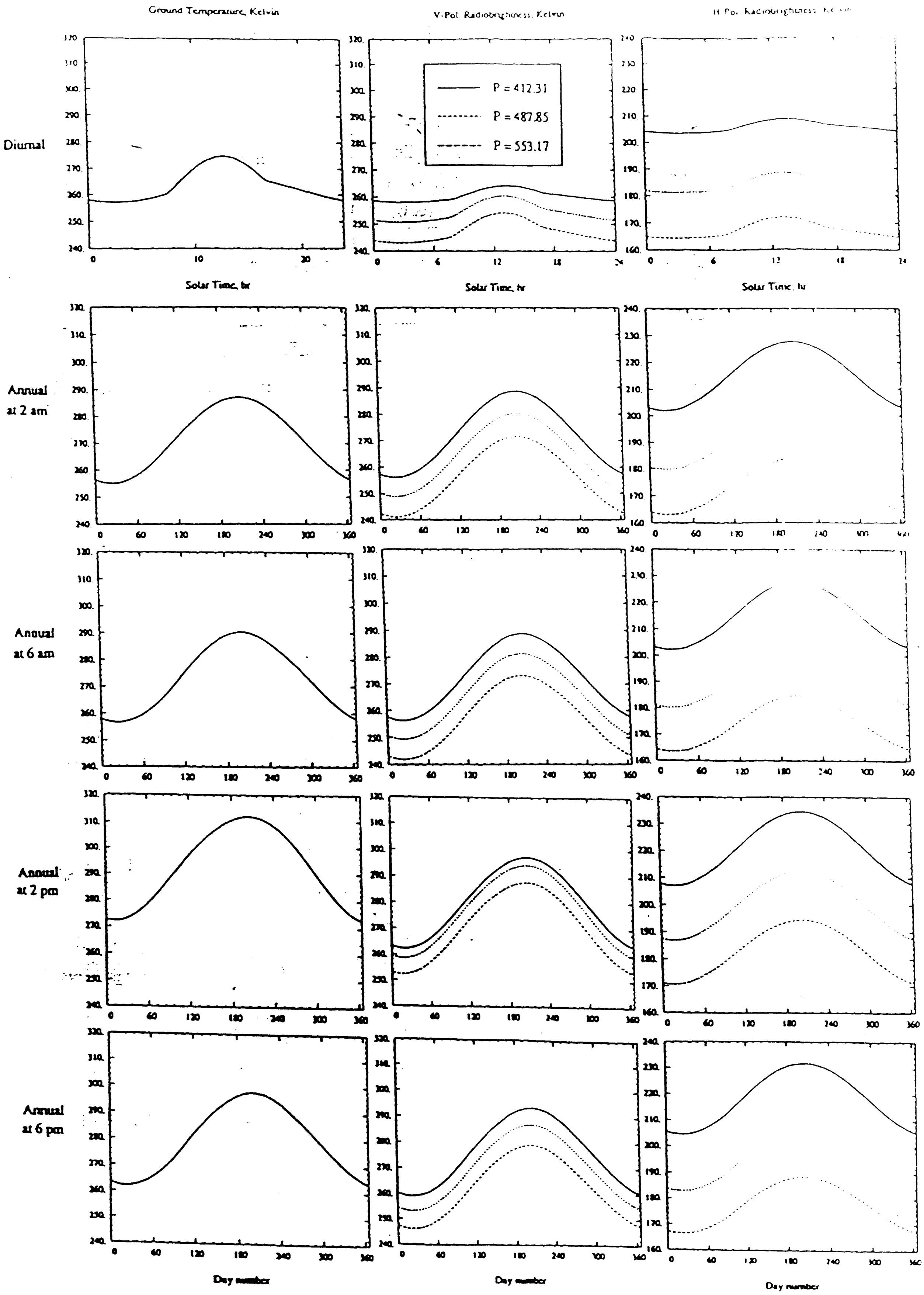

Fig. 1. Diurnal and annual surface temperature and radiobrightness of dry soil.

