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FINAL REPORT

Development of a Biosphere Model for Arctic Tundra with Linkages to Satellite Radiobrightness

NSF Contract: OPP-9409227

Anthony England
Edward Kim

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NATIONAL SCIENCE FOUNDATION
FINAL PROJECT REPORT

PART I - PROJECT IDENTIFICATION INFORMATION

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- The primary objectives and scope of the project
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Title: Development of a Biosphere Model for Arctic Tundra with Linkages to Satellite Radiobrightness
Award Number: OPP-9409227
PI: Dr. Anthony W. England
Co-I: Edward J. Kim
Date: September 1, 1998

Part II: Summary

The objective of this project is to develop and validate a land surface process/radiobrightness (LSP/R) model for arctic tundra that is linked to satellite observations.

Radiobrightness Energy Balance Experiment-3, a yearlong ground-based microwave brightness and micrometeorological experiment on the North Slope of Alaska, was successfully concluded in September, 1995. REBEX-3 field data have been submitted to the ARCSS archive, and are supporting ongoing model development. An technique for remotely classifying snow-free tussock tundra as frozen or thawed has been demonstrated using the REBEX-3 tower-based microwave observations. Existing SSM/I-based algorithms were not successful at distinguishing these cases when applied to the data.

Contemporaneous SSM/I satellite data have been processed using customizable EASE-Grid software developed for this work, and now available to the SSM/I user community. Very high correlations were found between the ground-based and the satellite data. The 380-day comparison is the longest and most regular that we are aware of to date for any region. This is highly encouraging, implying that such satellite observations can provide accurate estimates of surface emission signatures in arctic tundra regions. In turn, the signatures could be an effective wide-scale means of monitoring and, through an LSP/R model, estimating surface conditions.

A biophysical LSP/R model is being developed to improve our understanding of and our ability to estimate land-atmosphere energy and moisture fluxes and near-surface temperature and moisture conditions in arctic tundra regions. A similar model has recently been validated for prairie grassland regions.

PART IV - FINAL PROJECT REPORT — SUMMARY DATA ON PROJECT PERSONNEL

(To be submitted to cognizant Program Officer upon completion of project)

The data requested below are important for the development of a statistical profile on the personnel supported by Federal grants. The information on this part is solicited in response to Public Law 99-383 and 42 USC 1885C. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. You should submit a single copy of this part with each final project report. However, submission of the requested information is not mandatory and is not a precondition of future award(s). Check the "Decline to Provide Information" box below if you do not wish to provide the information.

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	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.
A. Total, U.S. Citizens	1				4					
B. Total, Permanent Residents										
U.S. Citizens or Permanent Residents[2]: American Indian or Alaskan Native										
Asian										
Black, Not of Hispanic Origin										
Hispanic										
Pacific Islander										
White, Not of Hispanic Origin										
C. Total, Other Non-U.S. Citizens										
Specify Country 1. Korea					1					
2.										
3.										
D. Total, All participants (A + B + C)	1				5					
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NSF ARCSS/LAII Final Project Report

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Award Number: OPP-9409227
PI: Dr. Anthony W. England
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Abstract

The objective of this project is to develop and validate a land surface process/radiobrightness (LSP/R) model for arctic tundra that is linked to satellite observations. Such land surface models attempt to provide realistic land-atmosphere boundary behavior for the atmospheric component of climate models and, in doing so, maintain estimates of surface state. However, the processes and interactions themselves are not completely understood, and the fidelity of the parameterizations used to represent the processes in operational LSP models also introduces uncertainties. Furthermore, the lack of adequate observational data has been repeatedly recognized as a serious impediment to model improvement. This lack is particularly felt in northern latitudes, where observing stations are widely scattered. Because the vastness and inaccessibility of arctic lands preclude a significant increase in the number of surface observing stations, satellite remote sensing may be the only practical means of determining land surface state and forcing/response variables at frequent intervals (e.g., daily) over large areas.

Our physically-based tundra LSP/R model is to be a tool for improving operational LSP model parameterizations and for providing insight at the process level. A year's worth of ground-based microwave emission (radiobrightness) and micrometeorological observations were taken on the North Slope of Alaska to support model development. Contemporaneous satellite data have been processed for comparison and investigation of scaling issues.

A. Background and Goal

Continental Atmospheric General Circulation Models (AGCMs) require radiant energy, sensible heat, latent heat, momentum, and moisture flux boundary forcings at the land-atmosphere interface (e.g., Bhumralkar, 1976; Wilson and Henderson-Sellers, 1985; Abramopoulos et al, 1988; Verstraete, 1989; Dickinson et al, 1989; Avissar and Verstraete, 1990; and Giorgi and Mearns, 1991). Land surface processes and feedbacks have been identified as key uncertainties that affect predictions of climate change (IPCC, 1992; Walsh, 1996). These processes are complex and interrelated. For example, the surface albedo feedback due to snow had been viewed as a simple positive feedback (i.e., warmer temperatures decrease snow cover, darkening the surface and resulting in increased absorption of solar radiation), but a recent study indicated this explanation to be overly simplistic—cloud interactions and longwave radiation may also influence the process (Cess et al, 1991). Similarly, warmer summers in the Arctic will stimulate plant growth, which may have a positive feedback (e.g., Rouse et al, 1992).

The 1992 Supplementary Report of the Intergovernmental Panel on Climate Change cited, and the 1995 Second Assessment reiterated, the lack of adequate observational data as a serious impediment to climate model improvement (IPCC, 1992, 1996). This lack is particularly felt in northern latitudes, where observing stations are widely scattered (Washburn and Weller, 1986). Because the vastness and inaccessibility of arctic lands preclude a significant increase in the number of surface observing stations, satellite remote sensing may be the only practical means of observing climate-forcing variables at frequent intervals (perhaps daily or semi-diurnally) over large areas at useful resolutions (Sellers, 1992).

Tundra/permafrost areas are of interest as important feedback elements in the climate system and as potentially sensitive indicators of a changing global climate. Several climate change scenarios have predicted that the greatest changes would occur at high latitudes. In the arctic, long-term changes in temperature would be reflected, for example, in the growth or retreat of permafrost regions and in the response of the vegetation. Polar-orbiting satellites are well suited to provide consistent spatio-temporal coverage of remote high-latitude regions. Microwave sensors are far less susceptible to interference by clouds than are optical sensors, and they are not dependent upon solar illumination, permitting observations at night and throughout the polar winter. Microwave radiometry is particularly sensitive to temperature and moisture distributions within vegetation canopies and the underlying soil, and these quantities are the gross physical parameters of greatest significance for land surface processes. Also, tundra-covered areas are a major terrestrial reservoir of carbon and changes in the thermal and moisture regimes will affect the storage and release of carbon by the tundra (Oechel 1996, Ping 1996, Hinzman 1992).

