INTEGRATED SNOW OBSERVATION DURING THE COLD LAND PROCESSES FIELD EXPERIMENT AND ITS APPLICATION FOR THE DEVELOPMENT OF RADIATIVE TRANSFER MODEL FOR SNOW

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This paper introduces microwave radiometric data, snow pack properties and meteorological forcing data observation collected 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 to constrain physically based snow models, intensive ground-based passive microwave observations have been implemented during the winter season. Furthermore regular observations of snow pit properties have been conducted, including the snow density and snow grain size profiles. The data set provides the possibility to evaluate and improve radiative transfer models for snow and satisfactory modeling results have been achieved using the dense media radiative transfer theory (DMRT). All data will be released to the public on October 1, 2004 and are 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 Theory*

1. INTRODUCTION

Due to the high albedo and thermal insulation of snow, it 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)].

Due to the sensitivity of the microwave emission of snow to the snow grain size and the snow water equivalent (SWE), passive microwave satellite observation (brightness temperature) can be used to monitor the snow depth or SWE and the snow state (dry/wet)[4)].

The objective of the field work at the Local Scale Observation Site (LSOS) in Fraser was to create a detailed data set of radiometric observations of snow covered terrain 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 model is the development of physical based algorithms to observe the SWE, e.g. by introducing the observed brightness temperature into land-surface schemes or snow models using data assimilation.

The paper is separated into five parts. After the introduction, the experiment set-up and the observations are introduced. The third section provides an analysis of the seasonal change of the observed brightness temperature. Afterwards the DMRT theory is briefly introduced and modeling results are presented. The paper concludes with some final remarks.

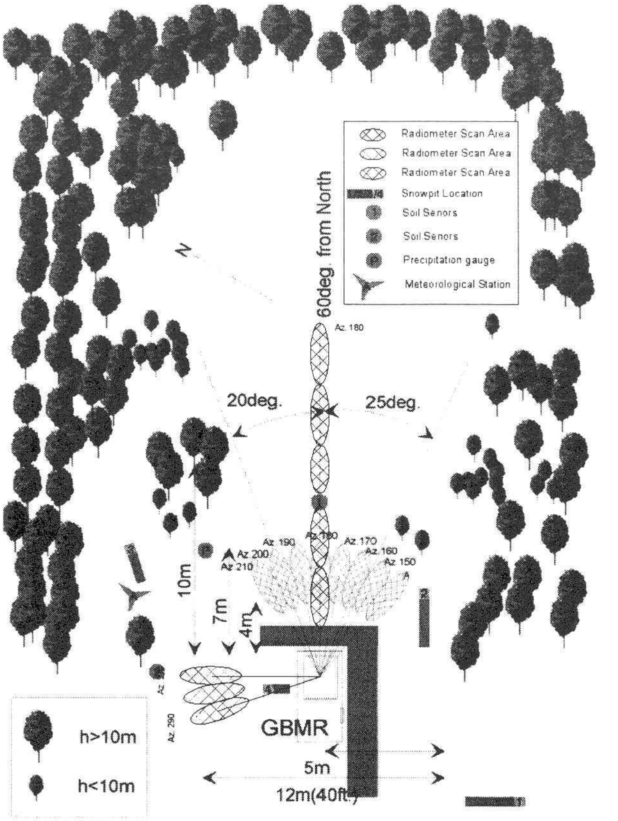

Fig. 1 Overview of Instrument Set-Up

2. OBSERVATION

(1) CLPX AND LSOS

The objective of the Cold Land Processes Field Experiment (CLPX) 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 processes at 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 Local Scale Observation Site (LSOS), which was the smallest of all study sites within the CLPX. The LSOS was located within the Fraser Experimental Forest (105°54'40'' W and 39° 50'49'' N). 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. Hardy et. al.[6] provides a complete overview of all data collected 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.

Fig. 2 GBMR-7 at the LSOS

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 have been selected to observe the snow brightness temperature. The location for snow pit observations and the weather station have been selected, so that they are close to the radiometer footprints. Furthermore also 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 frequencies similar to those of the Advanced Microwave Scanning Radiometers AMSR-E on Aqua and AMSR on ADEOS-II.

The GBMR-7 was developed for environmental research and is designed for extreme outdoor conditions. The operational temperature range of the radiometer is -30°C to +40°C, this wide temperature range is achieved by encapsulation of all critical parts of the receiver in a thermally 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°), enabling the system to exactly return to previously scanned areas.