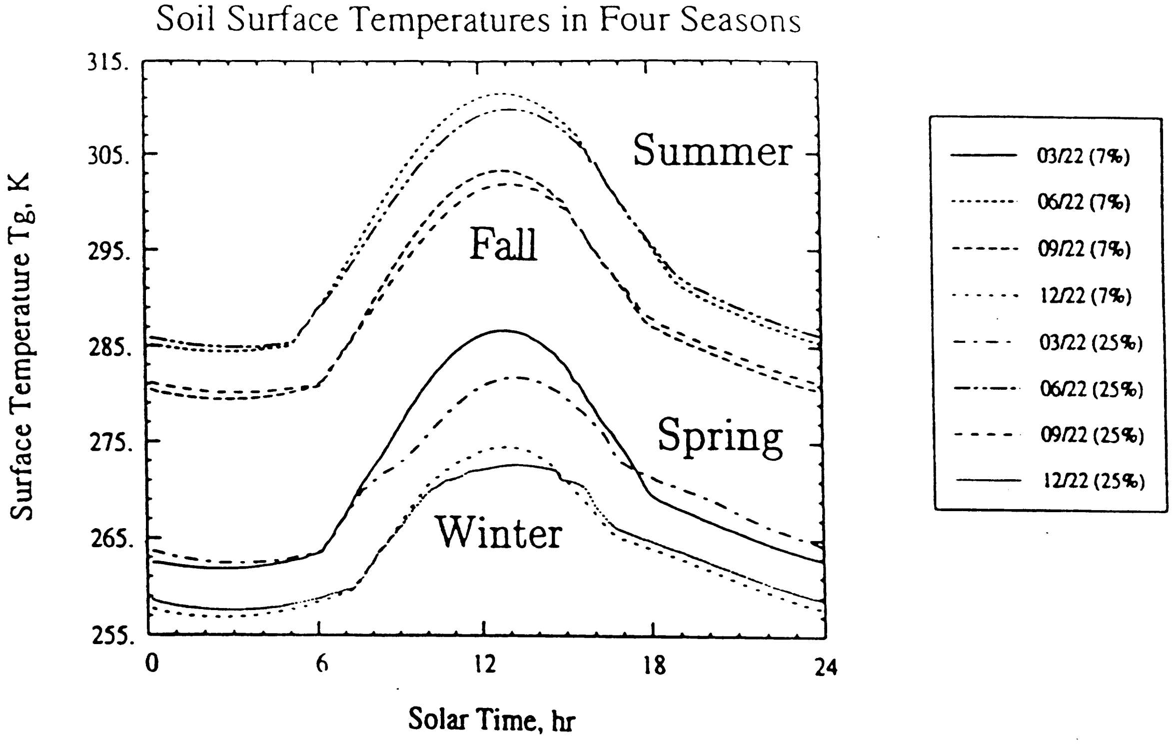

Fig 2. Predicted diurnal surface temperature for prairie near Bismarck, North Dakota.

