Effects of Forest on the Snow Parameters Derived from Microwave Measurements During the BOREAS Winter Field Campaign

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ABSTRACT

Passive microwave data have been used to infer the areal snow water equivalent (SWE) with some success. However, the accuracy of these retrieved SWE values have not been well determined for heterogeneous vegetated regions. The Boreal Ecosystem-Atmosphere Study (BOREAS) Winter Field Campaign (WFC) which took place in February 1994 provided the opportunity to study in detail the effects of boreal forests on snow parameter retrievals. Preliminary results reconfirmed the relationship between microwave brightness temperature and snow water equivalent. The pronounced effect of forest cover on SWE retrieval was studied. A modified vegetation mixing algorithm is proposed to account for the forest cover. The relationship between the microwave signature and observed snowpack parameters matches results from this model.

INTRODUCTION

In the Northern Hemisphere during winter, about 1/3 of the land areas may be covered by seasonal snow. Snow is one of the most valuable renewable natural resources. As much as 70% of the water supply for the western United States is derived directly from the spring runoff of the snowpacks. Better knowledge of snow water storage over large regions will improve the estimates of spring runoff and allow better management of the water resources. With the advent of satellite technology, the area covered by seasonal snowpacks is now relatively easy to monitor. However, various surface covers can obscure the snow as viewed by satellite sensors, thus obtaining accurate estimates of snow depth or SWE is a challenging task.

The remote sensing approach permits areal measurements to be made over large regions in a timely fashion. The measurements provided by a remote sensor are primarily a function of the electromagnetic energy emitted or reflected from the scene which is exiting in the direction of the sensor. This energy is dependent on the spatial arrangement and properties of the types of matter within the scene. Also influencing the sensor's measurements are the scattering, absorption, and emission of energy that occur in the atmosphere between the radiation source and scene, and the scene and sensor.

Microwaves penetrate the snowpack and provide a means to determine snowpack information. Snow crystals are effective scatterers of microwave radiation. The deeper the snowpack, the more crystals are available to scatter microwave energy away from the sensor. Hence, microwave brightness temperatures are generally colder or lower for deep snowpacks than they are for shallow snowpacks (Foster et al., 1984). Drawbacks of the microwave approach include poor resolution, and difficulty in interpreting the effects of snow structure on microwave response and in understanding microwave emission and interaction with other media (Hall et al., 1985, and 1991). Despite these drawbacks, several positive studies document the fact that microwave data have the potential for meaningful extraction of pertinent snow hydrology information (Rango et al., 1979; Rott and Aschbacher, 1989; Goodison et al., 1990; Chang et al., 1991).

The effect of scattering of microwave radiation by snow crystals has been reported by Chang et al., (1976), Kong et al., (1979), Tiuri and Hallikainen (1981), Kunzi et al., (1982), Rott and Aschbacher (1989) and others. Generally, for frequencies above 20 GHz, scattering by snow crystals becomes the dominant factor affecting

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microwave radiation passing through a snowpack (Chang, et al., 1987). In retrieving snow parameters there are complications that arise due to varying climate conditions, snowpack stratigraphy structure, and vegetation cover. The size and shape of snow crystals change after they have been deposited on the Earth's surface. At times, the crystal size can grow to be comparable with the wavelengths of the Special Sensor Microwave/Imager (SSM/I, with wavelength ranges from 0.3 to 1.5 cm). Under these conditions, scattering becomes the dominant physical process.

Snow grain sizes directly affect the microwave brightness temperature (Hall et al., 1986; Armstrong et al., 1993; Josberger et al., 1995). Thus, snowpack grain size profiles are essential for accurately inferring SWE using microwave techniques. Also, the depth of microwave penetration into the snowpack depends on the wavelength. For dry snow, typical microwave penetration depth is about 80 cm for 37 GHz, 150 cm for 19 GHz. To sense deeper snowpack, longer wavelengths are needed.

Since 1978 the Scanning Multichannel Microwave Radiometer (SMMR) on board the Nimbus-7 satellite has been acquiring passive microwave data that can be used to infer snow extent and snow depth on an areal basis (Chang et al., 1987). Snow grain size and snow density were assumed constant to simplify the retrieval algorithm. The resolution of the passive microwave data is about 25 km at 37 GHz which limits the size of the study area. But recent studies on basins such as the Rio Grande above Del Norte, Colorado have shown that reasonable snow water equivalent estimates can be made utilizing the coarse microwave data even on relatively small basins of less than 10,000 km^2 (Rango et al., 1989). There are, of course, complications that arise when one tries to apply a simple algorithm based on average snow condition to specific regions where the climate, snowpack structure, and vegetation cover vary. In this study only the effect of forests on microwave SWE retrieval is addressed.

