Annual Journal of Hydraulic Engineering, JSCE, Vol.49, 2005, February

Observation of Snow Properties, Meteorological Forcing and Brightness Temperature Data at the Local Scale Observation Site during the Cold Land Processes Field Experiment and the Application to a Dense Media Radiative Transfer Model

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This paper introduces radiometer, snow pack properties and meteorological forcing data observation during the winter season `02/`03 in Fraser, Colorado, USA. The observation was part of the NASA Cold Land Processes Field Experiment (CLPX) at the Local Scale Observation Site (LSOS). Apart from continuous observation of meteorological data, which can be used as forcing data sets for physical based snow models, intensive ground based passive microwave observations have been implemented during the winter season. Furthermore regular observations of the snow pit properties have been conducted, including the snow density and snow grain size profiles. The observed data set provides the possibility to evaluate and improve radiative transfer models for snow and good modeling results have been achieved using the dense media radiative transfer theory. All data will be released to the public on October 1, 2004 and is available from the website of the National Snow and Ice data center.

Key Words **:** *Cold Land Processes Field Experiment, Local-Scale Observation Site, Ground Based Passive Microwave Radiometer, Snow Properties, Dense Media Radiative Transfer*

1. Introduction

Due to its high albedo and thermal insulation, snow plays an important role in the global energy and water balance, e.g. it changes the runoff characteristics of a catchment and influences the soil moisture and evaporation[1)].

Up to 53% of the northern hemisphere and up to 44% of the world land mass can be covered with snow at any given time[2)]. World wide one third of the water used for irrigation is temporarily stored as snow[3)]. In the Rocky Mountains 90% of the runoff is from snow melt and 75% of total annual precipitation is solid[1)].

Passive microwave satellite observation (brightness temperature) can be used to monitor the snow depth or water equivalent (SWE) and the snow state (dry/wet)[4)]. The objective of the field work in Fraser was to create a detailed data set of snow radiometer observation in combination with the actual snow pack state in order to evaluate and improve current radiative transfer models for snow. A possible application for radiative transfer models for snow is the assimilation of satellite brightness temperature observations into land-surface schemes or snow models.

(1) CLPX and LSOS

The objective of the Cold Land Processes Field Experiment was to improve our understanding of the terrestrial cryosphere[5)]. The CLPX followed a multi-sensor and multi-scale approach, to improve our possibilities to understand cold land process at

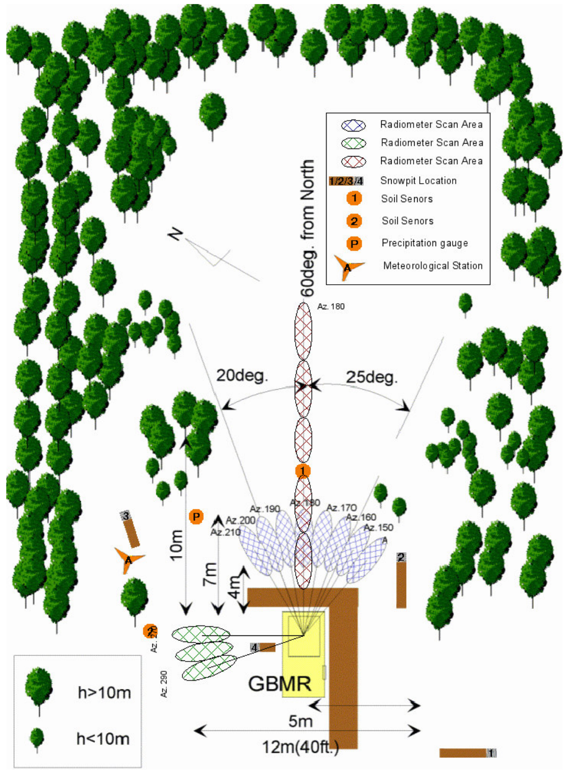

Fig. 2: Overview of Instrument Set-Up

local scale to larger scales. During the CLPX, four intensive field observations (IOP) have been implemented in February (dry snow) and March (wet snow) 2002 and 2003.

Our observations have been implemented at the LSOS, which was the smallest of all study sites within the CLPX. The LSOS was located within the Fraser Experimental Forest.

Within the CLPX the LSOS was used to implement very detailed observation of the local snow conditions, soil properties, vegetation and energy balance characteristics, which allow the investigation of scaling issues between ground based observations and airborne-/satellite-based sensors. Janet et. al.[6] provides a complete overview of all data collected during the CLPX IOPs at the LSOS.

