

This discussion paper is/has been under review for the journal Hydrology and Earth System Sciences (HESS). Please refer to the corresponding final paper in HESS if available.

CREST-Snow Field Experiment: analysis of snowpack properties using multi-frequency microwave remote sensing data

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Received: 30 May 2012 – Accepted: 22 June 2012 – Published: 4 July 2012

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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The CREST-Snow Analysis and Field Experiment (CREST-SAFE) was carried out during winter 2011 at the research site of the National Weather Service office, Caribou ME, USA. In this ground experiment, dual polarized microwave (37 and 89 GHz) observations are conducted along with detailed synchronous observations of snowpack properties. The objective of this long term field experiment is to improve our understanding of the effect of changing snow characteristics (grain size, density, temperature) under various meteorological conditions on the microwave emission of snow and hence to improve retrievals of snow cover properties from satellite observations in the microwave spectral range. In this paper, we presented the overview of field experiment and preliminary analysis of the microwave observations for the first year of experiment along with support observations of the snowpack properties obtained during the 2011 winter season. SNTHERM and HUT (Helsinki University of Technology) snow emission model were used to simulate snowpack properties and microwave brightness temperatures respectively. Simulated brightness temperatures were compared with observed brightness temperature from radiometer under different snow conditions. On the time series, large difference in the brightness temperature were observed for fresh compared to aged snow even under the same snow depth, suggesting a substantial impact of other parameters such as: snow grain size and density on microwave observations. A large diurnal variation in the 37 and 89 GHz brightness temperature with small depolarization factor was observed due to cold nights and warm days, which caused a cycling between wet snow and ice-over-snow states during the early spring. Scattering analysis of microwave brightness temperatures from radiometers were performed to distinguished different snow conditions developed through the winter season.

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1 Introduction

The storage of water in snowpack affects the surface runoff and soil moisture, and is therefore important at the regional scale for various applications such as flood prediction and water resource management. Rain on snow together with warm air temperatures can lead to fast snow melt. These conditions are responsible for the majority of spring floods in mid- and high latitude areas (Erman et al., 1988; McCabe et al., 2007; Papa et al., 2007; Singh et al., 1997). Snowpack is a complex medium with large spatial and temporal variability, and can consist of several layers with different densities and grain size distributions. An adequate knowledge of snow depth and snow water equivalent (SWE) is necessary to run hydrological, meteorological, and climate models (McCabe et al., 2007).

Satellite observations in the microwave spectral range have been used for the global monitoring of snow cover properties for more than three decades. Microwave emission from snowpack depends on the snow grain size, density, depth, snowpack and soil temperature, along with snow and soil wetness (Grody, 2008a). Deeper snow promotes increased scatter of the microwave signal and hence results in a lower brightness temperature of the scene (Ulaby and Stiles, 1980). For given snow depth, scattering of microwave radiation depends on snow grain size, which increases as snow ages causing reduction in brightness temperature (Grody, 2008). Further, as a time progress smaller grains locked together to form bigger grains. This increase in grain size as snow ages gives rise to the snow density (Azar et al., 2008). During diurnal and synoptic melting and refreezing cycles, grains of relatively fresh and dry snow are transformed into large rounded polycrystalline grains (snow metamorphism), which causes a reduction in the brightness temperature. In addition, the snowpack temperature and evolution of soil temperature throughout the winter season dominates microwave emission (Brucker et al., 2011) is not well studied. Microwave emission of wet snow depends on the liquid water content in the snowpack. Therefore, the snow profile physical temperature can

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be critical to interpreting microwave signals during the spring melting and refreezing period (Chang et al., 2003).

Several research studies have used the brightness temperature from combination of 19, 37 and 85/89 GHz microwave frequencies from satellite-mounted instruments including the Special Microwave Imager (SSM/I) and Advanced Microwave Scanning Radiometer (AMSR-E), for estimation of snow depth and snow water equivalent (Durand et al., 2008; Grody and Basist, 1996; Kelly et al., 2003; Romanov et al., 2000; Simic et al., 2004). Earlier snow depth retrieval algorithms (Chang et al., 2003; Foster et al., 1997) provided an “instantaneous” daily snow depth estimate based on differences in brightness temperature in microwave frequencies. Several models have been proposed to describe the relationships between microwave emission and snow parameters such as mean snow grain size, density, and depth (Grody, 2008; Kelly et al., 2003; Pulliainen et al., 1999; Wiesmann and Mätzler, 1999).

Accurate estimation of snow grain size and density (Kelly et al., 2003), soil temperature (Brucker et al., 2011) and other parameters from snow thermo dynamic model will be needed to improved performance of snow emission model (Langlois et al., 2009). In situ observations of the microwave emission of snow are critical to the development and validation of algorithms to retrieve snow depth or SWE from microwave measurements. Previous snow field experiments (Chang et al., 1981; Elder et al., 2009; Hewison and English, 1999; Langlois et al., 2007; Macelloni et al., 2005) that have used microwave radiometers to study snowpack microwave emission properties. Such experimentation plays an important role in understanding the complex influence on microwave retrievals of change in snow characteristics (grain size, density, snow temperature) under various meteorological conditions.