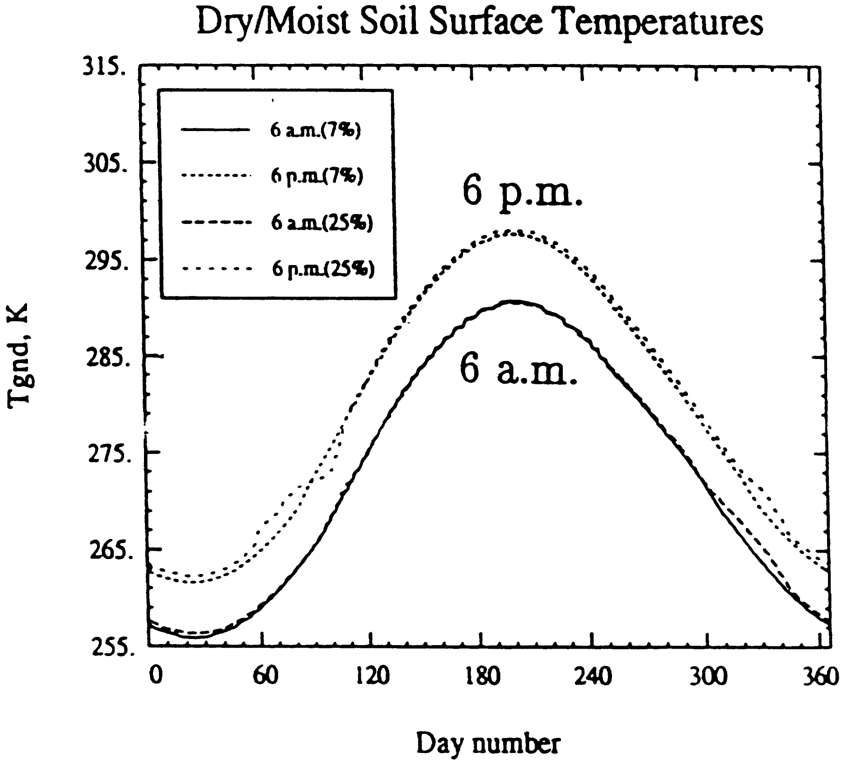

Fig 3. Predicted annual surface temperature for prairie near Bismarck, North Dakota.

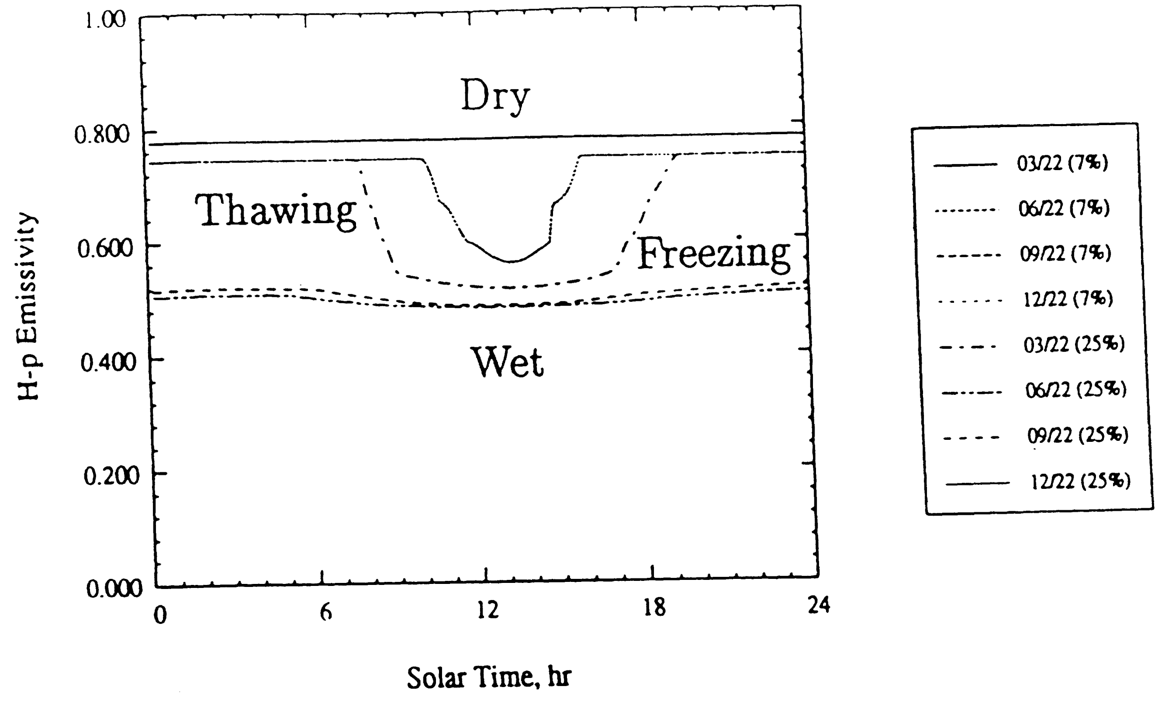

Fig 4a. 19 GHz, H-polarized diurnal emissivity.