There has been considerable effort in determining temperature and moisture distributions from microwave brightness (radiobrightness) spectral signatures. While there has been some success in modeling radiobrightness for specified target states, inversion of such models is problematic because measured "instantaneous" radiobrightnesses represent emission from near-surface soils and overlying vegetation integrated over a range of depths, and do not necessarily correspond to unique states of moisture and temperature. Possible solutions to the non-uniqueness problem include the addition of passive or active microwave sensors with other frequencies and polarizations, and the synergistic use of optical and infrared data where feasible.

B. Our Approach

An alternative approach to the non-uniqueness problem is to model the temporal signature of the target and then to use temporal patterns of observed radiobrightness together with known or estimated previous states to estimate the current state. This is the basis of the Land Surface Process/Radiobrightness (LSP/R) approach. Land surface process models are numerical simulations of the response of the soil/vegetation system to diurnal solar and atmospheric forcing. Examples include the Biosphere-Atmosphere Transfer Scheme (Dickinson 1986), the Simple Biosphere model (Sellers 1986), the Canadian Land Surface Scheme (Verseghy 1991), and Land Surface Model (Bonan 1996). A land surface process/radiobrightness model couples a radiative transfer module to a LSP module in order to predict microwave emission signatures.

Our LSP/R model for arctic tundra is a one-dimensional, physically-based model of energy and moisture fluxes within tundra and between tundra and the atmosphere. It is based on a recently validated prairie grass LSP/R model (Liou 1996). Required input data are typical of energy balance field measurements and similar to those of operational LSP models such as LSM (Bonan, 1996). While the LSP/R model is too computationally intensive to be an operational LSP model, it can be run retrospectively for selected regions to obtain much higher fidelity estimates of temperature and moisture profiles within tundra than would be available from any operational LSP model. The choice of a physical model is intended to provide insights into the land surface processes, guidance when developing or improving parameterizations for an operational LSP model, and a better chance of extendibility to regions with different vegetation and different conditions than other, less physical approaches.

Note that observed radiobrightnesses themselves do not directly give us physical temperature or moisture profiles within the vegetation and soil. And, exploring inversion and assimilation techniques based on an LSP/R forward model is outside the scope of the work reported here. But since the LSP/R model must first simulate the thermal and moisture regimes in order to predict microwave emission, the model does estimate these canopy and soil quantities. The microwave observations are a means of remotely assessing the model's accuracy. Deviations between predicted and observed radiobrightnesses could be used to 'nudge' or otherwise correct the model state in a regular fashion. Current operational numerical weather prediction models routinely assimilate remotely sensed and in-situ observations through such techniques.

By assimilating passive microwave observations made over a period of time to constrain the model, surface fluxes of latent and sensible heat, as well as near-surface and subsurface temperature and moisture conditions may be determinable for areas with relatively thin vegetation, such as tundra and prairie. If satellite observations can be used, then regular wide-scale estimates may be determinable. Again, these estimates will come from the model state, not from a direct inversion of radiobrightness data.

By linking the LSP/R model to satellite observations, the performance of the model over a region such as the North Slope of Alaska can be monitored and estimates of surface temperature and depth and moisture content of the active layer with a spatial resolution of ~40 km—the resolution of the 37 GHz channel of the Defense Meteorological Satellite Program's (DMSP) Special Sensor Microwave/Imager (SSM/I)—should be possible.

Comparisons between radiobrightnesses observed by our ground instruments and radiobrightnesses observed by satellites will guide our management of the scaling issue. Our basic approach to scaling up to an ARCSyM grid cell (20 x 20 km) or an SSM/I pixel (43 x 69 km on a 25 km grid) shall be to use an area-weighted aggregate of the LSP/R model for wet acidic tundra and versions for wet non-acidic tundra, coastal tundra, and open water.

It is worth noting that the spatial resolution of current passive microwave satellite sensors is comparable to that of current medium-scale climate models--hundreds to thousands of square kilometers in area. At these scales, it can be difficult to obtain a meaningful density of point *in-situ* observations for comparison or assimilation purposes, particularly in regions like the arctic where access is difficult and expensive.

C. Completed Tasks
C.1. REBEX-3 Field Experiment

Our Radiobrightness Energy Balance Experiment 3 (REBEX-3) was successfully concluded in September, 1995. Data were collected for one full annual freeze-thaw cycle at a moist acidic tussock tundra site on the North Slope of Alaska (68 45'47" N, 148 52' 55" W) approximately 160 km south of the Arctic Ocean (Figure 1). The tundra at the site is representative of a large fraction of North Slope tundra areas (Auerbach 1995), typically consisting of sedges, mosses, and lichens overlying Pergelic Cryaquept soils (Michaelson 1996). Continuous permafrost underlies the entire region, and the active-layer depth at the site reached approximately 50 cm.

The site was adjacent to the Alaska Department of Transportation Sag River Maintenance Camp on the North Slope at mile 306 on the Dalton Highway. This is approximately 20 miles north of the Toolik Lake/Imnaviat Creek area and 30 miles south of Happy Valley in a region along the Haul Road transect where few other energy balance measurements suitable for model input were made. These distances are such that at the resolution of both the 20-km ARCSyM and 25-km Equal Area Scalable Earth-Grid (EASE-Grid) grids, a grid cell containing the REBEX-3 site would be between cells containing the Toolik/Imnaviat vicinity and the Happy Valley vicinity (Figure 2).

The instruments were deployed on a flat moist acidic tussock tundra area adjacent to an abandoned gravel pad west of the pad used by the DOT camp. The support trailer housing the controlling computer was parked on this abandoned pad. Measured quantities included ground and sky radiobrightnesses at the SSM/I frequencies of 19.35 and 37.0 GHz (horizontal and vertical polarizations) and 85.5 GHz (vertical polarization), thermal infrared ground brightnesses, net radiation, upwelling and downwelling solar radiation, Bowen ratio, soil moisture and soil temperature profiles, soil heat flow, air temperature, relative humidity, wind speed and direction, liquid precipitation, snow depth, and snow temperature profile. An Alter-type wind shield was added to our precipitation gage so that data would be compatible with precipitation data collected by the Hinzman/Kane LAII group. The field system, the Tower Mounted Radiometer System (TMRS2) (Figure 3, Table 1), used to collect these data was developed under NASA grants NAGW-1983 and NAGW-3430, and a small grant from the U.S. Geological Survey. A detailed report of the experiment and the data collected will be available shortly (Kim, 1998a).

TMRS2 operated automatically during the year-long experiment, making observations every 30 minutes. A radiotelephone link provided remote control and data dump capabilities back to Michigan. In fact, the remote link would have allowed total reprogramming of the system, had it been necessary. Although we spent enough time in the field in person to ensure that our measurements accounted for the unique character of the tundra and the rigors of the North Slope, the remote link enabled us to collect data over a much longer time period than would otherwise have been possible. In addition to the deployment and retrieval trips, only 3 other visits were made to the site by the investigators for instrument calibrations, maintenance, and repair. After REBEX-3, TMRS2 was deployed for REBEX-4, a 1996 summer prairie experiment in South Dakota (a pre-ARCSS commitment funded under NAGW-3430), and REBEX-5, part of the Southern

Great Plains 1997 hydrology/remote sensing experiment at the ARM/CART site in Oklahoma. REBEX-4 was conducted jointly with the Canadian Atmospheric Environment Service. A major refit of TMRS is currently underway, with redeployment to the arctic an important design consideration.