This paper presents the overview of CREST-Snow Analysis and Field Experiment (CREST-SAFE) and preliminary analysis of the microwave observations for first year of experiment along with support observed and modeled snowpack properties obtained during the 2011 winter season. The objective of this long term field experiment is to improve understanding of the behavior of snow-emitted microwave radiation throughout

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the winter season. The principal point is that the ground microwave observations are conducted along with detailed synchronous observations and modeled snowpack properties. That to relate the observed changes in the microwave emission of snow-covered land surface to changes in the state and physical properties of the snow pack and of the soil beneath the snowpack. The effect of snowpack temperature (related to dry and wet snow conditions) on microwave brightness temperature can be examined and interpreted.

2 Study area

The measurement site (Fig. 1) is located near the National Weather Service office and Caribou Municipal Airport at Caribou, Maine, USA (46°52'59" N, 68°01'07" W, 190 m elevation). Caribou, with a cool, humid continental climate, offers ideal conditions for snow studies. Historically the cold season lasted from mid-December to early March, with an average daily high temperature below 0°C. The season in which snow is relatively likely to be on ground, spans from mid-November to early April. The mean annual snowfall in Caribou is approximately 116 inches (2.9 m). The winter season accumulated snowfall record in Caribou was 197.8 inches (5.02 m) during the 2007–2008 winter season. Measurement of radiometric and in-situ observations of the snowpack properties began on 10 February 2010, and are reported here for the subsequent winter season.

3 Instrumentation

3.1 Microwave radiometers

The set of instrumentation installed at the measurement site includes two dual-polarization microwave radiometers operating at 37 and 89 GHz. Radiometers have been manufactured by Radiometrics Corporation, Boulder Colorado. Both instruments

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are mounted on top of a trailer at about 4 m height (Fig. 2a) and are pointed at the surface at an incidence angle of 55° . The value of the observation angle was selected to match the observation geometry of Special Sensor Microwave Imager (SSM/I) on-board DMSP satellites and The Advanced Microwave Scanning Radiometer for EOS (AMSR-E) onboard Aqua satellite Measurements of the microwave brightness temperature at two frequencies are taken routinely at one minute interval These radiometers are specifically designed to function as a transportable, scientific instrument optimized for snow signature measurements. The assembly consists of the two radiometers, antenna, the azimuth and elevation rotator, and the mounting pedestal. These radiometers have a 6-degree half-power beamwidth (HPBW) antenna. The radiometers are enclosed in a fabricated and machined aluminum casing for robustness, light weight, and superior heat dissipation. System gain and receiver temperature are measured continuously and applied to the transfer function in real time to generate accurate calibrated brightness temperatures with no lengthy calibration interruptions. A 4 point calibration and non-linear transfer function are used to compensate for small, finite system linearity errors.

3.2 Snow temperature profiler

A temperature profiler (Fig. 2b) is built with 16 Watlow Rigid Sheath Thermocouples to measure air/snow temperature at predefined depth intervals. The thermocouples are placed at 2 to 4 inch intervals. The Watlow rigid sheath thermocouples have a 3/16 inch diameter sheath, 24 gauge stranded fiberglass lead with stainless steel overbraid, grounded junction, and split lead termination. These thermocouples are connected with two battery powered Madgetech OctTemp Dataloggers. Madgetech OctTemp dataloggers are all-in-one compact, portable, easy to use devices to record up to 500 000 measurements per channel. The storage medium is nonvolatile solid state memory, providing maximum data security even if battery power is lost. The temperature profiler is placed near the microwave radiometer footprint.

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3.3 Snow depth and heat flux datasets

A number of additional datasets in support of the measurements at the CREST-SAFE have been collected. The reference data for the snow depth consisted of daily in-situ snow depth observations performed at the NWS weather station in Caribou, Maine.

5 Snow grain size and snow density vertical profile at 15 cm intervals were measured on 10 March 2011. Sensible and latent heat flux were used in this study to understand the heat transfer and temperature gradients across the snowpack and their impact on the microwave emission. Latent heat flux associated with energy transfer across the snow surface and air interface is a function of specific humidity. Similarly, sensible
10 heat flux is related to magnitude temperature exchanges between the atmosphere and the snow surface. Surface energy flux data (sensible and latent heat flux) for the site location were obtained from National Operational Hydrologic Remote Sensing Center's Snow Model (NSM). NSM is an energy-and-mass-balance, spatially-uncoupled, vertically-distributed, multi-layer snow model, ingesting ground-based, airborne, satellite, numerical weather prediction (NWP) model, and radar data to produce hourly gridded snowpack state variables.

4 Radiometric observations and interpretations

4.1 Temporal analysis of snowpack response

20 Radiometric brightness temperature, snowpack temperature, radiation flux and snow depth data acquired during the time period from the beginning of January to the end of March 2011 were analyzed. During this period, four major (snowfall greater than 10 cm) and seven minor (snowfall less than 10 cm) snowfall events were observed at the site. Cumulative snow fall over January–March 2011 was 85 cm and maximum snow depth reached 50 cm during the period of observation.

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The observation time series were examined to quantitatively examine changes in the physical and emissive properties of the snow pack and to establish the relationship of the meteorological and snow physical parameters with recorded microwave brightness temperature. The winter observation period was divided into three phases: accumulation (Fig. 3), subfreezing and melting (Fig. 4) and melting and refreezing phase (Fig. 5). Each plot shows time series of (a) radiometric observations using the 37 and 89 GHz radiometer in horizontal and vertical polarization (referred hereafter as 37 H, 37 V, 89 H and 89 V), (b) sensible and latent heat flux, (c) integrated average snowpack temperature from temperature profiler, air temperature at 2 m from soil surface, and the difference between the soil temperature (at 10 cm depth) and the snowpack temperature and (d) snowpack temperature gradient with respect to snow depth.