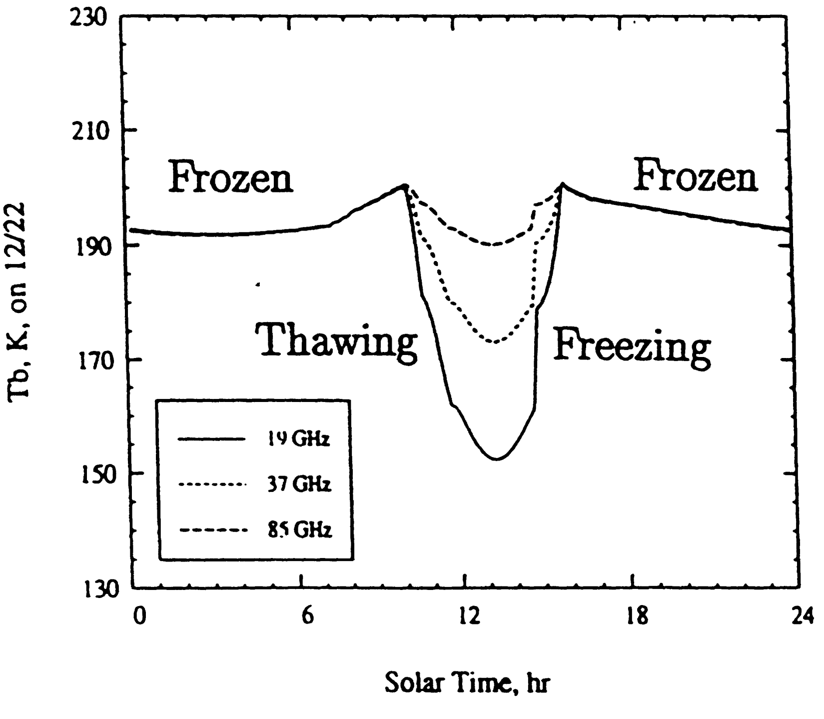

Fig 4b. 19.35, 37.0, and 85.5 GHz, H-polarized diurnal radiobrightness.

sensitive to moisture content but annual extremes are not. Moisture dependent anomalies in the annual cycle occur during fall freezing and spring thawing.

The radiobrightness model (based upon (10)) for the annual model predicts V- and H-polarized radiobrightnesses for a choice of incident angle and frequencies appropriate to either the Nimbus 7 Scanning Multichannel Microwave Radiometer (SMMR), (50° and 10.7, 18.0, and 37.0 GHz [Gloerson and Hardis, 1978]), or the Defense Meteorological Satellite's Special Sensor Microwave/Imager (SSM/I), (53.1° and 19.35, 37.0, and 85.5 GHz [Hollinger et al, 1987]). Microwave emissivity, e_m, ray angle within the soil, θ_g, and microwave absorptivity, κ_m, are each a function of the complex permittivity of the moist soil. Because of the moisture, this complex permittivity varies with temperature and, thus, with time so that emissivity, ray direction, and optical depth become time dependent.

Figures 4a and 4b show examples of the 19 GHz, H-polarized emissivity during a diurnal cycle and the corresponding radiobrightness, respectively. Note that moisture causes an extreme variation in emissivity for winter and spring days when freezing and surficial thawing occur. Figure 5 shows the annual radiobrightness at 6:00 am and 6:00 pm—times of SSM/I overflight. The precipitous drop in radiobrightness during the spring thaw or rise during the fall freeze should be evident among the SSM/I data.