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

Total Depth (cm):			80
Ht above ground (cm)		Density	Density
		Profile A	Profile B
top	bottom	kg m-3	kg m-3
80	70	148	151
70	60	200	191
60	50	263	254
50	40	227	235
40	30	213	215
30	20	226	231
20	10	284	238
11	1	278	281

Height above ground (cm)	Temp. °C
80	-4
70	-5
60	-5
50	-4
40	-3
30	-2
20	-1
10	-1
0	0

Stratigraphy Ht above ground		Grain Size (mm) nearest 0.1 mm			Grain	Comments
top	bottom	Sm	Md	Lg	Type	
80	70	0.1	0.2	0.3	m	very thin ice layer 1-2 mm at 70cm. Top 3 cm is new snow.
		0.2	0.2	0.4		
70	59	0.3	0.4	1	f	
		0.4	0.6	1		
59	6	1	1.2	1.3	f	
		1	1.5	2		
6	0	n/a	n/a	n/a	n/a	melt-freeze basal ice layer (discontinuous and variable depth)
		n/a	n/a	n/a		

Table 1 LSOS Snow pit Feb. 19, 2003 (10:40 to 12:00)

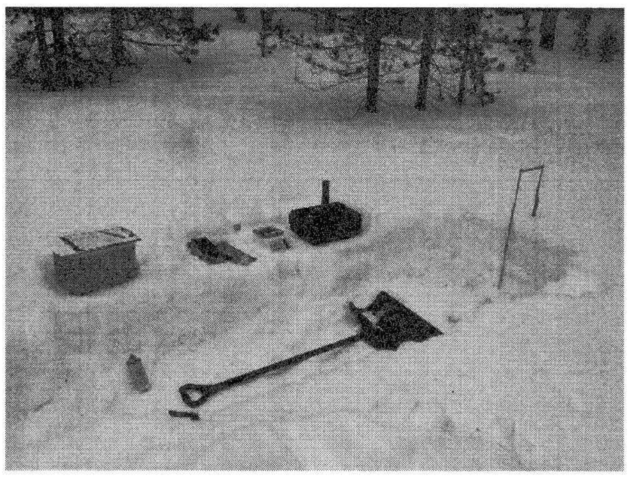

Fig. 3 Snow Pit Observation during the CLPX

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°, which is similar to the AMSR and AMSR-E sensors.

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 have been performed at different incident angles.

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 snow pit and the tools used during the CLPX. On the picture it is possible to 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.

Daily snow pit observations 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 an example of the data collected during a snow pit from Feb. 19, 2003[8].

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.

d) Automated Weather Station & Soil Probes

The automated weather station (AWS) was installed to continuously monitor the meteorological 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 depths (see also **Fig. 1**).

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).

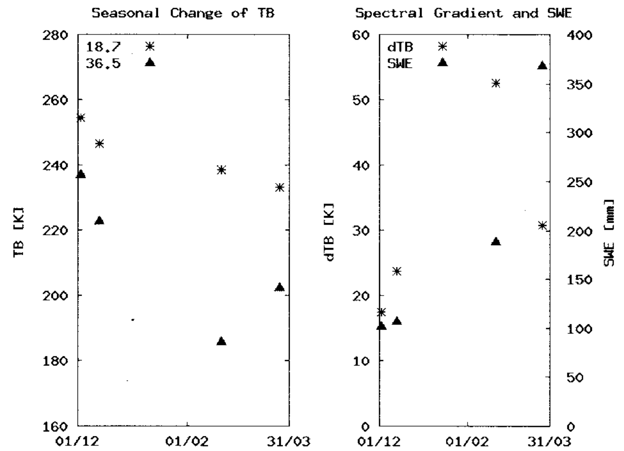

Fig. 4 Change of TB, Spectral Gradient and SWE

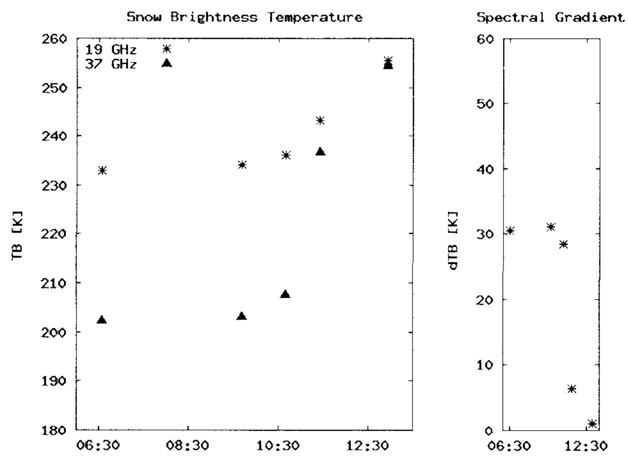

Fig. 5 Influence of wet snow on TB and Spectral Gradient

3. SEASONAL CHANGE OF THE SNOW BRIGHTNESS TEMPERATURE

Accumulated snow affects the emission from the underlying ground, due to the volumetric scattering effect of the snow grains, therefore snow on the ground results in a microwave emission on top of the snow cover that is less then the emission from the underlying soil[4]. The scattering effect increases as the number of scatterers and their size increases. Furthermore the scattering effect is also frequency dependent and increases as the frequency is increasing.

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. 4**. The right graph displays the difference between both frequencies, the so-called spectral gradient, and the total observed SWE.

With the exception of the case for March, the results in **Fig. 4** show, that the observed brightness temperature at both frequencies decreases during the winter season as the snow accumulates. Furthermore an increase of the spectral gradient can be observed, because the 36.5 GHz channel is more sensitive to the scattering effect of the snow.