4.1.1 Snow accumulation phase

A temperature gradient in the snowpack developed due to low air temperature at the snow surface compared to the insulated base of the snowpack. The base temperature of the snowpack fluctuated between 268–273 K, with cooler temperatures in early winter and temperatures close to the melting point (273 K) in late winter. The diurnal variation of brightness temperature during the snow accumulation phase was smaller due to slow snow metamorphism compared to the later winter period.

In January and early February snow is accumulated during snowfall events, due to consistently below freezing temperatures without melting. During this period, the observed snowpack temperature ranged mostly within 265–270 K, indicating that melting did not take place. Diurnal variations in brightness temperature corresponding to air temperature and snowpack temperature change were observed.

We have found that 89 GHz is more responsive to snowpack temperature compared to 37 GHz. Figure 3 illustrates changes in the snowpack properties and corresponding changes in the microwave emission during the snow accumulation phase. The 89 GHz channels show higher sensitivity to snowpack changes associated with changes in the surface temperature and in grain size during DOY 15 thru 19 (Event E1 in Fig. 3), when

the snowpack was thin (5 cm). The reduction of TB in 89 GHz band at both vertical and horizontal polarization was primarily associated with the change in surface temperature accompanied with the change in snow grain size. Good correlation ($R = 0.86$) was observed between soil temperature versus brightness temperature (37 V and 89 V) in vertical polarization compared to horizontal polarization ($R = 0.79$) from DOY 7 to 18. The observed brightness temperature at 37 H shows some sensitivity to changes in the soil temperature (top 10 cm of soil below snow layer), whereas TB in the 37 V band remains insensitive to soil temperature.

The first major snow storm on DOY 19–20 added 12.5 cm of snow on site, which increased the snowpack depth to 17.5 cm (Event E2 in Fig. 3). The snowfall caused noticeable fluctuations and a general increase in the brightness temperature at 89 GHz. We believe that BT fluctuations at 89 GHz are caused by falling snow particles and by the quick change of the snowflake shapes as they hit the ground or the top snow layer. That the BT fluctuations at 89 GHz correspond to snowfall events was confirmed through the hourly precipitation record obtained from NCDC. The increase of the brightness temperature at 89 GHz immediately after the snowfall event is due to the greater microwave scattering of the fresh snow as compared to soil or aged snow.

The snow depth remained at around 20 cm with little snow melt due to temperatures below the freezing level. Even though there was no significant change in the snow depth, the BT at 89 VH gradually decreased over time. This reduction is apparently related to changes in the snowpack properties particularly to the increase of the grain size. The range of brightness temperatures measured in the 89 GHz channels could help to distinguish between fresh and aged snow (Grody, 2008; Kongoli et al., 2004).

The increased polarization difference observed after DOY 20 at both 37 and 89 GHz frequencies is the response to increased snow depth. This difference was mostly due to the increased horizontally polarized BT. In the vertical plane reflectivity is smaller than the horizontal plane due to the Brewster angle. The decreasing penetration depth and the increased scattering caused by the increasing grain size is the main cause of the higher sensitivity of 89 GHz observations (Rosenfeld and Grody, 2000). Eleven days of

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below freezing temperature on DOYs 21–33 caused slow snow metamorphic process resulting in gradual increase of the grain size. The temperature gradient of snowpack was close to linear with temperatures changing from about 270 K at the bottom of snow (soil surface) to ~250 K at the top of the snow surface. During this period, brightness temperatures gradually decreased by 10 K and 15 K for 37 GHz at vertical and horizontal polarization, respectively. This fact shows that brightness temperature at horizontal polarization is more sensitive to the increase in the grain size in thick snowpacks than the brightness temperature at vertical polarization.

Through the snow accumulation period average modeled values of latent and sensible heat flux values were 38.0 W m^{-2} and 2.95 W m^{-2} (negative) respectively. This was associated with low air temperature that reduces near surface moisture gradient. The latent and sensible heat flux were very stable thorough this period. The lower value of latent heat flux is due to cooler air reducing surface moisture gradient preventing heat loss through sublimation.

4.1.2 Subfreezing and melting

The time series (Figs. 3 and 4) for both frequencies illustrated that the main contribution to variations in the recorded brightness temperature for both dry and wet snow is primarily variation of snowpack properties. Snow metamorphism, which transforms smaller grains into larger grains, is slow when below freezing temperatures persist. In the middle of February (DOYs 35–57), the soil temperature beneath the snowpack warmed up by $1\text{--}3^\circ$ and reached the temperature ranged over 270–272 K. This increase in temperature should have stimulated metamorphic process that cause the formation of larger snow grains and eventually lead to the melt of snow at the bottom of the snowpack. The second major snow storm (E3 in Fig. 4) was observed on DOY 37, and added 15 cm of snow for an aggregate 38 cm of snow depth. This increase of snow depth increased the difference in brightness temperature between horizontal and vertical polarization by 5 K at 37 GHz and by 8–12 K at 89 GHz. At the same time, there was a reduction in brightness temperature observed on 89 GHz between the horizontal

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and vertical polarizations. The reduction in snow depth at events E4 and E5 without snow melting is mainly due to high wind gust at the speed around 30 and 36 miles per hours respectively.

