



NASA Cold Land Processes Experiment (CLPX 2002/03): Local Scale Observation Site

JANET HARDY,* ROBERT DAVIS,* YEOHOON KOH,* DON CLINE,⁺ KELLY ELDER,[#]
 RICHARD ARMSTRONG,[@] HANS-PETER MARSHALL,[@] THOMAS PAINTER,[&]
 GILLES CASTRES SAINT-MARTIN,** ROGER DEROO,** KAMAL SARABANDI,** TOBIAS GRAF,⁺⁺
 TOSHIO KOIKE,⁺⁺ AND KYLE McDONALD^{##}

*Cold Regions Research and Engineering Laboratory, Engineer Research and Development Center, U.S. Army Corps of Engineers, Hanover, New Hampshire

⁺NOAA/NWS/National Operational Hydrologic Remote Sensing Center, Chanhassen, Minnesota

[#]USDA Forest Service, Fort Collins, Colorado

[@]University of Colorado, Boulder, Colorado

[&]University of Utah, Salt Lake City, Utah

**University of Michigan, Ann Arbor, Michigan

⁺⁺University of Tokyo, Tokyo, Japan

^{##}NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

(Manuscript received 12 January 2007, in final form 19 March 2008)

ABSTRACT

The local scale observation site (LSOS) is the smallest study site (0.8 ha) of the 2002/03 Cold Land Processes Experiment (CLPX) and is located within the Fraser mesocell study area. It was the most intensively measured site of the CLPX, and measurements here had the greatest temporal component of all CLPX sites. Measurements made at the LSOS were designed to produce a comprehensive assessment of the snow, soil, and vegetation characteristics viewed by the ground-based remote sensing instruments. The objective of the ground-based microwave remote sensing was to collect time series of active and passive microwave spectral signatures over snow, soil, and forest, which is coincident with the intensive physical characterization of these features. Ground-based remote sensing instruments included frequency modulated continuous wave (FMCW) radars operating over multiple microwave bandwidths; the Ground-Based Microwave Radiometer (GBMR-7) operating at channels 18.7, 23.8, 36.5, and 89 GHz; and in 2003, an L-, C-, X- and Ku-band scatterometer radar system. Snow and soil measurements included standard snow physical properties, snow wetness, snow depth transects, and soil moisture. The stem and canopy temperature and xylem sap flux of several trees were monitored continuously. Five micrometeorological towers monitored ambient conditions and provided forcing datasets for 1D snow and soil models. Arrays of pyranometers (0.3–3 μm) and a scanning thermal radiometer (8–12 μm) characterized the variability of radiative receipt in the forests. A field spectroradiometer measured the hyperspectral hemispherical-directional reflectance of the snow surface. These measurements, together with the ground-based remote sensing, provide the framework for evaluating and improving microwave radiative transfer models and coupling them to land surface models. The dataset is archived at the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado.

1. Introduction

The local scale observation site (LSOS) is the smallest study site of the Cold Land Processes Experiment (CLPX; D. Cline et al. 2008, unpublished manuscript) and

is located within the Fraser mesocell study area (MSA), near the Fraser Experimental Forest headquarters facility in Fraser, Colorado [39°54'13"N, 105°52'59"W; 2780 m asl (meters above sea level); Fig. 1]. The 0.8-ha triangular site consists of a small clearing, a managed uniform pine canopy, and a discontinuous, mixed age canopy (Fig. 2). The LSOS was the most intensively measured site in the CLPX, where the measurement detail far exceeded similar measurements at the larger scales. The data collected at the LSOS allows for a

Corresponding author address: Janet P. Hardy, CRREL, Engineer Research and Development Center, U.S. Army Corps of Engineers, 72 Lyme Road, Hanover, NH 03755.
 E-mail: janet.p.hardy@usace.army.mil

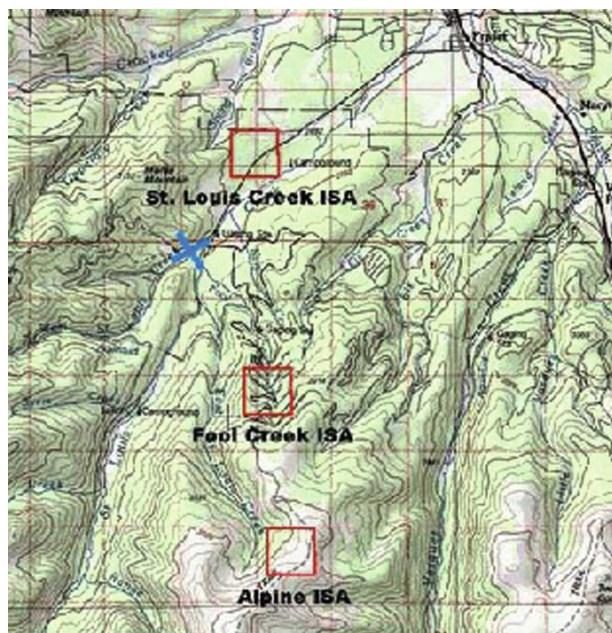


FIG. 1. The LSOS (X) relative to the three Fraser ISAs and Fraser, CO.

complete and detailed characterization of the local snow conditions, soil properties, vegetation, and energy balance characteristics. Additionally, measured ground-based microwave remote sensing (active and passive) at the LSOS provided data to relate to the measured snow and canopy properties as well as remote sensing signatures. The dataset is archived at the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado (available online at <http://nsidc.org/data/clpx/>).