C.2 Data Submission & Data Exchange with other LAII Researchers

REBEX-3 meteorological data have been submitted to the ARCSS data archive at the National Snow and Ice Data Center and are available to the ARCSS community and others via the World Wide Web. These data have been used as part of LAII investigator Amanda Lynch's synthesis paper effort (Lynch, 1998). The radiobrightness data will be submitted pending completion of student thesis work. Jim Laundre, working with LAII researcher Gus Shaver, has provided us with 1994-95 meteorological data from their Sag River Long Term Ecological Research (LTER) site, located approximately 2 km east of the REBEX-3 site. Since full energy balance and subsurface measurements were not made at the LTER site, we cannot use their data for model validation. However, we have been able to use some of their data to replace some of our missing data and vice versa. LAII researcher Chien-Lu Ping has provided us with soil composition data from pits excavated at Sag River. LAII investigator Matthew Sturm has provided us with detailed snow stratigraphy data from snow trenches dug at our site on March 31, 1995. Although our present work involves LSP/R modeling of only the snow-free season, when combined with a snowpack emission model (Galantowicz, 1995) that was developed under separately-funded work, these data will be valuable in any future study of the remote sensing of snowpack conditions in arctic regions--an important separate research topic. Figure 4 shows the locations of these various sites in relation to the REBEX-3 site.

C.3 Examples of REBEX-3 Field Data

Horizontally and vertically polarized radiobrightness observations at 19.35, 37.0, and 85.5 GHz are shown for the entire REBEX-3 year (September, 1994 to September, 1995) in Figure 5a. On this annual time scale several general features are evident, most notably that snow-covered periods (days 280-480) and snow-free periods (days 500-620) are distinctive in such multi-frequency and multi-polarization data. The onset and rapid completion of the spring snow melt, probably the most important hydrological event each year, is clearly identifiable around day 480.

C.3.a Snow-Covered Period:

Although the focus of this project is on the snow-free season, it is difficult to ignore the fact that three-fourths of the year, and therefore, three-fourths of our field data involve the snow-covered season. An empirical classification technique developed using REBEX-3 field data is presented here as an example of the potential of these data.

Snow cover and a frozen active layer greatly influence the exchange of energy between arctic tundra and the atmosphere. For example, the disappearance of snow cover at the beginning of the summer removes a thermal barrier to the thawing of the active layer, and the simultaneous drop in albedo increases the net insolation available for ground heating and other land-atmosphere exchange processes. Decadal or longer-term warming is apparent in borehole temperature profiles (Lachenbruch 1986), has resulted in a loss of permafrost (Williams 1989; IPCC 1996), and will result in changes in the regional ecosystems (Oechel 1996; Michaelson 1996). These climatic changes, if they represent a trend in regional or global warming, will cause changes in the timing and duration of the snow-free season, and, through their effect upon the freezing and thawing of the active layer (Hinzman 1992), in nearly every aspect of the climatology and ecology of the arctic tundra.

A snow detection and freeze/thaw discrimination technique based on microwave satellite remote sensing observations can provide more consistent observations and more automated retrieval techniques compared with ones based on visible wavelengths. The Special Sensor Microwave/Imager series of polar-orbiting passive microwave sensors, for example, have been operational since 1987, and provide coverage of the entire arctic several times per day. One drawback of passive microwave satellite sensors is their relatively coarse spatial resolution; e.g., SSM/I's worst case: 43 x 69 km for the 19.35 GHz channel. Visible-wavelength sensors can offer higher resolution, but clouds often cover these regions, and bright clouds are similar in appearance to snow. Due to problems such as these, the current NOAA/NESDIS operational snow cover product requires significant manual subjective processing and thus is compiled only on a weekly basis (Grody 1996). Greater temporal resolution might be beneficial, for example, in detailed snowmelt pattern analyses since snowmelt duration is typically 10 days or less (Hinzman, 1991).

REBEX-3 data have been used to demonstrate a snow/no-snow frozen/thawed tundra classification technique (Kim, 1996) based, respectively, on the difference between the V-polarized and H-polarized emission at 37 GHz (Figures 6e and 6f) and the 19.35 GHz-37 GHz spectral gradient (Figures 6c and 6d). While snow cover detection techniques and frozen/thawed classifications have been presented for many land cover categories, distinguishing between dry snow and frozen snow-free ground has not been previously demonstrated. (Ulaby 1986, Grody 1994) Existing SSM/I-based snow detection algorithms can misclassify frozen snow-free ground as snow-covered if only a spectral gradient discriminant is used. Grody (1996) describes a classification method which can remove this ambiguity in some areas using the 19.35 GHz polarization difference. However, the ambiguity remained when this classifier was applied to the REBEX-3 data. We found that the classification tree approach described below, which uses a 37 GHz polarization difference discriminant, was completely successful at distinguishing between snow-covered and snow-free frozen conditions at the REBEX-3 tussock tundra site.

To detect snow cover of 5 cm or less, a change in the polarization difference of 1.5 K must be detectable. If this level of precision is not available, then a classifier based on polarization difference can still be applied but the minimum detectable snowpack thickness increases. Based on this threshold, snow was present before and after days 254-256 (11-13 Sept., 1994) and on days 505-507 (20-22 May, 1995). This was verified by TMRS2 video images and by observers on site. The sensitivity of the 37 GHz polarization difference to the presence of snow can be explained as follows. Snow-free (frozen or thawed) tundra vegetation has an essentially unpolarized signature due to the isotropic geometry of tussocks and tussock vegetation. Snow, on the other hand, has been shown (Schanda, 1983) to have consistently greater V-polarized emission over a wide range of water equivalent values, snowpack thicknesses, and other parameters. Thus, the presence of even a few centimeters of snow is enough to polarize the signature from tundra.

Snow-free tundra which is thawed from the surface to a depth of at least 5 cm displays a positive spectral gradient of 0.2 K/GHz. Snow-free tundra which is frozen from the surface to a depth of at least 5 cm displays a near-zero or slightly negative spectral gradient of 0 to -0.2 K/GHz. When the upper 5 cm were partially thawed, an intermediate spectral gradient was observed. Snow-covered periods are characterized by negative spectral gradients in general, however, daytime warming can apparently increase the gradient to even positive values as seen on days 262, 264, and 265. Note that anomalies such as these may be identified through the temporal context of the radiobrightness signatures.

The 19.35 GHz-37 GHz spectral gradient, when used with the polarization difference information, can be used to further classify the snow-free tundra surface as frozen or thawed provided that a spectral gradient accuracy of at least 0.2 K/GHz (ΔTB of 3.5 K) is available. A thawed tundra surface displays a positive spectral gradient of 0.2 K/GHz, and a snow-free frozen tundra surface displays a slightly negative spectral gradient of 0 to -0.2 K/GHz. These ground-based results imply that satellite data used with this classification must meet the above accuracy requirements after any effects of spatial scaling and any atmospheric corrections. Field measurements of 1-cm and 5-cm subsurface temperatures were used to verify results (Figures 6g and 6h).