In the second half of February (DOY 49–51), a storm system with heavy clouds moved into the study area bringing higher relative humidity. This caused relatively higher sensible and latent heat flux (E6 in Fig. 4). This higher sensible heat flux caused the snow temperature profile to collapse to the melting point, indicating snowmelt and wet snowpack formation. Warm daytime air temperatures with increased sensible heat flux of approximately 100 W m^{-2} brought the snowpack temperature to above the freezing level and caused about 13 cm snow melt. This snowmelt in the top layer brought the brightness temperatures of 37 and 89 GHz closer, with the convergence and slightly higher value for T_b at 37 GHz associated with the increase in wetness. Refreezing of melted snow in the top layer formed a 5 cm thick ice layer after this warming episode. During the melting and refreezing period, the average modeled values of latent and sensible heat flux were 46.15 W m^{-2} and -8.38 W m^{-2} . The sensible and latent heat flux have different magnitudes but opposite sign through the mid-winter except during melting events (E6).

4.1.3 Melting and refreezing phase

In the month of March, two major snow storms affected the study site. The combination of above freezing temperatures during daytime and below freezing temperatures at nights have caused multiple freezing and melting events in the snowpack. The melting and refreezing caused a large variation in the microwave brightness temperature during this period. The ice layer that formed after the snowmelt on DOY 50 (E6 in Fig. 4) was buried under a fresh snowfall of 15 cm that occurred on the DOY 59 (E7 in Fig. 5). The temperature profile does not provide any evidence of the ice layer since the thickness of the ice layer was less than the vertical interval between the thermocouples. This ice layer within the snowpack amplified the difference between the BTs for the polarizations and reduced the brightness temperature considerably, by 50 K in 37 H and 40 K in 37 V.

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Strong snow melting and refreezing events were observed in the middle of March 2011 starting from DOY 70. The sharp increase in the brightness temperature during melting is caused by liquid water in the top layer of snowpack. In the case of wet snow, the collapsing of 37 and 89 GHz brightness temperatures shows the effect of real part of the dielectric constant of wet snow related to liquid water content and independent of snow grain size (Tiuri et al., 1984). During melting and refreezing, the trends in the 37 and 89 GHz brightness temperatures were consistent and correlated with the snowpack temperature (Event E10 in Fig. 5). This is likely associated with the presence of liquid water in the snowpack. The degree of difference between the BTs for each polarization also appears to change with the daily temperature changes.

The snow melt processes are complex and difficult to distinguish using single microwave frequencies as water coated snow particles are highly emissive when compared to dry or wet soil (Grody, 1988). The smaller difference in horizontal and vertical polarized brightness temperature of melting snow (E8, E9 and E10 in Fig. 5) is almost equal to that seen in the dry snow condition (Fig. 3). This melting and refreezing can build a relatively thick ice layer, which during cold days keeps the microwave emission much lower (Event E11 in Fig. 5).

Through the melting and refreezing phase average modeled values of sensible heat flux was 51.0 W m^{-2} with larger variations (standard deviation 35.8) through the period. Similarly, latent heat flux also attains higher peak (145 W m^{-2}) during melting phase caused by warmer air temperature and heavy evaporation. These variations in upper and lower peaks of latent and sensible heat flux were clearly noticed during melting and refreezing period.

This time series analysis suggests that the wetness of snow is an important parameter when understanding snow response during melting and refreezing of snow. The physical temperature of the snow profile can be used as a proxy for the liquid water content of wet snow.

4.2 Classification analysis of brightness temperature for snowpack conditions

As it was shown above, the microwave brightness temperature at 37 and 89 GHz varies with changing snowpack physical properties and is independent of variation in the snow depth. The temporal variation in snowpack properties was analyzed by classifying the snowpack in to the categories. The snowpack properties were classified based on the radiometric observations as correlated with in situ observations into the following snow categories: (a) Fresh Snow (Shallow) (b) Fresh Snow (Deep) (c) Aged Snow, (d) Melting Snow, and (e) Refreezing Snow. Supervised classification analysis was carried out to understand and discriminate between different snow conditions based on polarization and frequency differences of microwave observations in the 37 and 89 GHz channels.

Typical signatures for a variety of snow categories can be derived from the cluster means and ranges for the polarization and frequency differences for the 37 and 89 GHz channels. Figure 6 shows the brightness temperature classification of five snow conditions. The brightness temperature statistics in terms of range, mean, and standard deviation for the snow categories are given in Table 1. The fresh dry snow and refreezing snow conditions are better distinguished from other clusters compared to the aged and wet snow conditions.

Figure 6 clearly shows the decrease in BT for fresh and aged snow covered surfaces. This decrease is a unique feature for snow and can therefore be used as reliable indicator of dry snow (Grody, 1988). Higher BT values of the 37 and 89 GHz with smaller depolarization factors, which were associated with the melting snow conditions, can be correlated with observed higher snow temperatures. The brightness temperature values for melting (wet) snow conditions are higher and can be easily distinguished from other three snow conditions. These higher values are due to liquid water in wet snow that can absorb and re-emit the microwave radiation. Further, the smaller BT difference between 37 and 89 GHz during wet snow condition can help separate this cluster. The larger depolarization value in 37 GHz separates the aged snow and/or the ice-covered

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snow conditions. The refrozen snow conditions were distinct from the others at 37 GHz due to lower brightness temperatures linked with larger snow crystals formed during melting and refreezing which reduce the emission. The distinct microwave signature of melting and refreezing conditions could be due to a combination of greater absorption by the water and less scattering since the water is no longer in the original snowflake structure, which has many more ice facets to scatter the radiation.