The purpose of the LSOS measurements was to allow scaling between ground-based and airborne- and satellite-based instruments. The detailed measurements allow full characterization of the test site and can be used to validate small-scale models and further extrapolate and test algorithms at larger scales. The ground-based remote sensors viewed a homogeneous snow-covered clearing and a small forest stand. Snow scatters the microwave emissions from the soil, and the amount of this scatter is related to the snow properties, including snow water equivalent (SWE), grain size, wetness, depth, and density. Surface energetics drive the energy balance components that influence these snowpack physical properties, which in turn affect the signal received by the ground-based sensors. The measurement approach within the LSOS consisted of a high sampling density within relatively uniform areas of the LSOS to facilitate a comparison of microwave remote sensing data, radiative transfer models, detailed physical models of the snow and the underlying soil, and ground observations.

A network of footpaths was established throughout the LSOS to prevent the disruption of the specific measurement sites.

2. Summary of collected data parameters

a. Canopy characterization

In the fall of 2001, Cold Regions Research and Engineering Laboratory (CRREL) scientists of the Engineer Research and Development Center (ERDC) defined and extensively mapped the canopy in the LSOS. The area was divided into seventy-eight $10\text{ m} \times 10\text{ m}$ plots (Fig. 2), and the canopy in each plot was characterized using hemispheric photography. The individual tree locations in 62 plots were mapped and linked to their physical measurements (tree height, crown height, diameter at breast height, and crown diameter). The LSOS was grouped into three main canopy types: uniform pine canopy, discontinuous pine canopy, and small clearing.

b. Snowpack physical properties

Snow pits at the LSOS consist of three snow pits per day during all intensive observation periods (IOPs): one in each of the two canopy types and one in the clearing. The protocol from all the physical measurements used in the intensive study areas (ISAs) (Elder et al. 2009a) were used for all the LSOS measurements to ensure data compatibility and to facilitate modeling and comparisons across scales. In addition to the standard protocol, we measured snow wetness during the spring IOPs at 10-cm depth intervals including the snow surface using the Denoth snow wetness meter. Additionally, scientists operating the Ground-Based Microwave Radiometer (GBMR-7) measured the snow properties outside the IOPs to support their radiometer measurements.

c. Snow surveys

Systematic measurements of snow depth and snow water equivalent (SWE) were made during each IOP in each of the three canopy types. Snow depth was measured to the nearest centimeter using a calibrated snow probe inserted into the snow each meter along the paths. In 2003 only, SWE and density measurements were made approximately every 5–10 m along the paths using the Canadian ESC-30 sampler.

d. Subcanopy energetics

Standard meteorological data collected at the LSOS ranged from subcanopy temperature, relative humidity,