It is worth noting that the multi-temporal data are what make possible (1) the use of the 37 GHz polarization difference as a snow-detection discriminant by making a change from a constant "background" level visible, and (2) temporal averaging of the noisy observations (the data in Figure 6 are not averaged) in order to increase the percentage of correctly classified cases.

C.3.b Snow-Free Period

A typical summertime REBEX-3 diurnal signature is shown in Figure 6b beginning with day 507. The radiobrightness signature of snow-free vegetation or soil is primarily a function of temperature and moisture. An unexpected result is that tussock tundra appears to be nearly a scaling surface at these frequencies.

Note that the large amplitude range of the diurnal signal means that a temporally isolated observation can yield a wide range of radiobrightness values depending on the measurement time. This is a potential problem inherent in classification or inversion algorithms using infrequent observations, but one which is addressed by an approach such as ours in which observations would be used to guide or constrain the LSP model that generates the estimates of surface conditions.

C.4 SSM/I Data

The temporal coverage of major arctic tundra-covered regions provided by the polar-orbiting Defense Meteorological Satellite Program platforms is quite good. For example, each makes at least four sun-synchronous passes per day over points at the latitude of the REBEX-3 site. The passes occur in clusters 12 hours apart, and there were three healthy SSM/I sensors in orbit during the REBEX-3 period with staggered overflight times. The spatial resolution of the SSM/I sensors on the DMSP satellites varies from 69 x 43 km for the 19.35-GHz channel to 15 x 13 km for the 85.5 GHz-channel (Table 2). Spatial resampling techniques, such as those employed by NSIDC's EASE-Grid processing scheme, can be employed to standardize the resolution and pixel locations to a fixed grid.

For comparison with the REBEX-3 ground data, we have obtained the SSM/I global satellite radiobrightness data for the REBEX-3 time period at no cost from NASA's Marshall Space Flight Center. The SSM/I data have been geographically subsetted to Alaska and further to the Kuparuk basin/Haul Road region of the North Slope and have been gridded to the 25-km polar EASE-Grid used by NSIDC. An example image is shown in Figure 7. These data products as well as the subsetted but ungridded raw satellite data are currently archived for the ARCSS community at Michigan. SSM/I-based products are widely used by researchers studying high latitude regions, including ARCSS/OAII sea ice researchers and the Canadian AES for snowmelt runoff predictions. The comparison serves as a test of the issue of scaling point observations of radiobrightness at the REBEX-3 2 x 4 meter footprint, up to the area of an SSM/I pixel. [Note: EASE-Grid was recently selected by NSIDC as the gridding scheme for their Polar Pathfinder 1.25-km gridded AVHRR data products. And, the AVHRR grid is co-registered with the SSM/I grid.]

The gridded brightnesses were generated from a "custom" EASE-Grid software processor. This customizable automated processor (Kim 1998b) uses the exact same Backus-Gilbert interpolation routines as the NSIDC standard processor, but uses readily-available low-cost swath data in Temperature Data Record format , and is now publicly downloadable for use by the entire SSM/I user community.

The processor was used to extract pixels from all overflights of the REBEX-3 site from September, 1994 to September, 1995, including pixels which would have been discarded by the standard processor due to swath overlap. The accuracy of the EASE-Gridded data was verified against the original swath data for both F-11 and F-13.

Very strong correlations ($R^2 > 0.92$) between gridded satellite and ground-based brightness observations were found for the 19 and 37 GHz SSM/I channels over the 380-day REBEX-3 period (Figure 5), before adjusting for any atmospheric, topographic, or calibration-related effects. The differences are due to differences in the exact times of the respective observations, the effect of mountains within the REBEX-3 EASE-Grid footprint, errors in the cold calibration of the TMRS2 radiometers, and atmospheric effects. After adjusting for these effects, the residuals for the least-squares best-fits are 2.1-12.8 K (channel dependent) for brightnesses in the range 77-300.

The effects of a clear atmosphere were examined and found to be small under the combination of surface brightnesses and atmospheric conditions considered. Thus, SSM/I can be an excellent observational tool under such conditions without requiring complex atmospheric corrections at 19 and 37 GHz. This is fortuitous for a region where meteorological observations are very sparse.

The four-order-of-magnitude difference in footprint sizes between TMRS2 and SSM/I makes the degree of matching remarkable. We know of no other examples of either a comparison or such a regular and consistent match between surface (or aircraft) and satellite passive microwave observations of the Earth's surface over such a length of time (380 days). We know of only one example which comes close, namely our previous 190-

day comparison from REBEX 1 (Galantowicz 1995) for wintertime prairie. The most important implication is that passive microwave satellite observations may be effective for monitoring surface conditions in arctic tundra areas despite the relatively coarse spatial resolution.

C.5 LSP/R Model Development

The first version of the LSP/R model is being developed for moist acidic tundra - a major landscape unit of the Alaskan arctic. Model development is supported by data from REBEX-3. The tundra model can be conceptually divided into three modules: a soil thermal module, a vegetation energy balance module, and a radiobrightness module (Figure 8). The overall model's time step is adaptive, but is generally of the order of minutes.

The soil thermal module uses a finite-difference approach to solving coupled partial differential equations which govern the heat and moisture transport within a multilayer (40-60 layers) soil column, including under freezing and thawing conditions. It is based on the work of Philip (1957) and de Vries (1958), and it computes soil temperature, liquid water content, and ice content for each layer, plus evaporation, condensation, and latent and sensible heat exchange at the top interface.

The vegetation module computes vegetation temperature from an energy balance of shortwave and longwave radiation, and sensible and latent heat exchange with the atmosphere. Plant transpiration is regulated by stomatal resistance, which is computed as a function of soil water availability, air temperature and humidity, solar radiation, and plant temperature. Plant moisture is maintained by water uptake from the soil.

The radiobrightness module uses the temperature and moisture information from the soil and vegetation modules to compute total V- and H-polarized radiobrightnesses for incidence angles from normal through grazing and frequencies throughout the microwave spectrum.

We are currently modifying the model representation of the “soil” to reflect the organic upper portion of the active layer. Tundra biophysical data from Terry Chapin’s LAII and LTER research is serving as a reference in this effort. Descriptions of the LSM (Bonan 1994 ,1996), CLASS (Verseghy 1991, 1993), BATS (Dickinson, 1986), and SiB (Sellers, 1986) operational LSP models are also providing guidance. Figure 9 shows example output data from the tundra LSP/R model.

D. Summary

Radiobrightness Energy Balance Experiment-3, a yearlong ground-based microwave brightness and micrometeorological experiment on the North Slope of Alaska, was successfully concluded in September, 1995. REBEX-3 field data have been submitted to the ARCSS archive, and, along with data from other LAII investigators are supporting our ongoing model development. An empirical technique for remotely classifying snow-free tussock tundra as frozen or thawed has been demonstrated using the REBEX-3 tower-based microwave observations. Existing SSM/I-based algorithms were not successful at distinguishing these cases when applied to the data.