Aged snow clearly separated from fresh snow for lower and higher depth through independent or co-polarized measurements. These preliminary analysis shows assurance that these snow classes can be reliably discriminated or identified using available microwave measurements. However, we would like reserve our recommendation and proposing algorithm till we process two more winter seasons radiometric and snow observations.

4.3 Simulation and comparison of microwave brightness temperature

SNTHERM (SNOW THERmal Model) is a one-dimensional mass and energy balance model (Jordan, 1991) used to simulate the snow grain size and density in the absence of their daily field measurements. Meteorological data including solar radiation, air temperature, humidity, wind speed, and precipitation obtained from neighboring National Weather Service Office were used as an input to SNTHERM to simulate snow grain size, density and snowpack temperature. The simulated snowpack temperature from SNTHERM was compared with observed in-situ snowpack temperature. Simulated snowpack temperature shown good correlation with observed in-situ snowpack temperature (Fig. 7). The correlation coefficient is higher than 0.8 and means absolute difference is less than 1 °C for sensors below surface level for measured soil temperature (Table 2). However, as sensors close to snow surface shows larger difference (2–3 °C) in snowpack temperature were observed. SNTHERM temperatures of soil (5 and 10 cm below) were consistently higher for later part of winter.

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This good correlation between snowpack temperatures prompted to use other SNTHERM simulated variables such as: snow grain size and density, in microwave snow emission model for estimating brightness temperature.

Brightness temperatures over the study area were simulated for the 37 and 89 GHz frequency HUT (Helsinki University of Technology) snow emission model (Pulliainen et al., 1999). The HUT snow emission model is a semi-empirical model based on radiative transfer theory. The model describes the snowpack as a homogenous layer, using effective values for parameters influencing scatter such as snow depth, density and grain size. The simulated snow grain size and density from SNTHERM were used along with measured snowpack temperature and snow depth as an input to HUT Model to estimate the brightness temperatures. The measured soil temperature at the soil surface and 5 cm depth were averaged and used as the soil temperature input to the HUT model.

The predicted brightness temperature from the HUT model was compared to the observed radiometric brightness temperature (Fig. 8) for the range on input parameters given in Table 3. Atmospheric effects on the estimated brightness temperature were neglected, since the microwave data were acquired from a ground-mounted radiometer a minimal distance from snow characteristics being measured. It should be noted that the observed brightness temperatures were averaged for each of the 5 distinct snow categories. Figure 7 shows how the combination of the HUT model and SNTHERM was able to simulate the microwave emission from the characterized snowpack with relatively good accuracy, and showed potential to discriminate between different snow conditions. However, uncertainties related to the averaging of the model inputs need to be investigated. Notably, errors in the simulation (Table 4) show a correlation with the variability in the input parameters: the larger the variability, the bigger the error.

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5 Conclusions

In the initial phase of the CREST-SAFE field experiment, carried out during January to March 2011 and reported here, microwave and surface observations were collected to analyze snowpack transitions from dry to wet through melting conditions and their impact on passive microwave retrievals. We found that both snow grain size and snow temperatures have significant effects on brightness temperature at the 37 and 89 GHz channels. The simulated snowpack temperature using SNTHERM were shown good correlation with observed in-situ snowpack temperature. This type of long term field experiment allows the research community to improve our understanding of microwave radiative transfer during melting-refreezing, snow metamorphism, and under various meteorological conditions.

More investigation is needed to quantify the thickness of ice layers at the surface and within the snowpack and its impact on microwave emission. The effects of sensible heat flux, relative humidity and other meteorological parameters (including the wind effects which will speed up the melting and refreezing processes) on changes of the snow grain size are still not understood completely and need more data and analysis. The largest discrepancies between our measurements and models of snowpack evolution and microwave radiative transfer models were seen during the snowmelt season, when large diurnal variations in microwave brightness temperature were observed, associated with melting-refreezing cycles. More research is required to understand and simulate the snowpack properties' effects on microwave measurements in order to enable accurate retrieval of ground snow conditions from satellite microwave measurements.

Since the work reported here, the CREST-SAFE facility has been expanded by adding new instruments to measure solar radiation, soil moisture (at 2.5, 5, and 10 cm), snow skin temperature, air temperature, humidity, snow weight, snow depth, and rain/snowfall. Snow pillows will be used to measure snow water equivalent by weight displacement, while the ultrasonic snow depth sensor will remotely measure snow depth each minute. Future research work using this enhanced suite of instruments

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will include quantifying the thickness of ice layers at the surface and within the snowpack caused by melting and refreezing of snow and ice and their effect on microwave emissivity. The effect of within-snowpack temperature gradients on snow grain size and microwave emission will also be investigated further using multilayer snowpack radiative transfer models. Also, the impact of the seasonal behavior of snow grain size on brightness temperature will be better quantified. The continuation of long term observations of in situ snow properties combined with microwave radiances will facilitate the assessment of current snow retrieval algorithms and their capability to infer snow properties under different meteorological conditions.