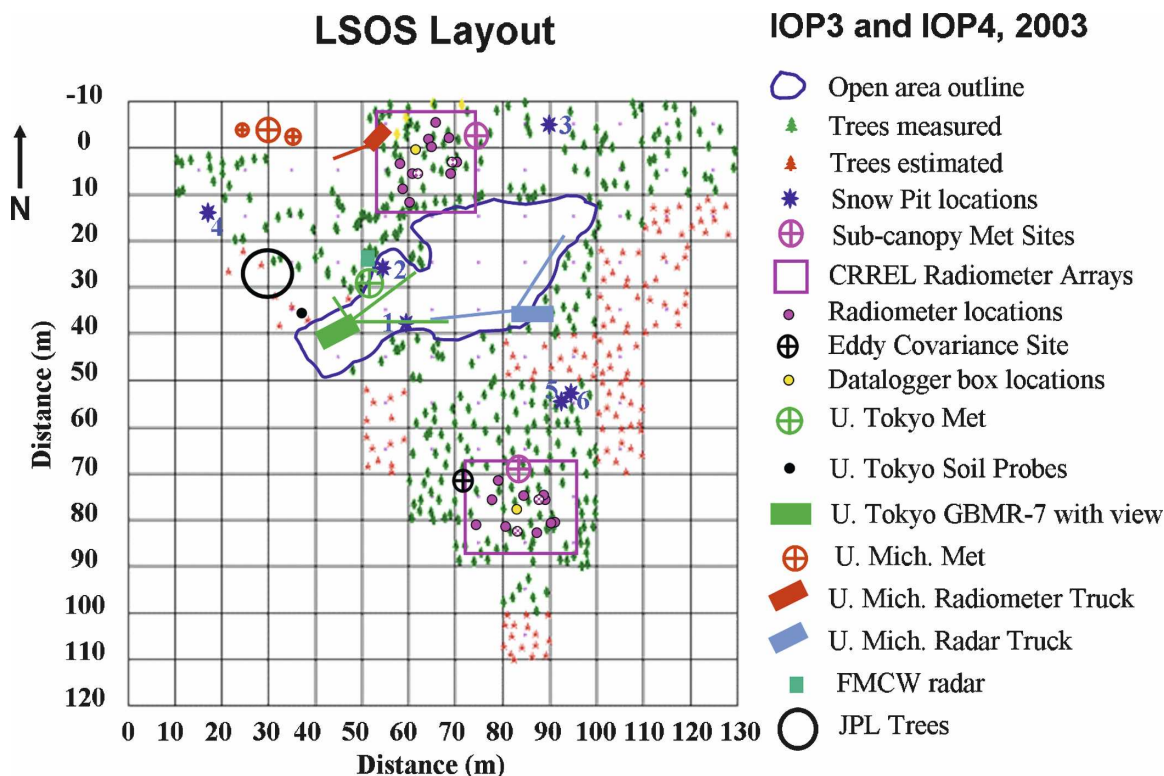


FIG. 2. Map showing the layout of the LSOS with approximate locations of instrumentation. The uniform pine canopy is southeast of the clearing. The discontinuous pine canopy is northwest of the clearing.

and wind speed measured in the uniform canopy in 2002 to five full weather stations (uniform canopy, clearing, two in discontinuous canopy, and one approximately 500 m west of the LSOS) and an eddy covariance (EC) system in 2003 (Marks et al. 2008). The measured meteorological data included solar and longwave downward radiation, snow, soil and air temperature, relative humidity, wind speed and direction, precipitation, soil heat flux, and soil moisture. Arrays of ten solar and two longwave radiometers sampled energy beneath the uniform coniferous canopy and the discontinuous canopy. The U.S. Forest Service measured the above-canopy radiation as well as other meteorological components at the LSOS (Elder et al. 2009b). Spatial variations in the longwave radiation emitted were compared between the tree trunks, snow, and ground foliage using a thermal infrared imaging radiometer (8–12 μm). The measurements of the hyperspectral hemispherical directional reflectance factor (HDRF) of the snow surface (wavelength range 0.35–2.5 μm), using a field spectroradiometer, provided calibration data for the optical airborne and spaceborne imaging spectrometers and the multispectral imagers used in the CLPX. These measurements will also be compared with field microwave measurements for synthesizing the models'

snow properties, including grain size, albedo, and surface liquid water content.

e. Microwave radiometer systems

The University of Michigan Radiation Laboratory managed a passive microwave radiometer system that operated at 1.4, 6.7, 19, and 37 GHz. These systems measured radiometric brightness in vertical (V) and horizontal (H) polarizations. The 19- and 37-GHz systems have beamwidths of 10° each, while the 1.4 and 6.7-GHz systems have beamwidths of 22° each. These systems were mounted on the end of a 10-m telescoping boom and allowed for incidence angle variation from nadir (0°) to zenith (180°; Fischman 2001). The radiometer systems were configured to operate continuously during IOP3 and IOP4, with an objective to characterize microwave emission from the snow cover and adjacent trees. The 6.7-, 19-, and 37-GHz systems collected microwave brightness data of a snow field at 54° incidence angle. Alternate targets were measured several times per day: 1) a scan in elevation from 0° to 65° of upwelling brightness from the snow field, 2) a scan in azimuth of upwelling brightness at 54° from short trees to the southwest of the radiometers, 3) a scan in azimuth of upwelling brightness at 54° from the sides of



FIG. 3. Photo of the GBMR-7 in operation at the LSOS.

trees taller than the truck boom to the north and northwest, and 4) a scan in elevation from 90° to 135° of the downwelling brightness from the same tall trees (De Roo et al. 2007).

f. Ground-based microwave radiometer

The University of Tokyo operated the GBMR-7 Advanced Microwave Scanning Radiometer (AMSR) simulator (Fig. 3), which observed the brightness temperature at 18.7, 23.8, 36.5, and 89 GHz (Kazama et al. 1999). The objectives of this passive microwave radiometer were to 1) observe the influence of snowpack metamorphism and the melting–refreezing cycle on the brightness temperature of the snow cover, and 2) develop a scheme, which couples a radiative transfer model with a physical-based snow model using data assimilation. To develop and validate the assimilation scheme, a very detailed dataset was collected, which comprised forcing data, radiometer observations, and

snowpack properties. The radiometer was mounted on a flexible positioning system, which allowed for variety in the observation direction and incident angle. Two observation areas have been used for the experiment: 1) the snowpack northeast of the radiometer (Fig. 2) was undisturbed during the winter and regularly scanned with varying incident angles (between 30° and 70°), and 2) the northern area was used for observing bare soil (after removing snow) and new snow on the ground. Both target areas were scanned several times a day during the IOPs.