Contemporaneous SSM/I satellite remote sensing data have been obtained and processed into gridded form using a customizable EASE-Grid software processor developed for this work. This software is now freely downloadable for use by the entire SSM/I user community. Very high correlations were found between the REBEX-3 ground-based and the SSM/I satellite data. This 380-day comparison is the longest and most regular that we are aware of to date for any region. This is highly encouraging, implying that passive microwave satellite observations can provide accurate estimates of surface emission signatures in arctic tundra regions at a spatial resolution comparable to the satellite footprint--which is comparable to that of regional climate models. Clear-sky atmospheric effects did not significantly affect the satellite observations. The signatures could, in turn, be an effective wide-scale means of monitoring and, through an LSP/R model, estimating surface conditions.

A biophysical land surface process/radiobrightness model is being developed to improve our understanding of and our ability to estimate snow-free land-atmosphere energy and moisture fluxes and near-surface temperature and moisture conditions in arctic tundra regions. The model is similar to one recently validated for prairie grassland regions and is designed to provide a linkage to satellite radiobrightness observations for remote monitoring and data assimilation applications in climatology and meteorology.

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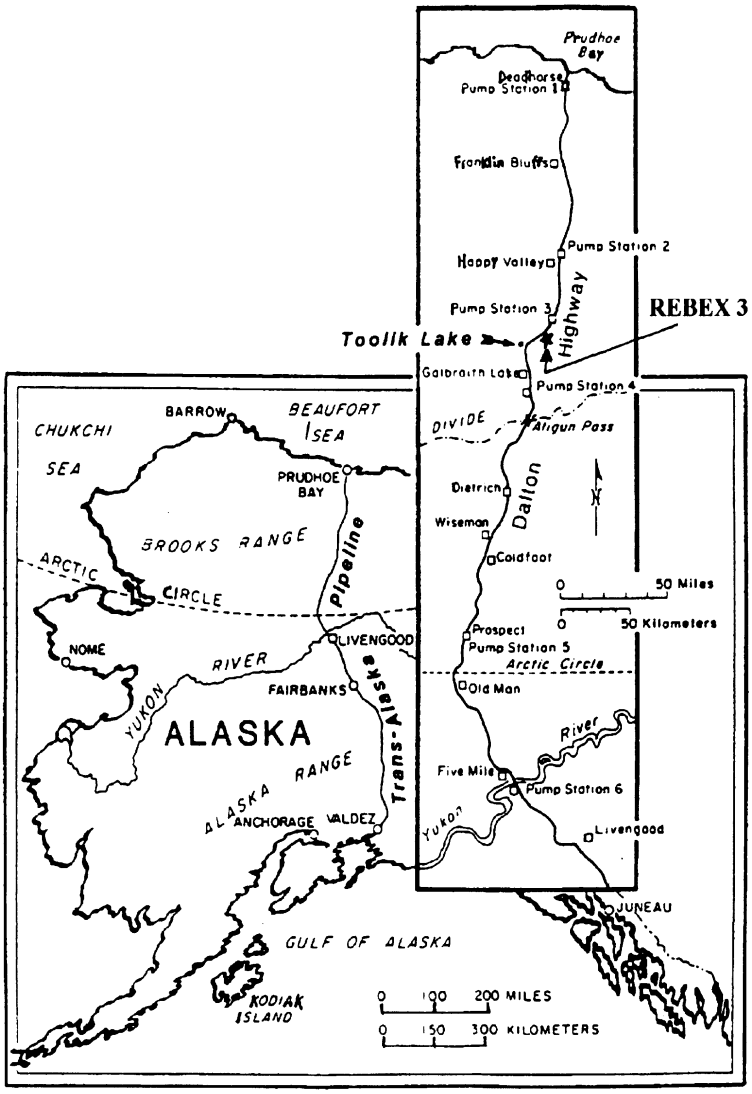


Figure 1: (adapted from Institue of Arctic Biology map).

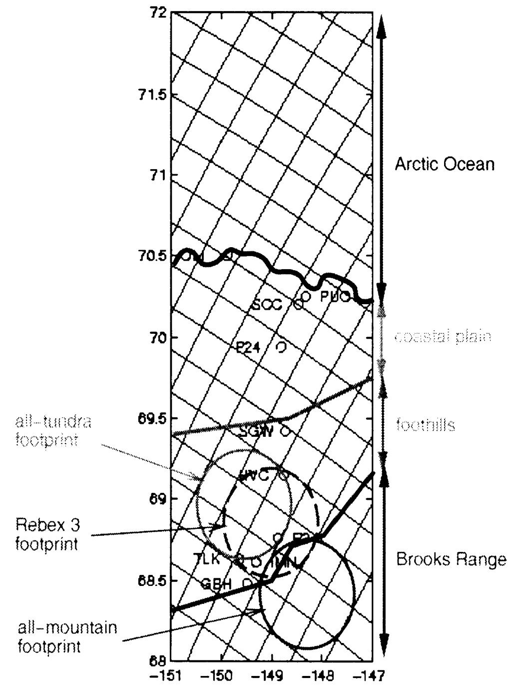


Figure 2: North Slope map with 25-km EASE-Grid overlay. Large circles represent EASE-Grid footprints. North is up. R3=Rebex 3 site; TLK=Toolik; IMN=Imnaviat; HVC=Happy Valley camp; GBH=Galbraith Lake; SGW=Sagwon Bluff; P24=Pipeline Mile 24; SCC=Deadhorse; PUO=Prudhoe Bay; OLI=Oliktok Point.

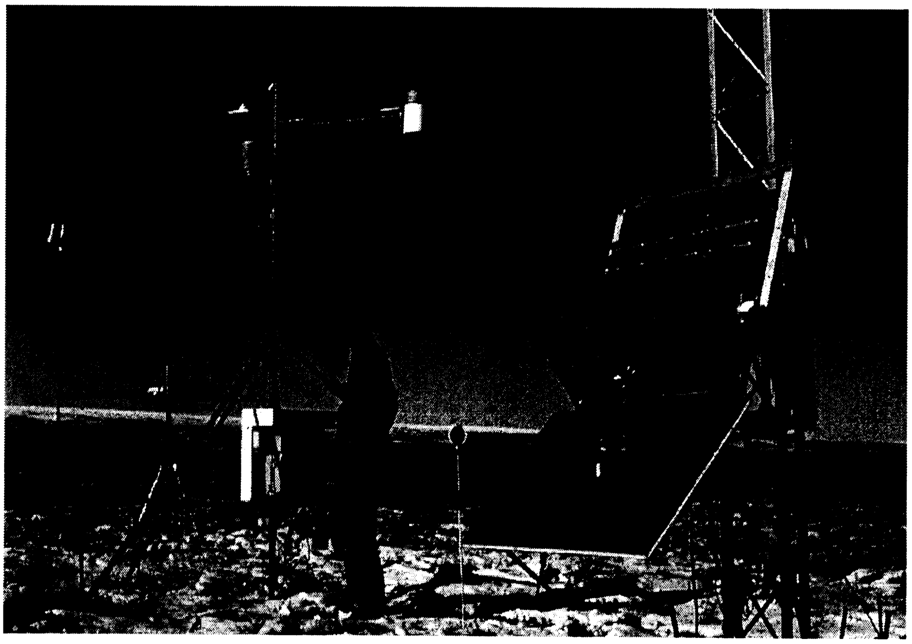


Figure 3: Tower Mounted Radiometer System 2 (TMRS2). Energy balance sensors are on tripod (left). Microwave sensors are in housing (right, here lowered for inspection).