Acknowledgements. This study was supported and monitored by National Oceanic and Atmospheric Administration (NOAA) under Grant NA06OAR4810162. The views, opinions, and findings contained in this report are those of the authors and should not be construed as an official National Oceanic and Atmospheric Administration or U.S. Government position, policy, or decision. The authors also acknowledge Peter Rahe and Bill Desjardins from NOAA's National Weather Service in Caribou, Maine for their help in the experiment setup. Thanks to Fred Solheim and team from the Radiometric Corporation for their quick help in instrument calibration and operation and thank J. Pulliainen and Juha Lemmetyinen from Helsinki University of Technology for providing the HUT model. Thanks to Marouane Temimi for useful discussion and comments on preparation of the experiment and this manuscript.

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Table 1. Observed statistics of brightness temperature (K) for snow conditions.

Snow Class	37 H				37 V				89 H				89 V			
	min	max	Mean	Std												
Fresh (LD)	250.8	256.6	253.2	1.2	261.4	265.5	263.0	0.9	231.1	248.4	237.6	3.3	247.4	256.7	250.6	1.9
Fresh (HD)	230.7	237.3	232.8	1.3	249.4	251.9	250.4	0.6	175.6	197.2	185.2	4.6	197.8	212.4	204.2	4.0
Aged	176.4	183.2	179.0	1.8	209.9	215.3	212.6	1.1	119.7	144.2	127.2	4.7	137.7	162.1	147.3	4.6
Melting	166.6	267.0	239.9	26.2	179.1	269.2	252.6	24.6	130.7	257.4	223.9	31.2	142.3	263.8	238.4	28.7
Refreezing	173.8	240.9	220.2	19.1	187.9	257.8	236.5	19.2	118.4	233.5	162.3	30.8	129.7	236.0	179.1	32.7

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Table 2. Statistical comparison of observed and modeled (SNTHERM) soil and snowpack temperature above and below soil surface.

Sensor Level (cm)	Correlation Coefficient (R)	Mean Absolute Difference (MSD) in $^{\circ}\text{C}$
$T(-10)$	0.813	0.695
$T(-5)$	0.834	0.541
$T(0)$	0.847	0.744
$T(5)$	0.850	1.091
$T(10)$	0.905	1.161
$T(15)$	0.910	2.050
$T(20)$	0.803	1.895
$T(25)$	0.759	3.383
$T(30)$	0.733	2.636
$T(38)$	0.507	2.335
$T(46)$	0.877	2.784
$T(53)$	0.881	3.595

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Table 3. Range of input parameters used to estimate the brightness temperature (K) from HUT snow emission model.

Property	Fresh (LD)				Fresh (HD)				Aged				Melting				Refreezing				Reference
	Min	Max	Mean	Std	Min	Max	Mean	Std	Min	Max	Mean	Std	Min	Max	Mean	Std	Min	Max	Mean	Std	
Snow Density (g cm^{-3})	0.10	0.20	0.14	0.02	0.05	0.28	0.17	0.04	0.10	0.34	0.26	0.03	0.10	0.41	0.34	0.08	0.10	0.41	0.34	0.08	SNTHERM
Snow Grain Size (mm)	0.20	0.79	0.53	0.13	0.16	1.56	0.92	0.33	0.18	1.67	1.18	0.29	0.27	1.88	1.52	0.45	0.18	1.88	1.52	0.45	SNTHERM
Snow Depth (cm)	2.50	5.00	3.00	1.05	17.50	40.00	21.96	6.87	25.00	30.00	27.05	1.88	25.00	30.00	27.50	2.24	25.00	30.00	27.50	2.24	Observed
Soil Temp (K)	270.5	272.1	271.3	0.48	270.9	272.2	271.7	0.33	272.0	272.6	272.3	0.15	273.0	273.1	273.0	0.02	271.5	273.1	272.6	0.51	Observed
Snow Temp (K)	266.8	272.9	269.4	1.67	260.0	267.7	263.7	2.07	263.6	272.7	268.3	2.42	273.3	273.9	273.6	0.12	272.9	273.1	273.0	0.03	Observed

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Table 4. Comparison of observed and simulated brightness temperature for snow conditions using HUT snow emission model.

Snow Class	Simulated Brightness Temperature				Difference between Observed and Simulated			
	37 H	37 V	89 H	89 V	37 H	37 V	89 H	89 V
Fresh (LD)	264.3	267.3	261.0	264.0	-11.1	-4.3	-23.4	-13.4
Fresh (HD)	242.0	248.0	173.1	176.8	-9.2	2.4	12.1	27.4
Aged	220.0	232.0	141.0	145.5	-41.0	-19.4	-13.8	1.8
Melting	231.0	262.0	251.0	264.0	8.9	-9.4	-27.1	-25.6
Refreezing	223.0	231.0	127.5	133.0	-2.8	5.4	34.8	46.05



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Fig. 1. CREST-SAFE location, near National Weather Service and Caribou Municipal Airport in Caribou, Maine.

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Fig. 2. (a) Microwave Radiometer (37 and 89 GHz) attached to automatic azimuth positioner. (b) Temperature profiler with 16 Watlow Rigid Sheath Thermocouples to measure air/snow temperature at defined depths.