g. L- and K_u -band scatterometer

The University of Michigan operated a scatterometer, a radar system capable of measuring the amplitude and phase of the backscattered signal, in the large clearing in the LSOS. The system operated at L-band (1.1–1.4 GHz) and Ku-band (15.25–15.75 GHz; Tassoudji et al. 1989). The measurements were taken from three different incidence angles (20° , 35° , and 50° from nadir). A total of 401 frequency points were recorded over the bandwidth for both scatterometers, and data collection was performed over 60 independent spatial samples at 20° , and 30 independent spatial samples at 35° and 50° . The measured data were calibrated using a metallic 36-cm diameter sphere and the single target calibration technique (STCT; Sarabandi and Ulaby 1990) algorithm. The polarimetric scattering data after calibration was formatted in Mueller matrix form and stored.

h. Frequency modulated continuous wave radars

The CRREL/ERDC and the University of Colorado obtained radar ground measurements using FMCW radars in three frequency bands [2–6 GHz (C-band), 8–12 GHz (X-band), and 14–18 GHz (Ku-band)] as well as narrow-band measurements (bandwidth = 1 GHz and 100 MHz) centered in each frequency range (Stove 1992). Metal reflectors placed on the surface and in the

TABLE 1. Temporal resolution of measured data. Refer to specific datasets for more details.

	PreIOPs	IOP1 2002	Interim IOPs	IOP2 2002	IOP3 2003	Interim IOPs	IOP4 2003
Canopy characterization	×			×			
Snow properties and snow surveys		×		×	×		×
Subcanopy energetics		×	×	×	×	×	×
Microwave radiometer					×		×
GBMR-7 radiometer	×	×			×		×
Scatterometer					×		×
FMCW radar		×		×	×		×
Biophysical properties			Ongoing, beginning with IOP1				

* Data only for 25 Mar 2003.

TABLE 2. Measured microwave frequencies (GHz) of various instruments. Here, $|-x-|$ indicates bandwidths.

	0	10	20	30	40–80	90
Microwave radiometer	x	x	x		x	
GBMR-7 radiometer			x	x	x	x
Scatterometer	x		x			
FMCW radar bands	$ -x- $	$ -x- $	$ -x- $			

snowpack allowed for calibration and attenuation calculations. These radar measurements simulated satellite and airborne measurements. This multifrequency approach for radar remote sensing was designed to support the investigation of snowpack parameters such as density, depth, and wetness. As the radar frequency increases, the effect of snow grain size becomes more important. Radars operating in the Ku-band contain the most information about the internal features of a *dry* snowpack; however, in a *wet* snowpack, the surface reflection dominates and ground return is insignificant. Radars operating at lower frequencies (C-band) are preferable for achieving the necessary penetration through a *wet* snowpack.

i. Biophysical activity in trees

The NASA Jet Propulsion Laboratory (JPL) monitored biophysical activity in six selected trees with instruments that included thermistors implanted in the soil and in the hydroactive tissues of the tree trunks, xylem sap flow sensors, and dielectric probes. Xylem flux was monitored using a constant energy input method (Granier 1987). The microwave dielectric constant of the hydroactive stem tissue was monitored with an automated dielectric monitoring system (McDonald et al. 1999). Data acquired by these instruments characterized the thermal regime within the trees and soil, and the water consumed by the plant. Two goals of this research were to determine the water conductive state of the trees during springtime thaw and to relate this information to measurements acquired with microwave remote sensing instruments.

The generalized temporal resolution of all collected data is summarized in Table 1. The preIOP was conducted from 2 to 6 November 2001, IOP1 from 17 to 24 February 2002, IOP2 from 24 to 30 March 2002, IOP3 from 17 to 25 February 2003, and IOP4 from 25 March through 1 April 2003. Table 2 summarizes the measured microwave frequencies of all radars and radiometers operating at the LSOS.

3. Example results

The data volume from the LSOS is too large for full presentation. To explain the results from the LSOS, we

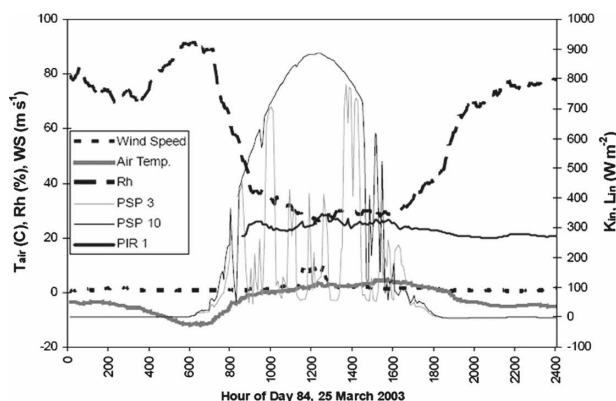


FIG. 4. Partial meteorological data from the discontinuous pine site on 25 Mar 2003. Solar and longwave irradiance data are from two pyranometers (PSP 3-tree well and PSP 10-canopy gap) and one pyrgeometer (PIR 1-tree well).