Tower Remote-sensing Instruments	
Microwave radiometers	subset of SSM/I channels
19 GHz V & H pol	U. Michigan
37 GHz V & H pol	U. Michigan
85 GHz V pol	U. Michigan
Thermal IR radiometer	Everest Interscience 4000ALCS
Micro-meteorological Instruments	
10-meter anemometer	Met-One 014A
Wind vane	Davis Instruments 7911
2m Air temperature & Relative humidity	Vaisala HMP-35AC
Bowen Ratio (intakes at 1 & 2 m)	Campbell 023
Downwelling shortwave hemispherical flux	Eppley 8-48 (black & white)
Upwelling shortwave hemispherical flux	Eppley 8-48 (black & white)
Net radiometer w/aspirator	REBS Q-6
Rain gage	Texas Electronics 525
Rain gage wind screen	Novalynx Alter-type
TDR Soil moisture subsystem (10 probes)	Campbell(Tektronix)
Subsurface temperature (12 probes)	Campbell thermistor 107, 107B
Snowpack temperature (12 probes)	Campbell-equivalent thermistors
Snowpack depth	graduated rod
Subsurface heat flux (3 disks)	Thornthwaite 610
Other Instruments	
Video camera	Panasonic 1410
Data logger & controller (hardware)	Apple Macintosh, National Instruments
Data logger & controller (software)	Hypercard/Hypertalk

Table 1: TMRS2 Instruments.

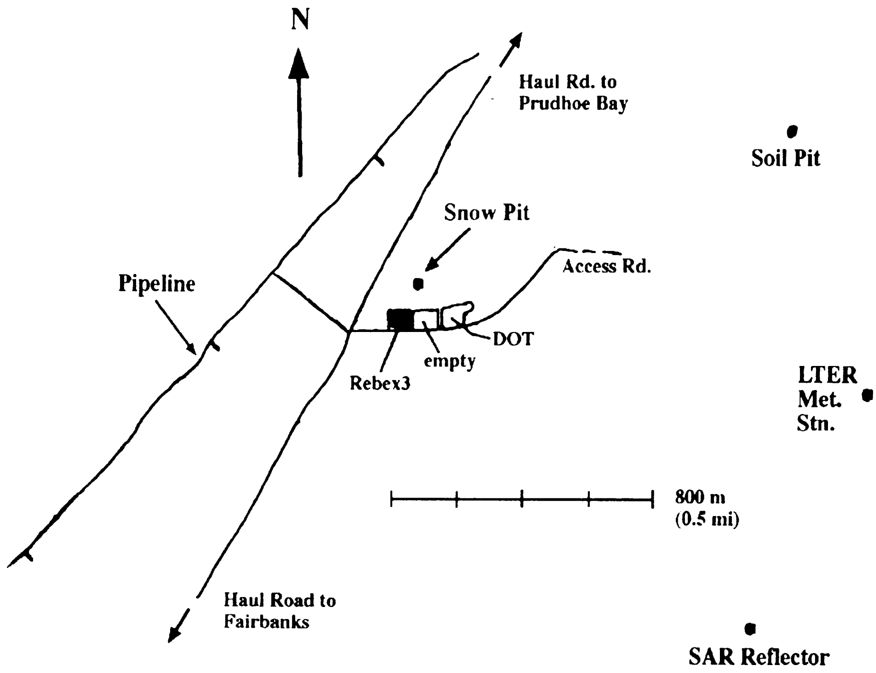
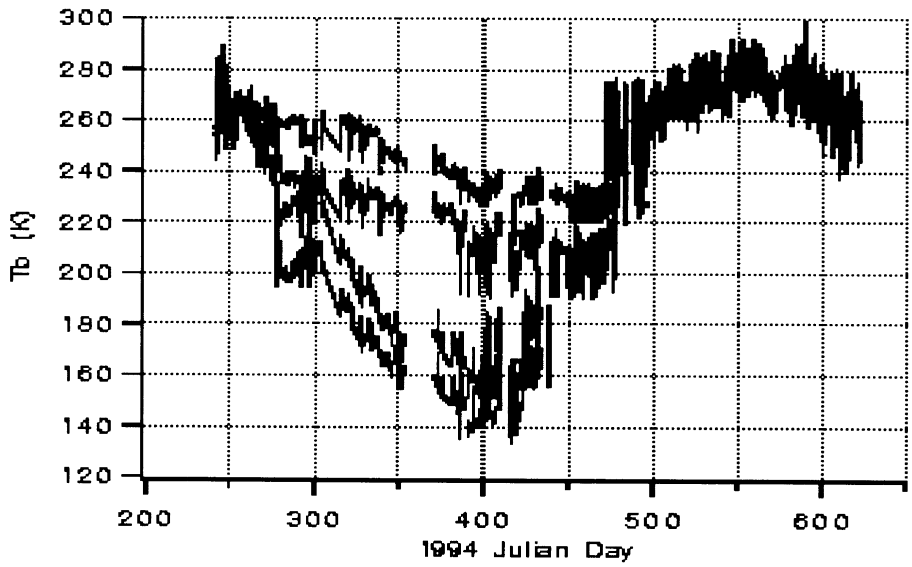


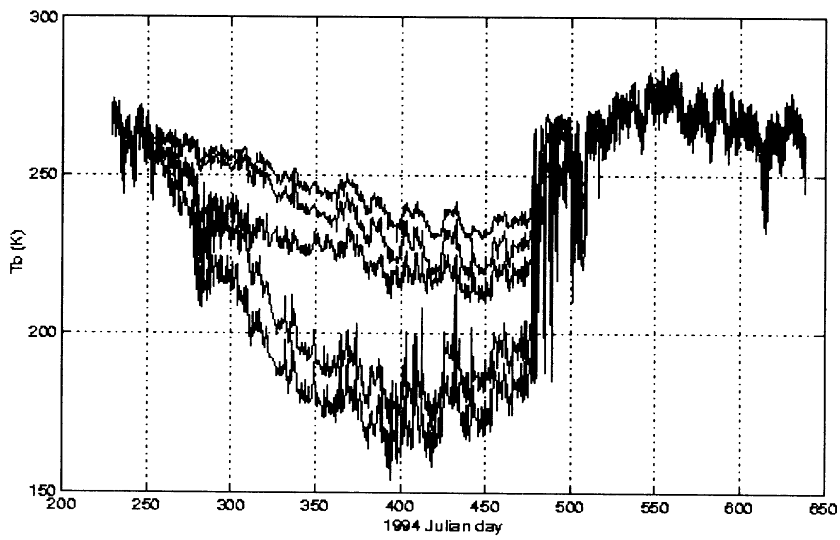
Figure 4: Nearby ARCSS/LAII and related sites.