Forest canopy modifies the local snowcover distributions. Maximum accumulations of snow often occur at the edges of a forest as a result of snow being blown in from adjecent areas. Though more snow is consistently found in forest openings than within the stand, absolute estimates of the interception amounts cannot be made because of the lack of information about the interception and loss processes (McKay and Gray, 1981). Many investigators have found snow accumulation to be inversely related to canopy density. Therefore forest density could likely be used as an index of the amount of interception. Because of limited field measurements, the effect of redistribution of snow interception on snowcover is largely unknown, however, Pomeroy (in press) and others are making progress in better understanding the role of the canopy in snow distribution. In this study interception of snow amounts less than 3 cm will be neglected due to its small microwave emission.

The goal of our studies on remote sensing of snow is to develop a method to monitor global snow storage using multifrequency passive microwave data. In this project a correction scheme for snowfields with forest cover has been developed based on airborne passive microwave data, and tested with spaceborne data.

EFFECT OF VEGETATION COVER ON MICROWAVE SNOW SIGNATURES

The vegetation canopy can be represented as a dielectric mixture consisting of dielectric elements (leaves, stalks, branches, etc.) embedded in a matrix of air (Ulaby and Jedlicka, 1984). In the 37 GHz region, vegetation is a strong absorber of microwave radiation and dominates the upwelling microwave radiation. Since the passive microwave footprint is on the order of 25 km or larger, a mixture of features and different types of surfaces within the footprints can be expected. Therefore, to improve the SWE retrievals, surface composition information is needed.

A simple model to separate the effect of the forest cover from the effect of snow depth was proposed for the SMMR 37 GHz data (Hall et al., 1982). Subsequently, a method to correct for the absorption of the snow signal by the forest cover has also been developed (Chang et al., 1990). Yet the relationship has not been extensively tested due to lack of adequate "snow ground truth" data. More recently a multiple regression model using vegetation index from AVHRR data as an independent variable has been developed to analyze the microwave brightness temperatures for the Rio Grande basin in southwestern Colorado (Chang et al., 1992). A relationship was obtained between the difference in microwave brightness temperature at two different frequencies (18 and 37 GHz horizontal polarization) and the basin-wide averaged SWE. Using an algorithm including information about the percentage of forest cover (Foster et al., 1991), it was found that in the boreal forests of Saskatchewan, the bias between the measured and remotely sensed SWE could be reduced by 22%.

Microwave radiation emanates from features on or near the surface of the Earth at an intensity that is proportional to the product of the physical temperature and the emissivity of the surface. The measured value referred to as the brightness temperature can simply be expressed as:

$$T_B = (R\, T_{sky} + (1 - R)\, T_{surf})\, e^{-t} + T_{atm} \qquad (1)$$

where e^{-t} is the atmospheric transmissivity and R is the surface reflectivity, T_{sky} is the sky radiation, T_{surf} is the surface emission, and T_{atm} is the emission from the intervening atmosphere. In the microwave region both T_{sky} and T_{atm} are small and can be neglected. Thus, the observed T_B is directly related to surface features.

Based on radiative transfer calculations (Chang et al., 1987), a relationship between brightness temperature and the number of snow crystals was developed for SWE retrieval. The differences between the 18 and 37 GHz horizontal polarization brightness temperature is linearly related to the snow water equivalent values when SWE is less than 200 mm. The scattering information comes largely from the 37 GHz signal. The 18 GHz signal serves as the background reference. The SWE - brightness temperature relationship of a homogeneous snow layer with mean radius of 0.3 mm and density of 300 kg/m^3 for SMMR data can be expressed as follows (Chang et al., 1987);

$$SWE = 4.8 \times (T_{18H} - T_{37H}) \text{ mm}, \qquad (2)$$

where SWE is the snow water equivalent in mm of equivalent water, T_{18H} and T_{37H} the brightness temperature for the 18 and 37 GHz horizontal polarization. Both vertical and horizontal polarization will generally give similar results in Eq (2). Due to differences in the surface snow characteristics, researchers have used either vertical or horizontal polarization (Hallikainen and Jolma, 1992; Goodison and Walker, 1994) in retrieving the SWE. Rott and Aschbacher (1989) proposed a generalized relationship for snow water equivalent and brightness temperature:

$$SWE = A + B * \Delta T_B \text{ mm}, \qquad (3)$$

where A and B are the offset and slope for brightness temperature difference and ΔT_B is the brightness