present a sample of data collected from most sensors on one day of IOP4: 25 March 2003. Data included snow and meteorological observations, ground-based microwave radiometer data, ground-based radar data, and biophysical measurements.

a. Snow and meteorological data

On 25 March 2003, the sky was clear, midday air temperatures climbed above freezing, and the measured daily total incoming solar irradiance beneath the discontinuous pine site varied between a minimum of 6.5 MJ m^{-2} (near a tree trunk) to a maximum of 20.6 MJ m^{-2} (canopy gap; Fig. 4). Hemispherical directional reflectance factor spectra data of the snow surface in

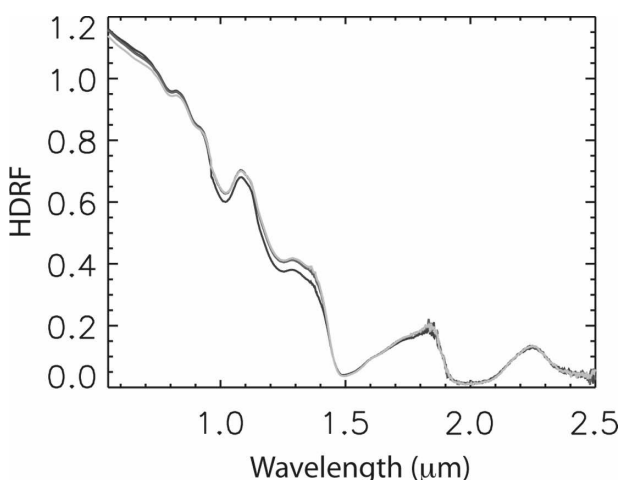


FIG. 5. HDRF spectra measured with a field spectroradiometer on 25 Mar 2003 at 1230 local time (LT). The solar zenith and azimuth angles were 38° and 188° , respectively. Each of the three lines represents a different measure of the spectra.

TABLE 3. Snowpack properties in the clearing on 25 Mar 2003 at 1300 LT. UTM is Universal Transverse Mercator.

Pit: LSOS_2a				Date: 20030325				UTM-E	UTM-N			
Total Depth (cm)		107		Time: 1300				Location (UTM)	424 545			4 417 739
Hit above ground		Mean density kg m ⁻³	Snow wetness %	Height above ground (cm)	Snow temperature °C	Hit above ground		Grain size (mm)			Grain type*	Comments
Top (cm)	Bottom (cm)					Top (cm)	Bottom (cm)	Sm	Med	Lg		
Snow surface		n/a	1.1			107	62	0.2	0.3	0.3	r	Wet snow
107	97	217	0	107	0			0.2	0.5	0.6		
97	87	173	0.6	97	0	62	57	0.5	1.2	2	r	Hard crust
87	77	230	0	87	0			0.5	0.7	1.2		
77	67	257	0	77	0	57	51	0.4	1.2	1.5	r	Saturated layer
67	57	346	0	67	0			1	1.5	2		
57	47	383	0.7	57	0	51	46	0.6	1.2	2	r	Depth hoar
47	37	302	0.02	47	0			0.6	1.5	2.1		
37	27	291	0.2	37	0	46	0	1.2	2	2.5	r	Depth hoar
27	17	322	0	27	0			1.5	2	3		
17	7	317	0.5	17	0							
7	0	n/a		7	0							
Snowpack mean:		284			0							

* r = rounded grains.

the clearing are presented in Fig. 5. Snow pit data collected from the clearing at midday showed an isothermal snowpack of 1.07-m depth with rounded grains and a mean snowpack density of 284 kg m⁻³ (Table 3). Of particular interest for interpretation of the radiometer and radar data was the measured stratigraphy and snow wetness data showing a wet snow layer at the surface and a midpack saturated layer height of 0.51–0.57 m. Snow depths in the discontinuous pine site were more variable than in the uniform pine site with a mean LSOS depth of 0.91 m ($n = 275$; Fig. 6).

b. Microwave radiometer systems

Microwave radiometer data from two separate sensors show brightness temperature, air temperature, and

snow wetness relationships on 25 March 2003 (Figs. 7 and 8). In Fig. 7, the University of Michigan measured increases in the 19-GHz brightness temperatures at midday and again around 0200 LT on 26 March 2003, coinciding with rising air temperatures. Similarly, the GBMR-7, operated by the University of Tokyo, showed an increase in brightness temperature from morning through midafternoon on 25 March, corresponding with an increase in snow wetness (Fig. 8a). Because of the unique microwave spectral signature of snow, the difference in brightness temperature between