Frequency	Wavelength	Polarization	Spot Size
19.35 GHz	1.55 cm	V,H	43 X 69 km
22.235	1.35	V	50 x 40
37.0	0.81	V,H	37 x 29
85.5	0.35	V,H	15 x 13

Table 2: SSM/I specifications.



(a) TMRS2(ground-based)



(b) EASE-Grid (satellite)

Figure 5: Rebex 3 SSM/I and TMRS2 brightnesses, no adjustments, September, 1994–September, 1995. EASE-Grid: top to bottom, channels are 19V, 22V, 19H, 37V, 37H. TMRS2: top to bottom, channels are 19V, 19H, 37V, 37H.

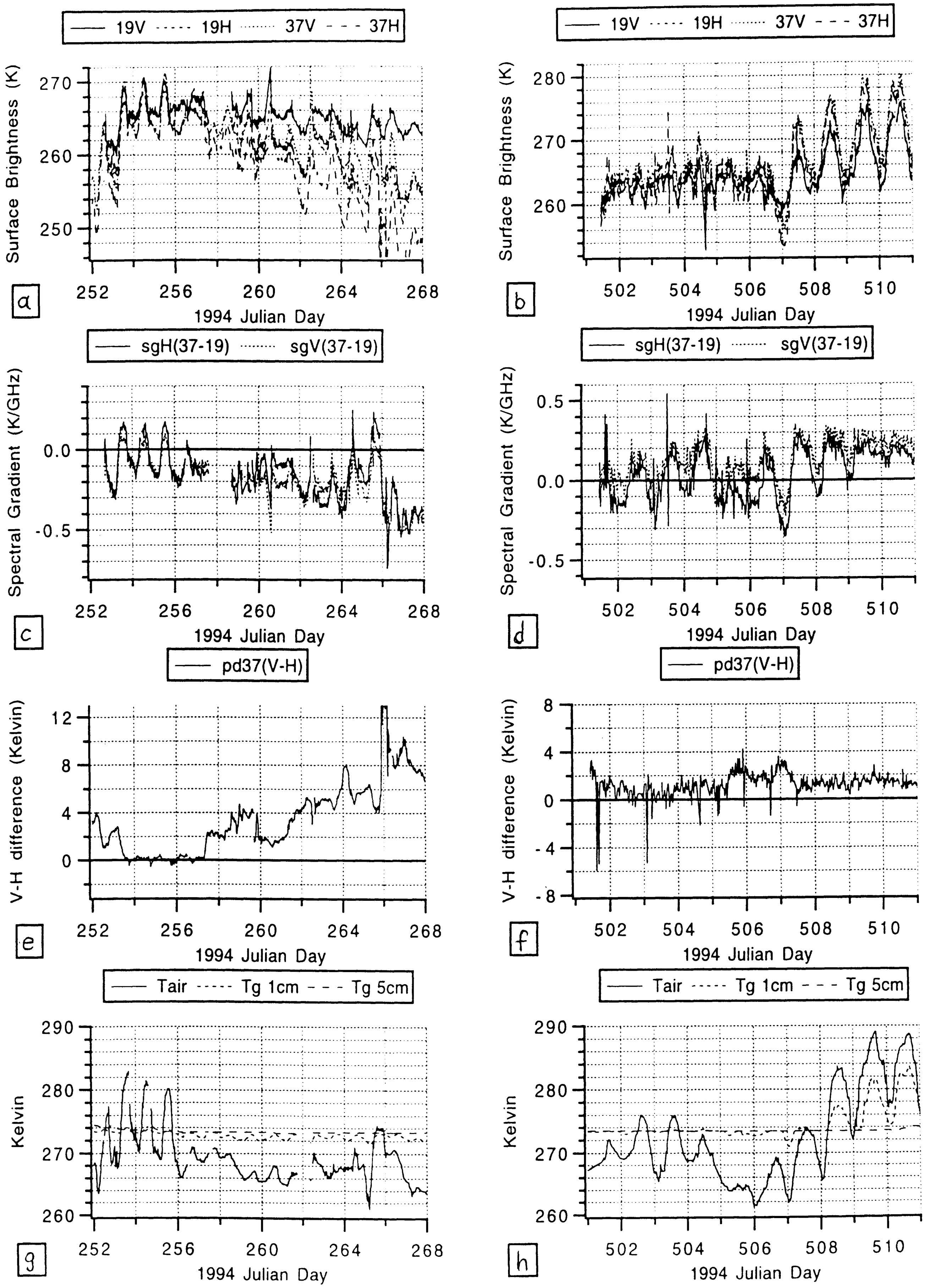


Figure 6: (left) Freeze-up and winter snow arrival. (right) Spring cold snap after thaw.

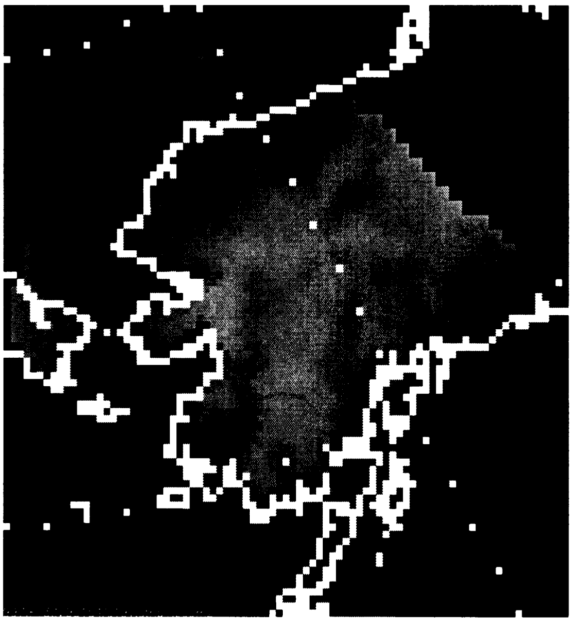


Figure 7: An example of custom EASE-Grid processor output zoomed to the region of interest. F-13, 19V channel, 1995 day 154, ascending pass.