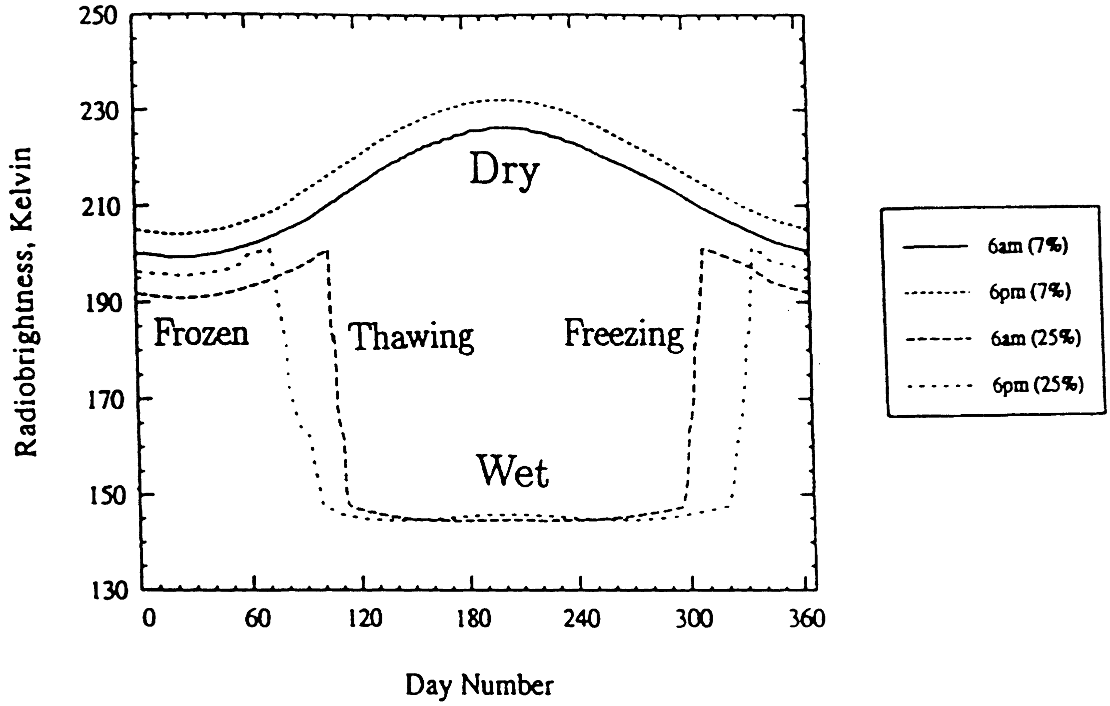

Fig 5. 19.35 GHz, H-polarized annual radiobrightness.

We have examined SSM/I data for August through December of 1988. Figure 6a is a plot of atmospherically corrected, temporally filtered, 19 GHz, H-polarized, 6:00 am radiobrightness averages for a 100 km square region centered on Fargo, North Dakota. Radiobrightness was estimated by correcting the SSM/I antenna temperatures for a standard atmosphere based upon observed differences between 19.35 and 22 GHz data, and upon an assumed water vapor scale height of 3 km. The temporal filter was a 7-day running boxcar. Relevant meteorological data of precipitation, snowpack thickness, and minimum and maximum air temperatures are shown in Figure 6b. Meteorological data are not temporally filtered. Qualitatively, the rainfall in mid-September correlates with the dip in radiobrightness during the second half of September; the snowpack during the second half of November correlates with the anomalously low radiobrightness during the same period; the low air temperatures beginning in mid-November and extending through December correlate with the rise in radiobrightness during December; and the new snowpack in late December correlates with the precipitous drop in radiobrightness in late December. We note that the period of cold temperatures and freezing soil does correspond to an increase in radiobrightness as predicted by the model. We also observe the dominant volume scatter darkening caused by dry snow.