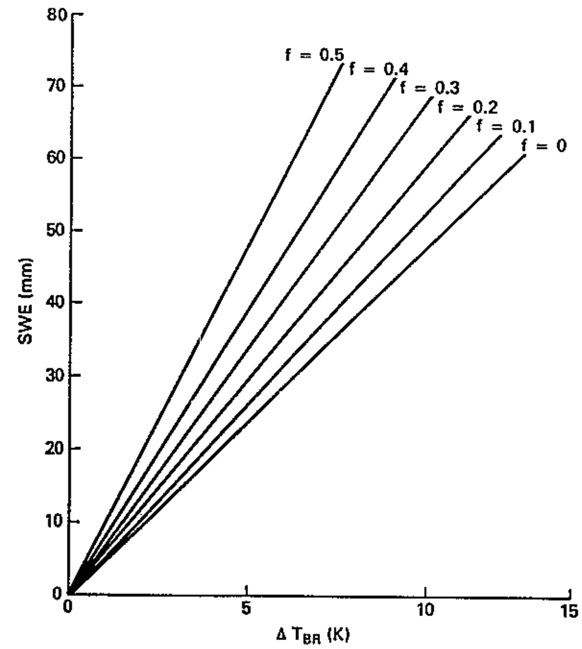


Figure 1. Calculated brightness temperature differences vs. SWE for different fractional forest cover.

temperature difference between a high scattering channel (37 or 85 GHz) and a low scattering channel (18 or 19 GHz) either vertical or horizontal polarization channels. For SSM/I data, the A and B coefficients for Chang et al. algorithm are -25 and 4.8, respectively.

The brightness temperature difference for forest covered areas will cancel out if the emissivities of forest for both the high scattering and the low scattering channels are about the same. This is based on the findings that the emissivities for forest in Finland at 37 and 18 GHz are very similar and have the values of 0.9 to 0.92 (Hallikainen et al., 1988). Thus, only the snow covered fraction contributes to the brightness temperature difference. For a footprint with f fraction of forest cover and (1 - f) fraction snow cover, Eq (3) will become

$$SWE = A + B * \Delta T_B /(1 - f) \text{ mm}. \qquad (4)$$

Eq (3) would underestimate the SWE if not corrected for the forest cover. The amount of underestimation depends on the fraction of forest cover in Eq (4). Figure 1 shows the relationship of the calculated ΔT_B and the estimated SWE as a function of fractional forest cover.

RESULTS

During the Boreal Ecosystem-Atmosphere Study (BOREAS) 1994 Winter Field Campaign (WFC) microwave radiometers operating at 18, 37 and 92 GHz were flown on-board the Canadian National Aeronautics Establishment's Twin Otter aircraft. The nominal aircraft altitude is 750 m and the corresponding radiometer footprint size is 75 m. Flight lines covered both the southern study area near Prince Albert, Saskatchewan, and the northern study area near Thompson, Manitoba, Canada. More detailed descriptions of the BOREAS project can be found in Sellers et al. (1995). To support the airborne campaign, extensive snow truth information, including depth, density and grain size of snowpacks was collected along most of the flight lines, jointly by US and Canadian investigators. Satellite data collected by the SSM/I are used for comparison.

To study the effect of vegetation, flight lines over spruce, aspen and pine were flown. As a reference, flight lines over agricultural fields were also flown. During the winter season, the agricultural fields are usually sparsely covered by dry wheat stubble that does not affect the microwave signal. Table 1 lists the snow ground truth information for each flight line. There are about 30 snow depth samples taken along each flight line.

Snow grain size information was taken in snow pits dug along the flight lines. The mean radius of the snow grain, measured at the top layer of the snowpack, typically was about 0.45-0.5 mm. This grain size is larger than that assumed 0.3 mm in deriving Eq (2). Using Eq (2) to estimate SWE in this case would over-estimate the SWE values for the

Table 1. Comparisons of observed SWE (in mm) with microwave estimated SWE (in mm) for different flight lines.