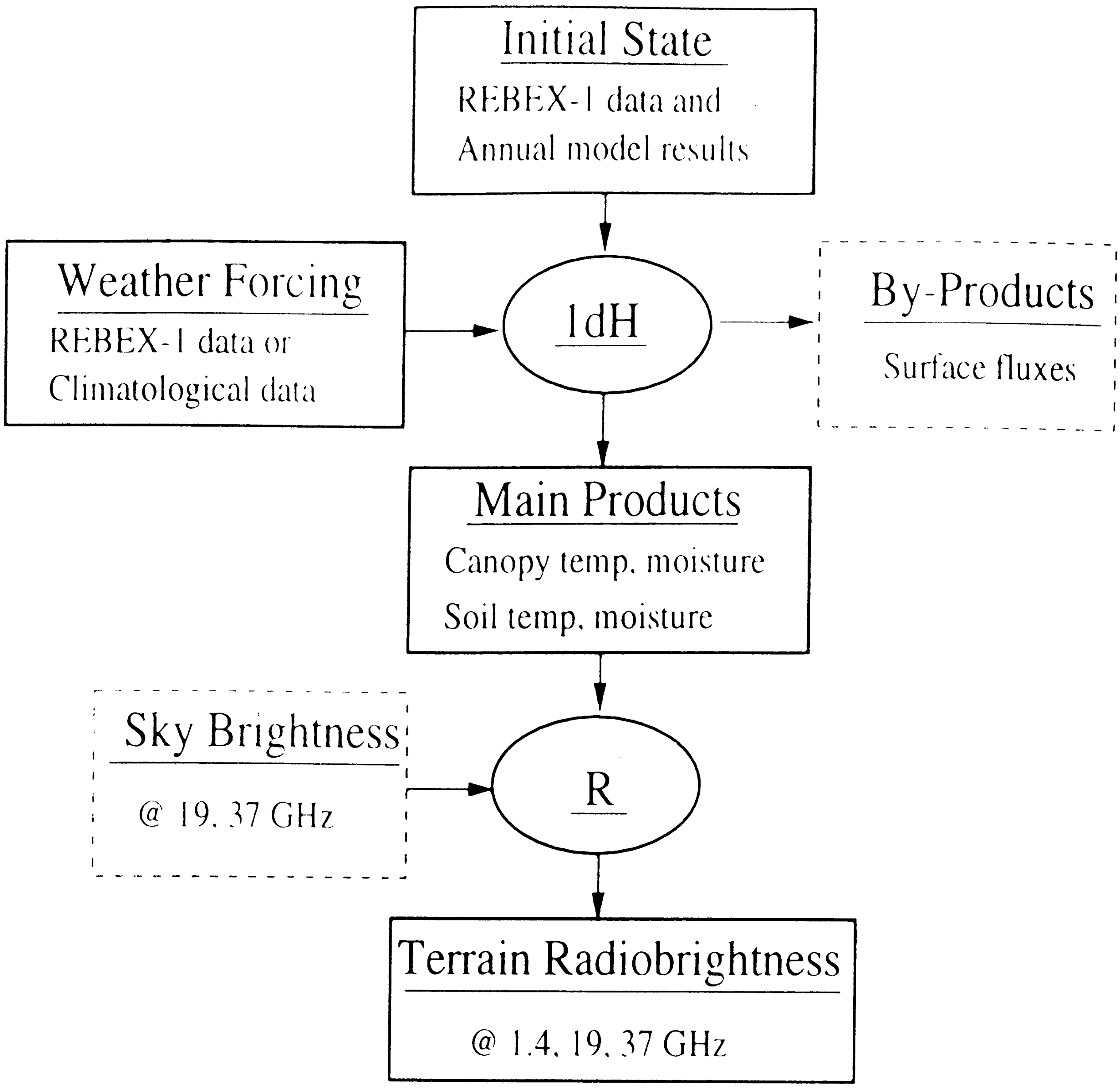
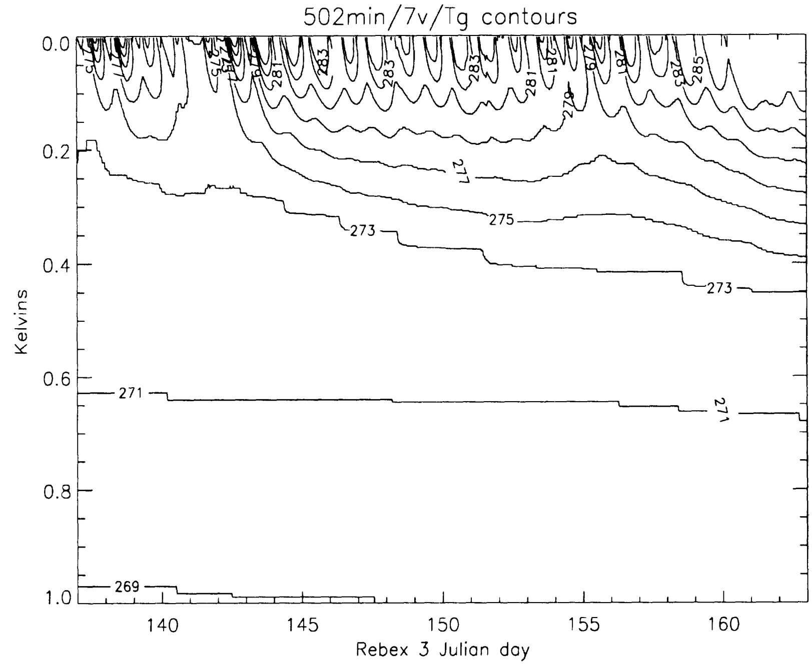
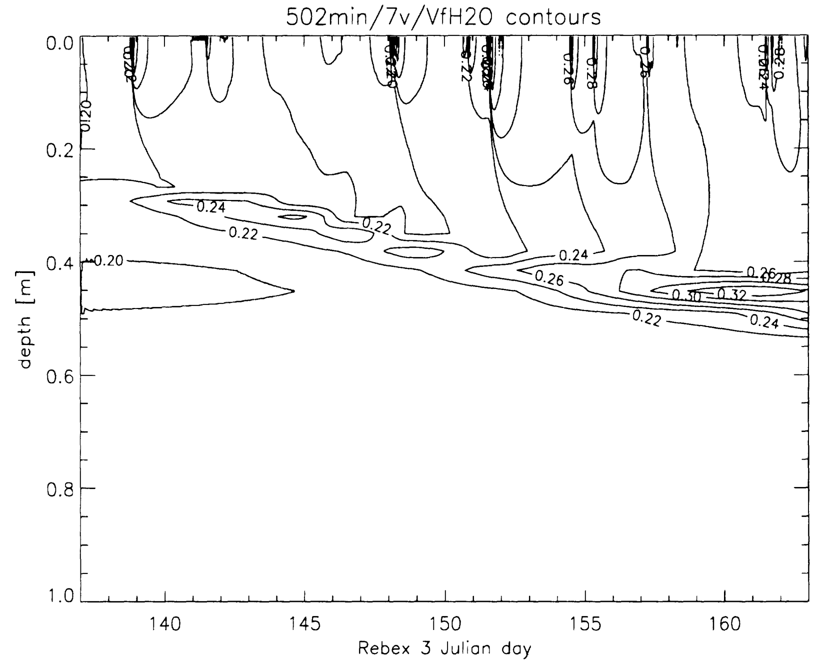


Figure 8: Schematic diagram of LSP/R model inputs and products.



(a) H2O volume fraction



(b) subsurface temperature

Figure 9: Example LSP/R model output. Top: subsurface temperature profile. Bottom: H2O (liquid+ice) volume fraction profile.