(2) Field Experiment

The main target of the field work was the observation of the brightness temperature of a seasonal snow pack in combination with the structural properties of the snow cover.

Apart from the observed snow characteristics, continuous observations of the meteorological forcing data have been implemented.

(a) Site Overview

Fig. 1 provides an overview of the instrument set-up. The radiometer system has been installed at the edge of a large clearing within the forest area of the Experimental Forest. Three different scan areas

Fig. 1: GBMR-7 at the LSOS

have been selected to observe the snow brightness temperature. The location for snowpit observations and the weather station have been selected, so that they are close to the radiometer footprints. Furthermore also the meteorological data and the soil probes are located close to the scan areas.

(b) Ground Based Microwave Radiometer

The ground based brightness temperature observations have been implemented by means of the 7 channel Ground Based Microwave Radiometer (GBMR-7). The GBMR-7 is a dual polarization, multi frequency passive microwave radiometer, which observes the brightness temperature at 18.7, 23.8, 36.5 and 89.0 GHz. The radiometer was developed to provide similar frequencies as the Advanced Microwave Scanning Radiometer (AMSR and AMSR-E) on board of Terra and Aqua.

The sensor was developed for environmental research and is designed for extreme outdoor conditions. The temperature range within the radiometer can operate is -30°C to +40°C, this wide temperature range is achieved by encapsulation of all critical parts of the receiver in a thermal stabilized box[7].

Fig. 2 provides a picture of the radiometer at the LSOS. The radiometer box contains the receiver electronic, which is placed on an accurate positioning system (azimuth: 0° to 360°, elevation: ±90°). The positioner enables the system to exactly return to previously scanned areas.

(c) Snow Pit Properties

All CLPX snow pit observation followed the same general sampling protocol[5]. The observed properties include, vertical profiles of the snow density, temperature and the snow stratigraphy and grain size. **Fig.** 3 shows a snowpit and the tools used during the CLPX. On the picture one can see (from right to left) a pocket ruler, a hand microscope to observe the size of the snow grains, a scale and a density cutter.

(d) Automated Weather Station

The automated weather station (AWS) was installed to continuously monitor the meteorological

Total Depth (cm):		51	
Ht above ground top (cm) - bottom (cm)		Density Profile A kg m-3	Density Profile B kg m-3
50	40	92	90
40	30	227	201
30	20	248	235
20	10	250	258
10	0	267	277

Height above ground (cm)	Temp. oC
48	-2.6
45	-3
40	-3.5
35	-3.4
30	-3
25	-2.4
20	-1.8
15	-1.4
10	-0.9
5	-0.3
2	-0.2

Stratigraphy Ht above ground top (cm) - bottom (cm)		Grain Size (mm) nearest 0.1 mm Sm	Med	Lg	Grain Type	Comments
51	42	n/a	1	n/a	n	new snow crystals
		n/a	1	n/a		
42	35	0.3	0.7	1.1	f	
		0.7	1	1.4		
35	25	0.5	0.9	1.2	f	
		1	1.1	1.5		
25	15	0.7	0.9	1	f	
		0.7	1.2	2		
15	1	0.9	1.4	1.8	f	
		1.1	1.4	2.4		
1	0	n/a	n/a	n/a		ice crust
		n/a	n/a	n/a		

Table 1: LSOS Snowpit Dec. 13, 2002 (10:40 to 12:00)

Fig. 4: Snowpit Observation during the CLPX

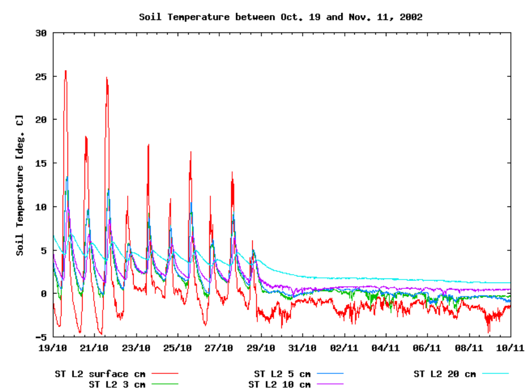

Fig. 3: Soil Temperature at Beginning of Winter Season

conditions at the site. The data set includes wind speed, wind direction, air temperature, relative humidity, downward long-wave and short wave radiation and precipitation. Furthermore ten soil temperature and six soil moisture sensors were connected to the AWS. The soil probes where installed at two different locations at different depth (see also **Fig. 1**).

2. Results

In this section example of the observed data will be presented.