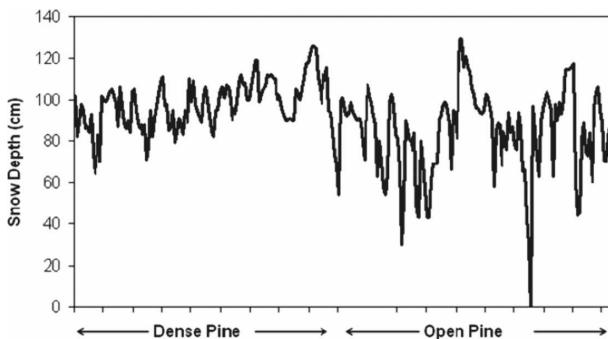


FIG. 6. Snow depth transect through both forest types. Each measured data point is ~1 m apart.

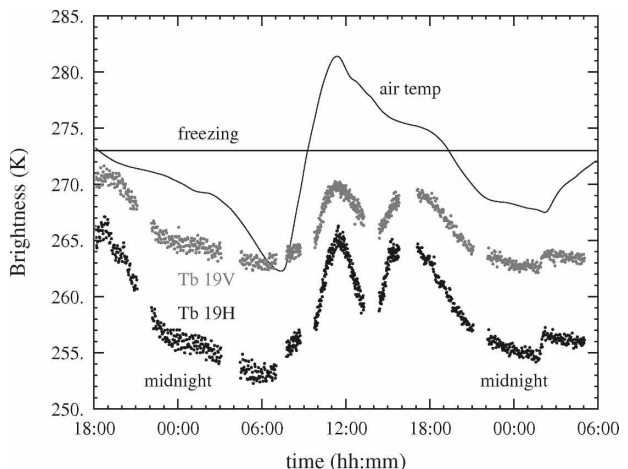


FIG. 7. Relationship between air temperature and snow surface brightness temperature as measured at 19 GHz by University of Michigan's microwave radiometer on 25 Mar 2003.

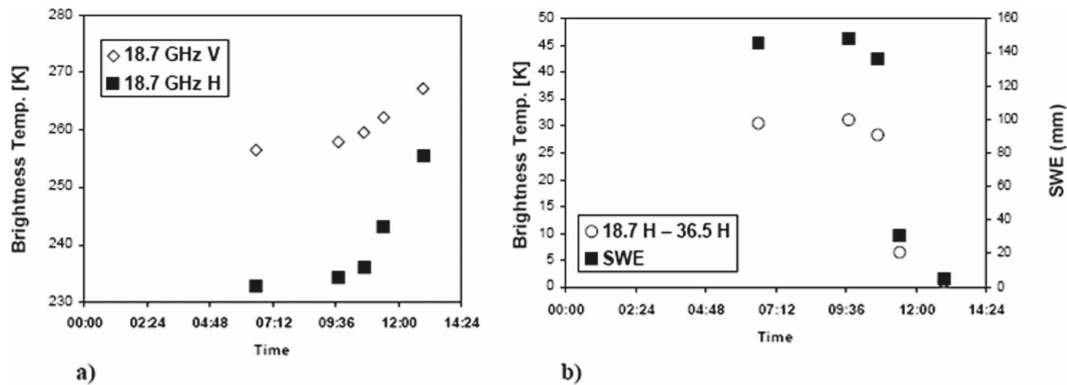


FIG. 8. (a) Influence of wet snow on the brightness temperature as measured by the GBMR-7 with horizontal and vertical polarization. (b) Estimated SWE based on the brightness temperature difference. Because of the wet snow surface, note that (b) incorrectly indicates the snowpack melted out completely after 1200 LT on 25 Mar 2003.

the lower (e.g., 18.7 GHz) and the higher (e.g., 36.5 GHz) frequencies provides an indication of the SWE (Schmugge et al. 2002). However, this relationship is only valid for a completely dry snowpack and will fail at the presence of liquid water. For example, in Fig. 8b, the SWE is calculated using an algorithm based on the work of Chang et al. (1987),

$$\text{SWE} = 4.77(\text{TB}_{18.7\text{H}} - \text{TB}_{36.5\text{H}}),$$

where SWE represents the snow water equivalent (in millimeters), and $\text{TB}_{18.7\text{H}}$ and $\text{TB}_{36.5\text{H}}$ are representing the brightness temperature observations at 18.7 GHz and 36.5 GHz (horizontal polarization). Figure 8b also provides a good example of the effect of a wet snowpack. The low SWE in the morning was caused by the wet midlayer snowpack (see Table 3). During later observations, the brightness temperature differences decreases because of an increasing snow surface wetness. Correspondingly, the estimated SWE decreases, and the observation after 1200 LT incorrectly suggests the absence of snow on the ground.