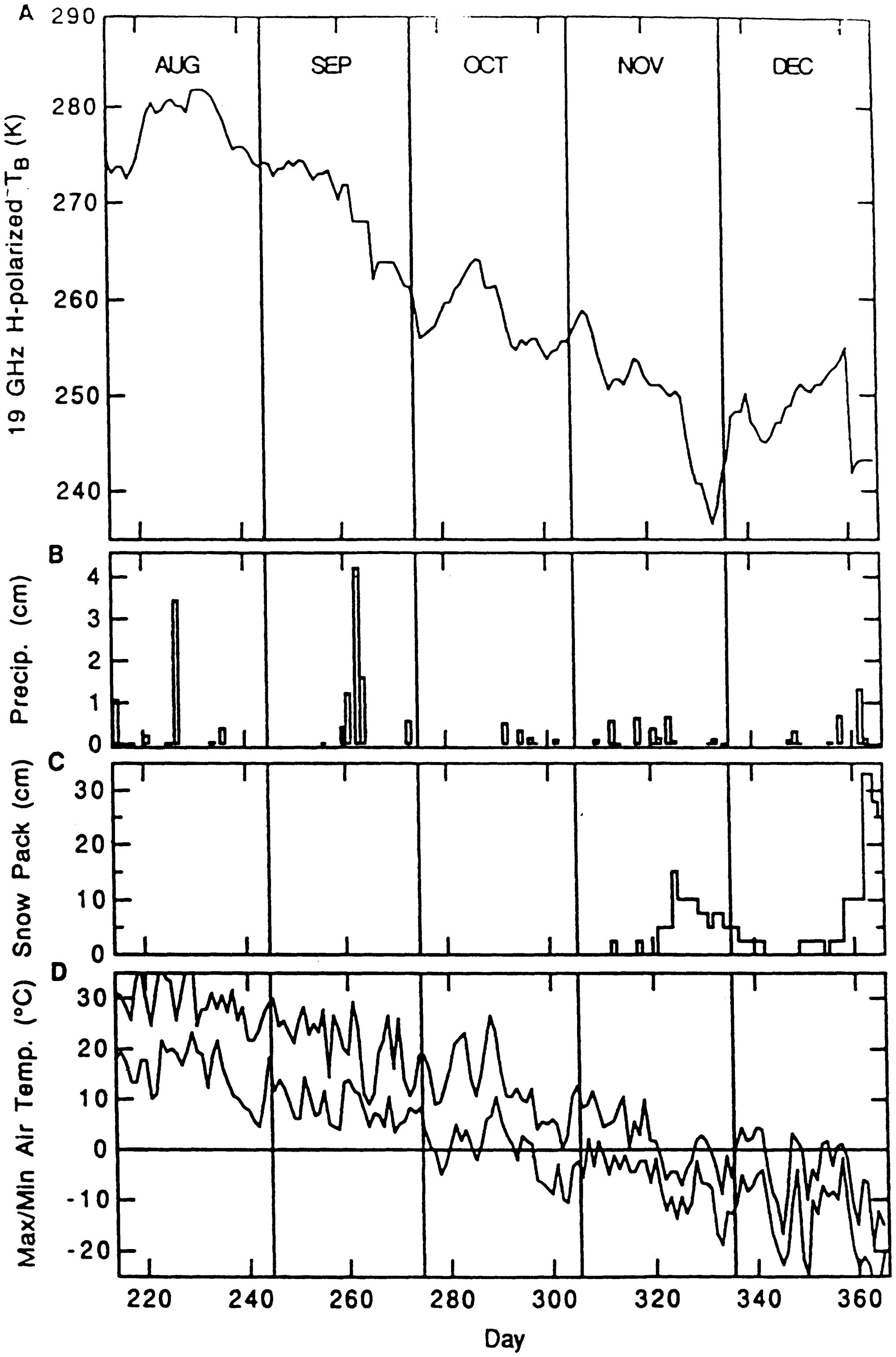

Fig 6. (a) 19 GHz, H-polarized, 6:00 am, SSM/I radiobrightness near Fargo, North Dakota (b) daily precipitation, (c) snow pack depth, and (d) high and low air temperatures, August through December, 1988.