(1) Snow Pack Properties

Daily snowpit observation have been done during CLPX IOP 3 and 4, in addition snow pit data was collected at regular intervals before and between the IOPs:
2002: 3, 27 Nov, 11-15 Dec
2003: 4, 22 Jan, 2, 3, 6, 7, 9, 10, 21, 25 Feb, 11 Mar

Table 1 shows the example of the data collected during a snow pit from Dec. 13, 2002.

The snow density profile was collected by measuring the snow density every 10 cm using a density cutter. At each level 2 measurements were done.

The snow particle size was also recorded according to the snow stratigraphy. At each level, three different snow grains were selected, which represented a typical small, medium and large snow grain. For each selected grain the longest axis and the one perpendicular to it were recorded.

(3) Meteorological Data

The AWS including the soil probes was installed before the start of the winter season. The system was continuously running between October 1, 2002 and March 29, 2003. The data was stored using a 10 min resolution (average).

Fig. 4 displays the soil temperature at the end of October 2003 at different soil layers. Until around October 29th, the diurnal variation of the soil is clearly visible. At the end of October, the dirunal variation disappears, this was around the time, when the snow started accumulating on the ground. This clearly shows the insulation effect of a snow cover.

(3) Brightness Temperature Observation

Radiometer observations have been implemented

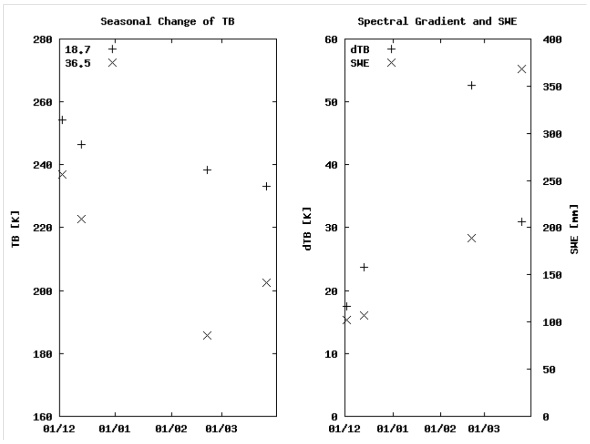

Fig. 5: Change of TB, Spectral Gradient and SWE

during CLPX IOP 1 (Feb. 2002), 3 (Feb. 2003) and 4 (Mar. 2003), an additional IOP was implemented in Dec. 2002.

Three different scan areas have been selected, with respect to different observation targets and measurement techniques.

Area I – Undisturbed snow cover: The snow cover in this area was undisturbed during the winter season and therefore the total accumulated snow was observed. The observations have been performed at a fixed incident angle of 55°.

Area II – New snow accumulation on the ground: In this area the snow was removed twice during the winter season to observe bare soil emission and the influence of a partial snow cover on the brightness temperature.

Area III – Angular Scans: In front of the container observations at different incident angles have been performed.

(a) Seasonal Change of the Snow Brightness Temperature

Accumulated snow effects the emission from the underlying ground, due to the scattering effect of the snow grains, therefore snow on the ground results in a microwave emission on top of the snow cover, which is less then the emission from the underlying soil[4]. The scattering effect increases, as the number of scatterer and their size is increasing. This effect can be used to monitor the snow cover and the SWE or depth.

The change of the snow brightness temperature at 18.7 and 36.5 GHz (horizontal) due to snow accumulation is displayed in the left graph of **Fig.** 5. The right graph displays the difference between both frequencies, the so-called spectral gradient, and the total observed SWE.

The spectral gradient is an indication for the total amount of snow on the ground, and is often used in current satellite algorithm to observe the SWE. An example for such a relationship is (for SMMR)[8]:

$$SWE = 4.77\left(TB_{18H} - TB_{37H}\right) \quad (1)$$

Date	dTB [K]	SWE_{calc} [mm]	SWE_{obs} [mm]
Dec 2, 2002	17.5	84	102
Dec 13, 2002	23.7	113	107
Feb 20, 2003	52.6	251	189
Mar 25, 2003	30.9	147	368

Table 2: Comparison between obs. and calc. SWE

where SWE is the snow water equivalent [mm] and TB [K] are the observed brightness temperatures at 18 and 37 GHz (horizontal polarization).

Based on the observed spectral gradient in Fraser the SWE was calculated using Eq. 1. The results of this calculation are summarized in **Table** 2. Except for the case at the end of March, the calculated snow water equivalent (SWE_{calc}) agrees well with the snowpit data (SWE_{obs}).