c. Scatterometer and FMCW radar

Figure 9 shows a representative set of polarimetric backscattering coefficients collected on 26 March 2003 by the University of Michigan's radar at Ku-band (15.25–15.75 GHz). The data show similar copolarized backscattering coefficients, which indicates that the snow volume entirely dominated the scattering. This result is also evident from the copolarized ratio to the cross-polarized ratio (~ 9 dB), which is mainly caused by the multiple scattering within the snow medium. CRREL/ERDC and the University of Colorado's multiband radar profile for the wet snow of 25 March (Figs. 10a and 10b) showed the presence of a small

amount of water affected radar interaction with the snowpack. C-band (2–8 GHz) measurements (Fig. 10a) resolved the lower layers in the snowpack; however, at the Ku-band (14–18 GHz) frequencies (Fig. 10b), the surface reflection was the dominant effect in the wet snow, and ground return was insignificant. For this wet snowpack, radars operating at lower frequencies were preferable to achieve necessary penetration. These results suggest that a dual-frequency approach for radar remote sensing is necessary to retrieve snowpack parameters such as density, depth, and wetness.

d. Biophysical activity in trees

An example of the NASA JPL dataset from one of the six trees continuously monitored for two years shows snow, soil, and stem temperatures below freezing on 25 March 2003 (Fig. 11). These data change dramatically later in the spring as air, soil, and stem temperatures increase and sap flow begins. This change is used

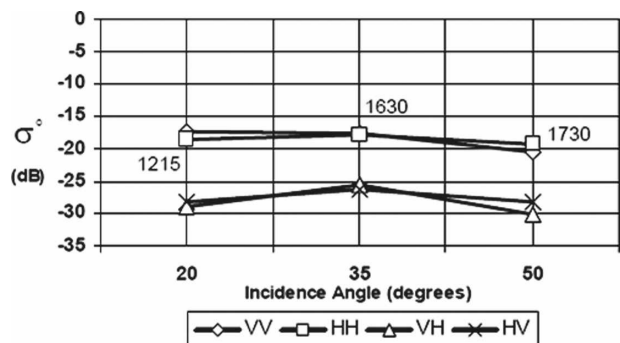


FIG. 9. Time series of backscattering coefficients as a function of the incidence angle for the Ku-band scatterometer on 26 Mar 2003. The backscattering coefficient is the ratio of the radar cross section of the target to its areal extent, expressed in decibels.

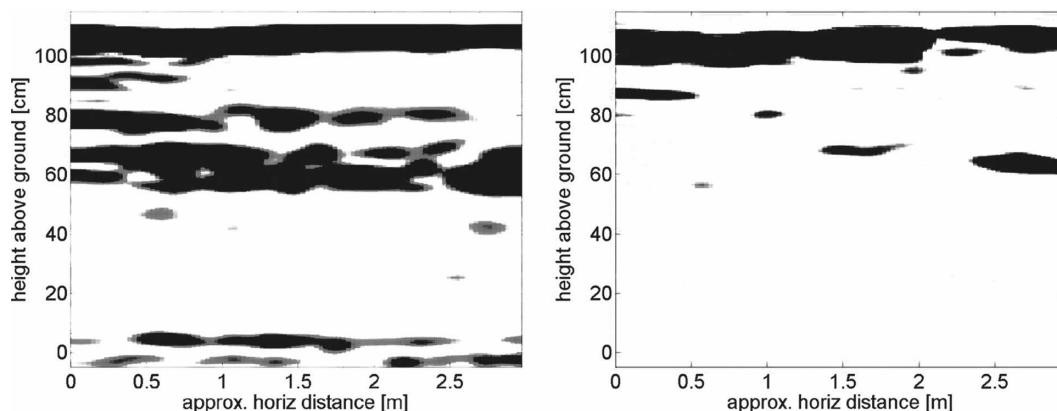


FIG. 10. (a) C-band and (b) Ku-band data from the FMCW radar on 25 Mar 2003. Black indicates strong reflection, and white indicates no reflection. Note that the C-band measurement penetrates to the ground in this wet snowpack and shows reflections from midpack layers. The Ku-band measurement has a very strong surface reflection as a result of the moisture content and shows midpack reflections, but it is attenuated before reaching the snow-ground interface.

to determine the onset of the growing season for LSOS conifer trees. These data will augment and support the interpretation of the measurements acquired with microwave remote sensing instruments.

4. Summary

Data were collected at the local scale observation site over a period of two years and by several cooperating institutions and numerous people. The data presented here were intended to show the contents of the larger database. This database provides details of fully characterized snow, soil, canopy, energy balance, and microwave properties. Using this database, physically based models, remote sensing retrieval algorithms, and theories can be confidently evaluated with minimal ambiguity. Scaling exercises, in conjunction with the full CLPX dataset, will test the performance of these algorithms and models at the 1- and 25-km scales (ISA and MSA, respectively), and the regional scale.