The increase of the spectral gradient is used in current satellite algorithm to estimate the SWE or the snow depth.[4]

The observations at the end of March do not correspond to the expectation. In mid-March the temperature at the LSOS increased, 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 discussed in the next paragraph, 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, which explains the changed behavior at both observed frequencies.

The influence of liquid water on the microwave emission from the snow cover is displayed in **Fig. 5.** 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 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. wet snow prevents the use of algorithms, which are based on the spectral gradient.

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 the case of wet snow, the medium approaches the characteristics of a blackbody radiator[9].

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

4. RADIATIVE TRANSFER MODEL

(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[10].

The effect of multiple-scattering on the extinction coefficient is displayed in **Fig. 6**. The graph displays the relationship between the extinction coefficient (scattering + absorption) and the fractional volume of ice in snow. The fractional volume is expressed

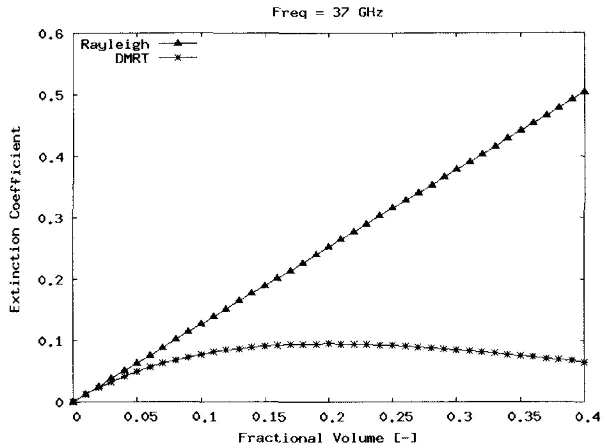

Fig. 6 Comparison between conventional RTM and DMRT

as the ratio between the snow density and the density of ice (917 kg/m³ at 0°C). Like the snow density, the fractional volume can be used to calculate the number and size distribution of the snow particles.

The graph is created 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 for the results using the classical approach, the extinction coefficient increases linearly as the fractional volume increases. On the other hand the DMRT results only show a linear behavior for small fractional volumes. In this example the extinction coefficient reaches its maximum at a fractional volume of around 0.2 and then it drops. If the curve would be continued to 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 scattering from correlated particles is the so-called dense media radiative transfer theory under the Quasi Crystalline Approximation with Coherent Potential (QCA-CP)[10,11]. 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[10,11]. The particle size distribution can be based on a log-normal distribution function[12].

(2) Modeling Results

Fig. 7 displays model results for the 18.7 and 36.5 GHz channels, using a model based on the dense media radiative transfer theory under the QCA-CP. The circles are showing observed brightness temperatures (solid = vertical, open = horizontal polarization) and the continuous lines represent the model results. The model results are obtained using

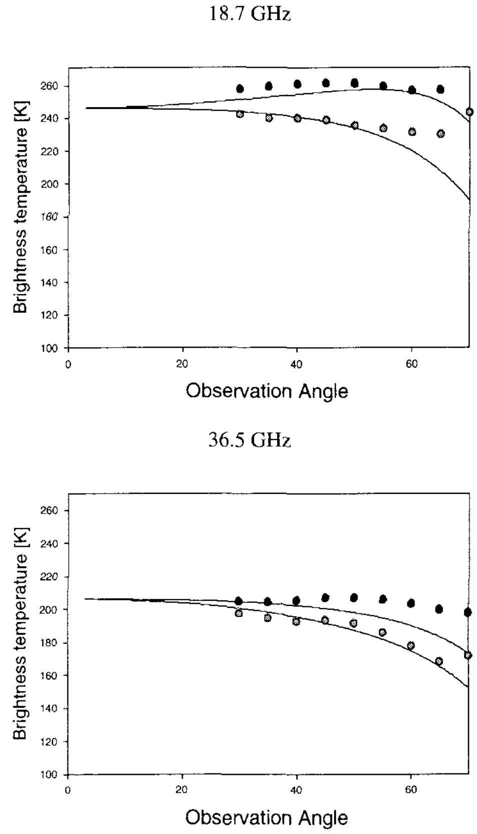

Fig. 7 Modeling results using DMRT

observed snow pack properties as input parameters collected Feb. 19, 2003 (see also **Table 1**), with the only exception of the snow grain size.

The snow grain size was estimated by minimizing the difference between the modelled and observed brightness temperature at 18.7 and 36.5 GHz. The difference between both values was expressed by calculating the Mean Square Error (MSE). During the minimization of the MSE, the snow grain size was adjusted.

For the current application only a single snow layer was considered, therefore the found snow grain size, is a representation of the vertical grain size profile. Furthermore because the model is a one-layer model, also the other snow parameters, such as snow density (fractional volume) and temperature have been averaged over the vertical profile. For Feb. 19 the model input for the fractional volume was 0.25 and 270 K for the snow temperature.

The calculated grain size for Feb. 19 using the DMRT was 1.2 mm, which agrees well with the observed average grain size (1.1 mm).

The graphs in **Fig. 7** show 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 channel.

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.

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

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