3.3 TMRS and the MMS

Our Tower Mounted Radiometer System (TMRS) and its associated Micrometeorological Station (MMS) were built in-house over the two year period from June, 1990, to June, 1992, primarily by Mr. John Galantowicz as part of his Ph.D. research (Galantowicz and England, 1992). The original design included 19.35, 37.0, and 85.5 GHz, H-polarized radiometers, a thermal IR radiometer, downwelling short-wave radiometer, a net flux radiometer, a met station, and soil heat flow and temperature probes. The radiometers were on a 10 m tower, the met station was on a 2 m tower, and the systems were controlled by a Macintosh computer in a 9 foot enclosed trailer pulled by a Jeep Cherokee. The data were multiplexed and stored on disk. Through a telephone link, the field computer could be slaved to our laboratory computer at the University of Michigan. Through this link, TMRS and MMS could be remotely controlled for data dumps, and for system monitoring and calibration. TMRS was used by Mr. Galantowicz in the first Radiobrightness Energy Balance Experiment (REBEX-1) that took place from September, 1992, through April, 1993, near Sioux Falls, Sought Dakota. The details of TMRS and the MMS have been described by Galantowicz and England, 1992, and the products of REBEX-1 have appeared in many of the papers in Section 2, in Mr. Galantowicz Ph.D. thesis, and in several papers that are being prepared for the Transactions of Geoscience and Remote Sensing.

The system was expanded after REBEX-1 by Mr. Ed Kim in preparation for the Alaska experiment that this grant made possible. The enhancement includes dual polarized radiometers at 19.35 and 37.0 GHz, an upwelling short-wave radiometer, time-domain reflectometer soil moisture probes at several depths, and two stacks of temperature probes for an overlying snowpack. Intermediate Frequency (IF) amplification for the microwave radiometers occurs within the radiometers on the tower. Originally, the IF signals were routed over coaxial cable to detectors in the instrument trailer. We were concerned that extreme temperature fluctuations during the Alaska experiment might result in cable losses that vary with time. Because this would appear as radiometer gain variations, we moved the detectors and the analog-to-digital sampling to the radiometer box on the tower where temperature is carefully controlled. The digital data and commands are now carried between the radiometers and the trailer over optical fibers.

3.4 REBEX-3

The enhanced systems were used in the third Radiobrightness Energy Balance Experiment (REBEX-3) lead by Mr. Ed Kim as part of his Ph.D. research. The experiment took place from September, 1994, through September, 1995, 20 miles north of Toolik Lake, Alaska. During REBEX-3, we used a VHF telephone link from the field site provided by the Alaska Communications, Inc. (Alascom). Data takes were programmed for 20 minute intervals and consisted of recording all MMS and housekeeping data, opening the radiometer door to the sky measurement position, recording sky radiance at all frequencies, opening the door to the ground viewing position (53 degree incidence angle), recording ground radiance at all frequencies, and closing the door. These data provide an entirely new and valuable data set for the energy balance and radiometric signatures of wetlands tundra throughout a complete annual cycle. The data are just beginning to be analyzed by Mr. Ed Kim.

4. A Discussion of Current and Future Work

4.1 Model enhancements

We have recently completed improved thermal and emission models for bare soil. The new thermal model couples moisture and temperature to permit diurnal moisture migration in the soil. The combination of moisture movement in soil and latent heat transfer at the soil surface leads to very different radiobrightness signatures than those predicted by a static moisture models. The new model also permits us to explore the dry-down signature of bare soil after precipitation. These models are complete and papers for the Transactions of Geoscience and Remote Sensing are being prepared.

Snow and vegetation are necessary refinements to the bare soil models. With vegetation comes transpiration and scattering, and with snow comes scattering. We have completed a thermal and emission model for snow that includes metamorphism and ablation of the snowpack. The predictions fit the REBEX-1 data relatively well. The results are part of Mr. Galantowicz Ph.D. thesis and will be published in the Transactions of Geoscience and Remote Sensing.