The results for the March case is significantly different then the observed SWE. Mid of March the temperature at the LSOS raised, so that the snow started melting. Between March 18 and 19, Colorado was hit by a big blizzard, which added a significant amount of snow on top of the wet snow pack. As shown in the next section, wet snow is opaque in the microwave region. For the March case, the snow base was wet, and therefore only the snow above the wet layer can be penetrated.

The results in **Table** 2, indicate some of the limitations of algorithms, which are based on the spectral gradient to estimate the SWE. As introduced the size of the snow grain influence the brightness temperature. Due to the continuous evolution of the snow pack during the winter season, the snow grains will change their size and shape, i.e. the same amount of snow on the ground can have different passive microwave signatures. This can lead to an underestimation of the amount of snow at the beginning of the winter season, or for examples in cold region where large depth hoar crystals develop, like in Fraser, to an overestimation of the scattering effect and therefore to an overestimation of the SWE[9], which e.g. can explain the rather large difference for the case in February.

(b) Influence of Wet Snow

The influence of liquid water on the microwave emission from the snow cover is displayed in **Fig.** 6. The left graph shows radiometer observation done in the early morning of March 25. During the night (March 24 to 25) the liquid water in the snow pack from the previous day was refreezing and the top of the snow pack was dry early in the morning (06:30). After the sunrise, the top layer of the snow pack starts to warm up and the snow starts melting as

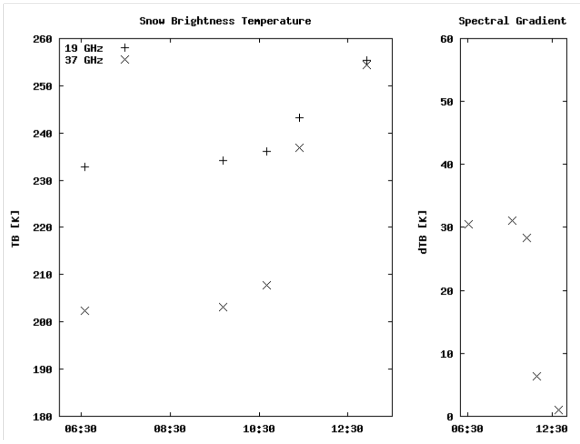

Fig. 7: Influence of wet snow on TB and Spectral Gradient

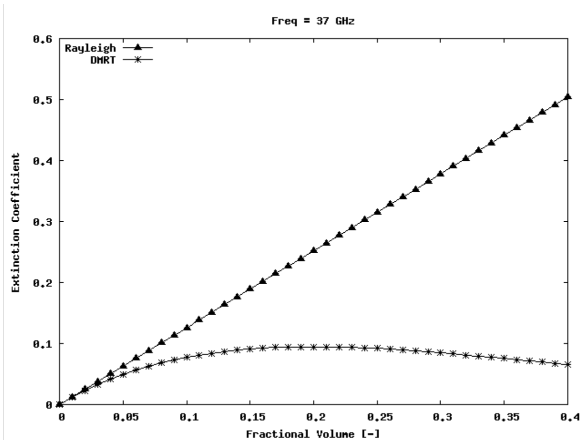

Fig. 6: Comparison between conventional RTM and DMRT

soon as the snow pack temperature rises to 0°C. With the increasing liquid water content in the snow pack the brightness temperature at both displayed frequencies is increasing and the spectral gradient disappears, i.e. Eq. 1 can't be used anymore to estimate the SWE.

The observed behavior can be explained with the increase of the absorption coefficient of the background medium (air + water), which increases from a value close to 0 for dry snow to a value much larger than the scattering coefficient. Therefore in case of wet snow, the medium approaches the characteristics of a blackbody radiator[10)].

The effect of liquid water in a snow cover on the microwave signature currently prevents algorithms to estimate the SWE for wet snow conditions[4)].

3. Radiative Transfer in Snow

(1) Dense Media Radiative Transfer Theory

In a dense medium like snow the classical approaches to calculate the radiative transfer can not be used anymore, because the correlated scattering (multiple-scattering) effect of the snow grains needs to be considered[11)].