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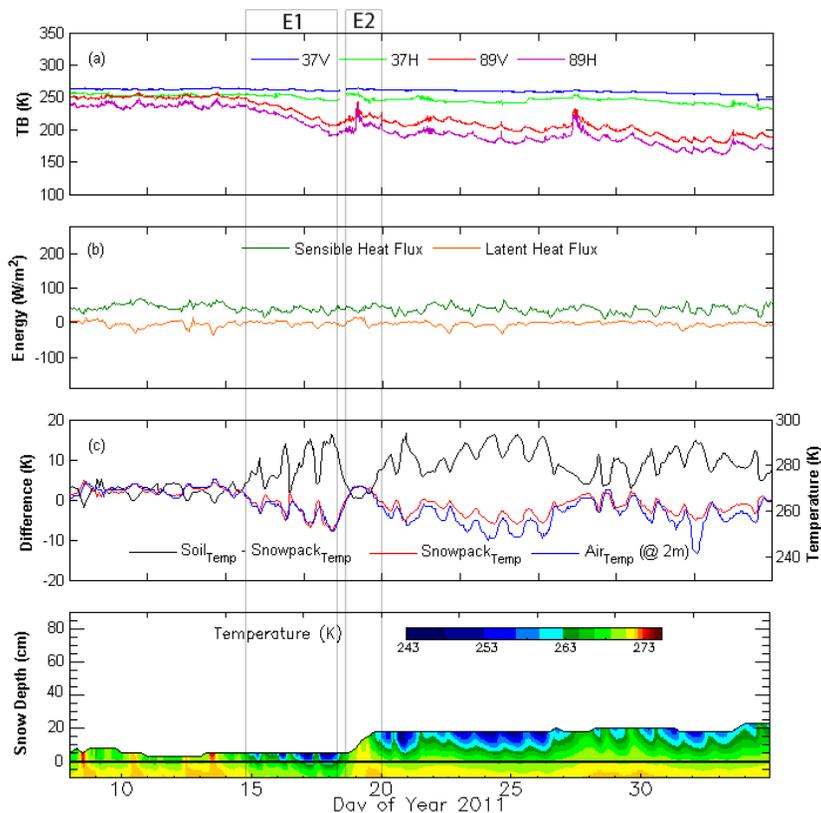


Fig. 3. Time series of observed radiometric and physical characteristics of snow pack in early winter. **(a)** Microwave brightness temperature at 37 and 89 GHz vertical and horizontal polarization, **(b)** modeled sensible heat flux and latent heat flux, **(c)** snow depth, air temperature at 2 m from surface, and integrated average snowpack temperature measured by temperature profiler, and **(d)** temperature measured at different depths below and above the ground surface.

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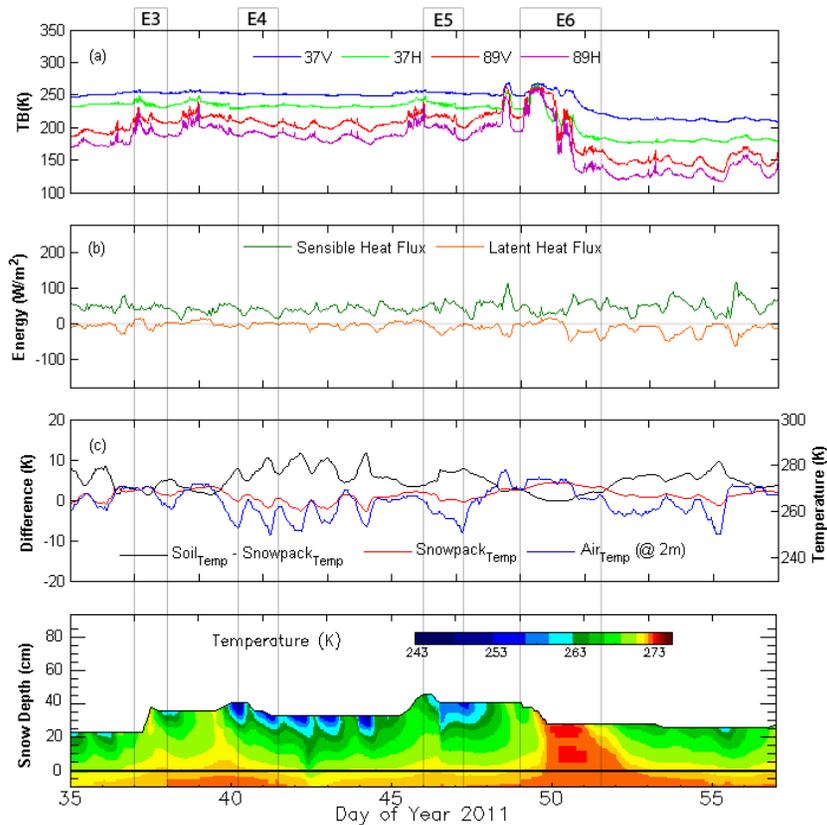


Fig. 4. Time series under accumulating and melting snow phases during mid-winter period. The quantities shown are the same as those described in Fig. 3.