We are collaborating with Dr. James Smith of Goddard for our vegetation model. He is working on a radiative transfer thermal model for vegetation that we will incorporate with our soil model and with existing schemes for transpiration. There are many volume scattering models which might be applied to microwave emission from grass and sedge vegetation (e.g., Lang and Sidhu, 1983; Ulaby et al, 1990a; and Sarabandi et al, 1990). One of the simplest would be to treat the canopy as a vegetation "cloud" of small particles above the soil. The most complex for vegetation would be to develop scattering matrices for leaves and stems based upon their dielectric properties, size, orientation, and distribution, and incorporate these scattering matrices in a multi-layer, radiative transfer model, e.g., the Michigan Microwave Canopy Scattering Model (MIMICS) (McDonald et al, 1989, and Ulaby et al, 1990b). The MIMICS models are likely to be unnecessarily complex. MIMICS is designed to predict radar backscatter where scattering is the dominant process. Emission, absorption, and scattering are equally important to a radiobrightness model of a canopy so that second order scattering might safely be ignored. That is, zero or first order scattering models based upon leaf and stem statistics should reliably predict scatter-induced darkening without the complexity of solving the radiative transfer equation. We have found that nearly 98% of the 19 and 37 GHz emission from prairie grass is accounted for with a simple refractive model that ignores scattering (a zero order model) (England and Galantowicz, 1995). We intend to develop a first order correction to the refractive model during the next 6 months.

Our vegetation models will be developed over the next two years. They will be tested with data from a growing season experiment near Sioux Falls, South Dakota, during the summer of 1996 (REBEX-4) lead by Ms. Jasmeet Judge as part of her Ph.D. research.

4.2 TMRS and MMS enhancements

TMRS and MMS have become very complicated systems. We are looking for an opportunity to refine and simplify their design. The funds to do that have not been identified. We plan to replace a land-based telephone link with a satellite link like that of Inmarsat M. There may be sufficient funds to do this in our current NSF grant. The satellite link will free us from the need to be near a land-based telephone link. We are also exploring portable power supplies so that, with the satellite telephone and portable power supply, we would be freed to carry out field experiments in more remote areas of the Alaskan North Slope.

4.3 Alaskan field work

We are in the final month of a one year experiment (REBEX-3) in wetlands permafrost near the University of Alaska's Toolik Field Station. The site is 20 miles north of Toolik Lake along the Alaskan Pipeline in the northern foothills of the Brooks Range at a Department of Transportation (DOT) refueling depot. The depot is open continuously and has a diesel generator. The Alaskan DOT was gracious enough to allow our access to an unused pad next to the depot and 150 m east of the Haul Road. We ran an underground 400 V power cable to their power bus and contracted for UHF telephone service from Alascom.

We intend to spend the next 9 months analyzing the REBEX-3 data before deciding how best to continue the Alaskan field experiment. The SSM/I data show radiobrightness signatures for the North Slope coastal lowland that are distinct from those of most of the North Slope tundra as characterized by the REBEX-3 site. We anticipate that our next field site might be in these coastal lowlands, but would not like to commit ourselves to that strategy until the current data are analyzed. If NSF will continue to support our Alaskan field work, we plan a second field experiment during the growing season of 1997.

4.4 EASE-Grid SSM/I data

SSM/I data are provided from NOAA's National Environmental Satellite Data and Information Service (NESDIS) and from NASA's Earth Observation System Data and Information System (EOSDIS) in swath format. While each pixel includes the location of the center of the antenna pattern, those locations move randomly from day-to-day. Furthermore, because each frequency channel on the SSM/I has a different spatial resolution, the brightness of a 19.35 GHz channel cannot be compared directly with the brightness of a 37.0 GHz or 85.5 GHz channel. Our models require comparison from day-to-day and among channels, so we resample the SSM/I data to a common Earth grid and spatial resolution. Because many other research groups have the same need, we helped the National Snow and Ice data Center (NSIDC) develop an Equal Area SSM/I Earth-Grid (EASE-Grid) resampling algorithm based upon the Backus-Gilbert inversion technique (Galantowicz and England, 1991). NSIDC has begun resampling the world SSM/I data with 1987, but would not get to the period of our REBEX-3 tundra experiment for several years. We are now in the process of resampling all SSM/I data for northern Alaska to an EASE-Grid format for the 1994-1995 period of REBEX-3. These resampled data will be used in our analysis of the REBEX-3 data and will be given to NSIDC for others use until the NSIDC resampling project reaches the 1994-1995 period.

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