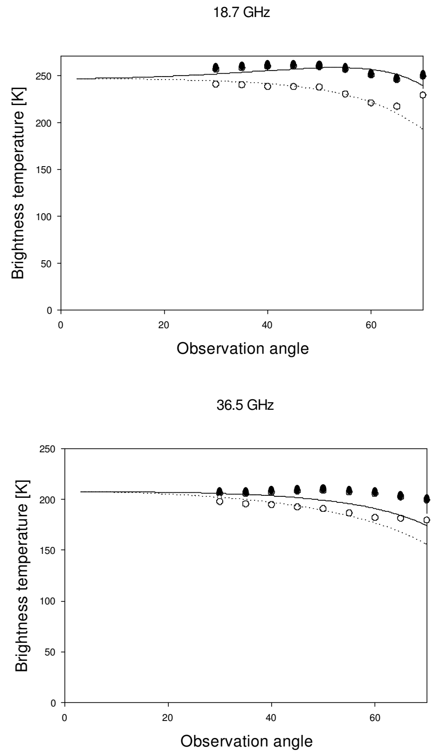

Fig. 8: Modeling results using DMRT

The effect of the multiple-scattering effect on the extinction coefficient is displayed in **Fig.** 7, the graph displays the extinction effect (scattering + absorption) for snow calculated using the conventional approach (Rayleigh Scattering) and the dense media radiative transfer theory (DMRT), which is briefly introduced in the next section. As it can be seen, the extinction coefficient increases linear, as the fractional volume increases. The DMRT results only show a linear behavior for small fractional volumes. For this example the extinction coefficient reaches its maximum at a fractional volume of around 0.2 and then drops. If the curve would be continued until a fractional volume of 1 (ice), the extinction coefficient would drop to 0 for a non-absorbing medium, because no scattering exists.

One approach to consider multiple scattering is the so called dense media radiative transfer theory under the Quasi Crystalline Approximation with Coherent Potential (QCA-CP)[12)].

The dense media radiative transfer theory is an analytical approach to consider the multiple-scattering effect of the snow grains as discrete scatterers. The correlation effect of the snow particles is calculated based on the conditional probability of the particle position, using the Percius-Yevick pair distribution function[11)]. The particle size distribution is based on a log-normal distribution function[13)].

(2) Modeling Results

Fig. 8 displays model results for the 18.7 and 36.5 GHz channels, using a dense media radiative transfer model for snow based on the QCA-CP[13)]. The circles are showing observed brightness temperatures (solid = vertical, open = horizontal polarization) and the continuous lines the model results. The results are based on snowpit observations from Feb. 21, 2003[14)]. The exception was the snow grain size, which was computed by minimizing the Mean Square Error between observed and model brightness temperature data. Furthermore because the model is a one layer model, the snow parameters have been averaged over the vertical profile.

The calculated grain size for Feb. 21 using the DMRT was 1.1 mm, which agrees well with the observed average grain size (1.5 mm).

The graph in **Fig.** 8 shows a good agreement between the modeled and observed brightness temperature data. The error increases at higher observation angles. Also the error at the vertical polarization is comparable or higher than the error at the horizontal polarization. In addition the error is larger for the 36.5 GHz channel compared to the 18.7 GHz.

Several problems can explain the error between the modeled and observed values. As stated, the model did not consider the actual stratigraphy of the snow, which for example will neglect scattering effects between snow layers, e.g. snow – ice – snow. Also in current radiative transfer models for snow, the snow grain is assumed to be of spherical form and the distribution of the snow particle size is assumed to follow the shape of a log-normal distribution. In addition for the scans at different observation angles, the assumption that the snow pack and also the soil conditions are the same might not be true. Furthermore at high observations angles, it might be necessary to consider the influence of the surrounding trees at the LSOS. Further studies need to be performed to quantify the effects on the radiative transfer modeling.

4. Discussion & Outlook

Due to the combined observation of structural snow pack properties and the snow brightness temperature data, the data set will be useful to evaluate current radiative transfer models for snow and help to identify their limitations.

The results achieved using the DMRT theory, show the possibility to use this approach to model the radiometer brightness temperature using observed data in the field, still several problems have been identified, which need to be addressed.

Furthermore the observed meteorological forcing data can be used for snow modeling and will help to develop relationships between the observed and modeled snow grains and their representation in current radiative transfer model for snow, which is e.g. necessary for data assimilation of satellite observations into land-surface schemes or snow models.

All data[15)] will be released to the public on October 1, 2004 and is available from the website of the NSIDC (http://www.nsidc.org/data/clpx).

ACKNOWLEDGMENT: The Authors would like to thank the Japan Aerospace Exploration Agency and the Japanese Science and Technology Corporation for funding the observations in Fraser and NASA, which provided us the possibility to participate in the CLPX.

Furthermore we would like to thank Don Cline for his great efforts in organizing the CLPX and also Janet Hardy who managed the LSOS.

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(Received September 30, 2004)