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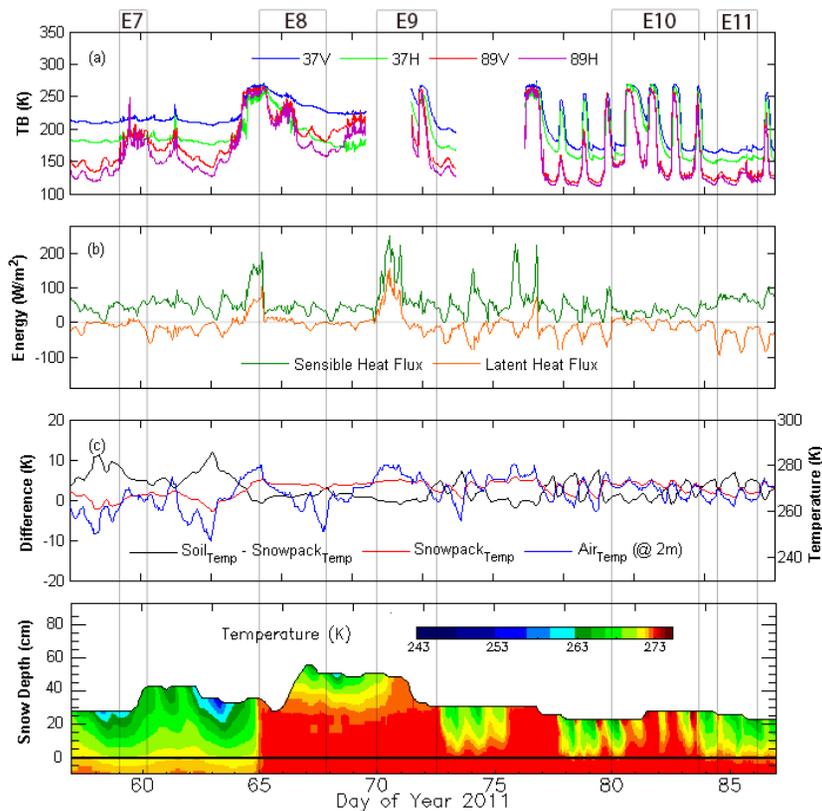


Fig. 5. Melting and refreezing snow condition during warm days (wet snow) and cold nights during early spring. The quantities shown are the same as those described in Fig. 3.

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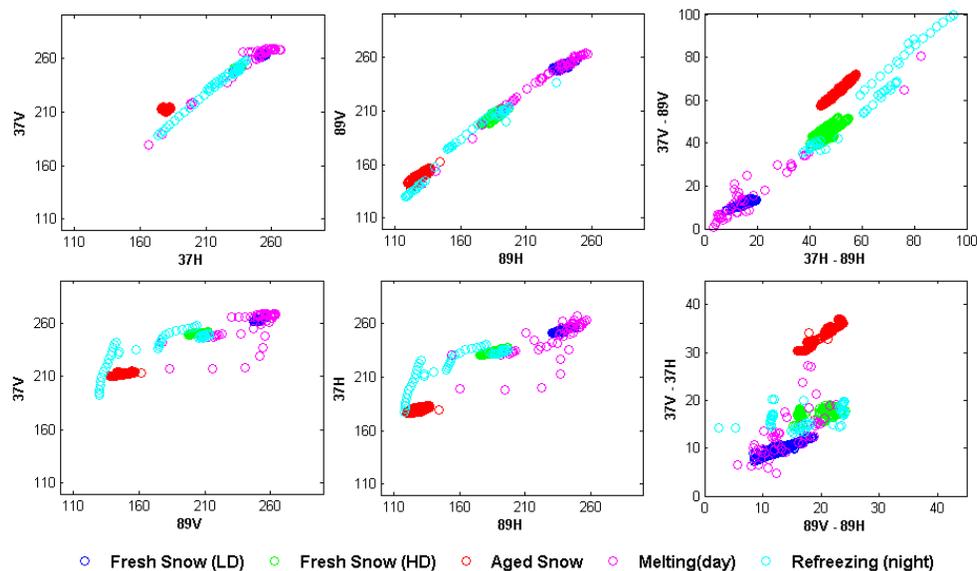


Fig. 6. Classification analysis of microwave observation for different snow conditions.

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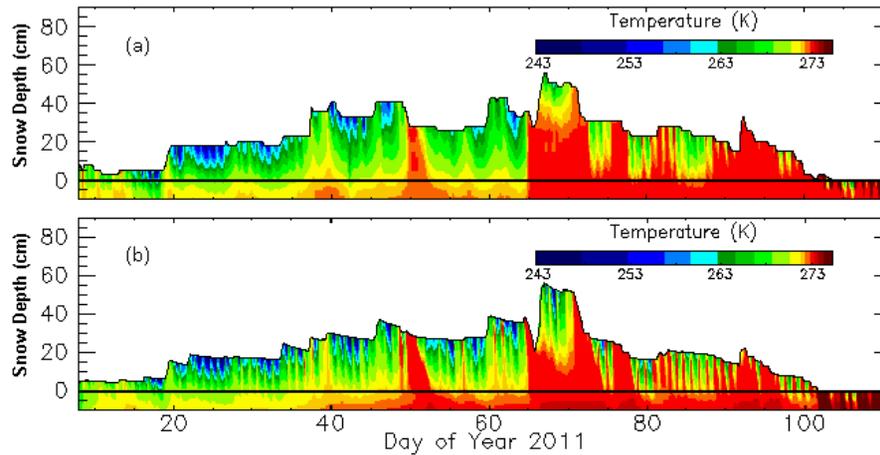


Fig. 7. Comparison of observed temperature with modeled temperature of snowpack at varying snow depth.

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