Acknowledgments. This work was funded through cooperation of many agencies and organizations including the National Aeronautics and Space Administration (NASA), the U.S. Army Corps of Engineers Civil Works Remote Sensing Research Program, the U.S. Army Basic Research Program, the Japan Aerospace Exploration Agency (JAXA), the Japan Science and Technology Agency, and the National Assembly for Wales, Strategic Research Investment Fund, Cardiff. A portion of this work was conducted at the Jet Propulsion Laboratory at the California Institute of Technology, under contract to NASA.

Many individuals contributed to the success of the data collection effort at the LSOS. Our gratitude is extended to H. Boyne, M. J. Brodzik, T. England, R. Essery, R. Forester, H. Fujii, G. Koenig, T. Link, D. Marks, M. Martinez, R. Melloh, N. Mulherin, E. Podest, J. Pomeroy, A. Rowlands, A. Twombly, and other staff at the U.S. Forest Service, Fraser Experimental Forest.

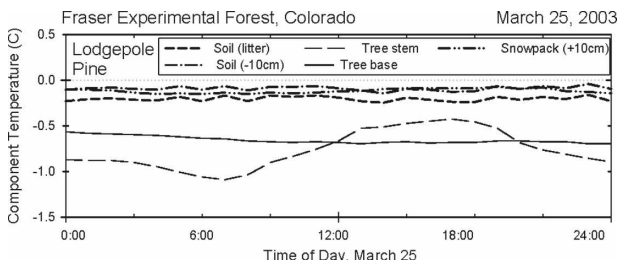


FIG. 11. Stem temperature monitored at 1.5-m height and at the stem base of one lodgepole pine tree on 25 Mar 2003. Snowpack temperature at 0.1 m above the ground surface, and soil temperature at the ground surface and at 0.1-m depth.

REFERENCES

- Chang, A. T. C., J. L. Foster, and D. K. Hall, 1987: Nimbus-7 SMMR derived global snow cover parameters. *Ann. Glaciol.*, **9**, 39–44.
- De Roo, R. D., A. R. Chang, and A. W. England, 2007: Radiobrightness at 6.7-, 19-, and 37-GHz downwelling from mature evergreen trees observed during the Cold Lands Processes Experiment in Colorado. *IEEE Trans. Geosci. Remote Sens.*, **45**, 3224–3229.
- Elder, K., D. Cline, A. Goodbody, P. Houser, G. Liston, L. Mahrt, and N. Rutter, 2009a: NASA Cold Land Processes Experiment (CLPX 2002/03): Ground-based and near-surface meteorological observations. *J. Hydrometeorol.*, in press.
- , —, G. Liston, and R. Armstrong, 2009b: NASA Cold

- Land Processes Experiment (CLPX 2002/03): Field measurements of snowpack properties and soil moisture. *J. Hydrometeor.*, in press.
- Fischman, M. A., 2001: Development of a direct-sampling digital correlation radiometer for Earth remote sensing applications. Ph.D. dissertation, University of Michigan, 232 pp.
- Granier, A., 1987: Evaluation of transpiration in a Douglas-fir stand by means of sap flow measurements. *Tree Physiol.*, **3**, 309–320.
- Kazama, S., T. Rose, R. Zimmerman, and R. Zimmerman, 1999: A precision autocalibrating 7 channel radiometer for environmental research applications. *J. Remote Sens. Soc. Japan*, **19**, 265–273.
- Marks, D., M. Reba, J. Pomeroy, T. Link, A. Winstral, G. Flerchinger, and K. Elder, 2008: Comparing simulated and measured sensible and latent heat fluxes over snow under a pine canopy to improve an energy balance snowmelt model. *J. Hydrometeor.*, **9**, 1506–1522.
- McDonald, K. C., R. Zimmermann, J. B. Way, and W. Chun, 1999: Automated instrumentation for continuous monitoring of the dielectric properties of woody vegetation: System design, implementation, and selected in situ measurements. *IEEE Trans. Geosci. Remote Sens.*, **37**, 1880–1894.
- Sarabandi, K., and F. T. Ulaby, 1990: A convenient technique for polarimetric calibration of single-antenna radar systems. *IEEE Trans. Geosci. Remote Sens.*, **28**, 1022–1033.
- Schmugge, T. S., W. P. Kustas, J. C. Ritchie, T. J. Jackson, and A. Rango, 2002: Remote sensing in hydrology. *Adv. Water Resour.*, **25**, 1367–1385.
- Stove, A. G., 1992: Linear FMCW radar techniques. *IEE Proc. Part F: Radar Signal Process.*, **139**, 342–350.
- Tassoudji, M. A., K. Sarabandi, and F. T. Ulaby, 1989: Design consideration and implementation of the LCX polarimetric scatterometer (POLARSCAT). Radiation Laboratory Rep. 022486-T-2, 79 pp.