Flight No.	Line No.	Observed SWE	Chang et al. Algorithm	Remarks
1	950	49	53	agricultural
1	805	44	47	agricultural
1	801	51	48	agricultural
2	603	61	46	agricultural
2	603	61	47	agricultural
3	950	49	52	agricultural
3	801	51	51	agricultural
3	805	44	49	agricultural
4	959	62	22	spruce/aspen
4	111	40	44	agricultural
5	110	50	18	spruce/aspen/pine
5	107	62	14	spruce/aspen/pine
6	113	48	21	spruce/pine
6	115	48	27	spruce
6	116	43	27	spruce/aspen/pine
6	117	43	21	pine
6	122	48	32	spruce/pine
6	120	52	20	spruce/aspen/pine
7	301	35	18	spruce/pine
7	302	38	26	spruce/pine
8	303	50	38	spruce/pine
8	304	61	19	spruce
8	305	65	51	spruce
9	203	59	38	spruce/pined
9	209	65	41	spruce/pine
13	111	40	41	agricultural
14	111	40	37	agricultural

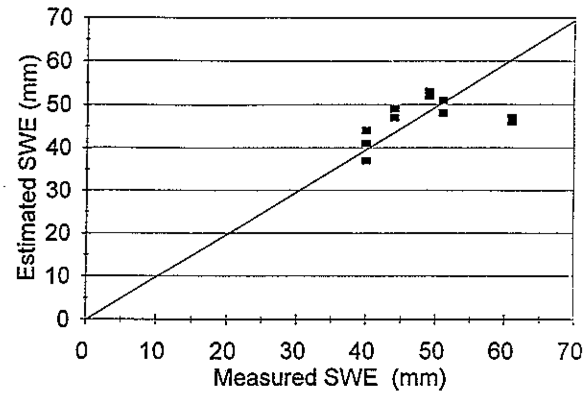
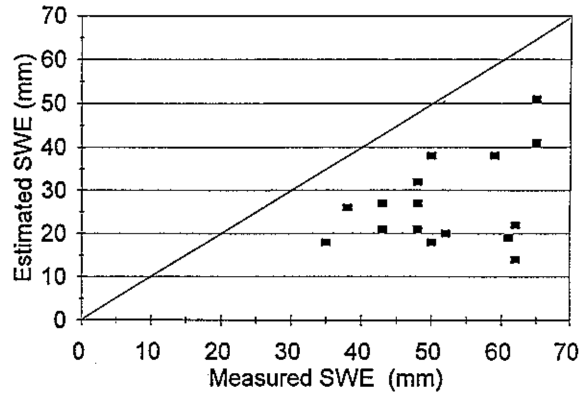
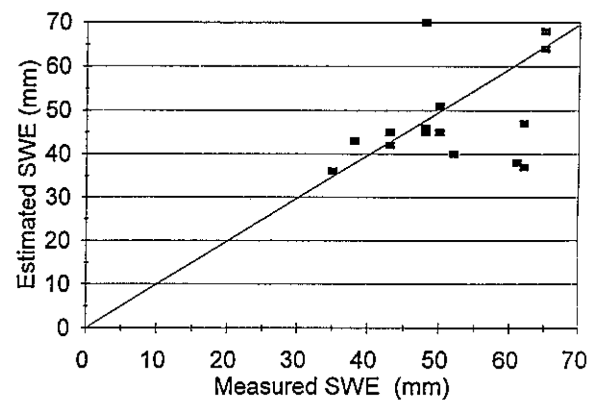


Figure 2. Estimated SWE (aircraft data) vs. observed SWE for agricultural lines, B = 1.7.



a. Without forest fraction correction.



b. With correction.

Figure 3. Estimated SWE (aircraft data) vs. observed SWE for forested lines.

agricultural lines. In order to obtain correct values, we have to recalibrate the coefficient B of Eq (3). By selecting the radius of 0.45 mm (Foster, 1995); the new coefficient of B is 1.7. Figure 2 shows the estimated SWE values versus observed SWE over agricultural fields using this adjusted coefficient. These estimated SWE values were close to the unity line of the scatter plot.

When the new coefficient is applied to the forest lines, estimated SWE values are much lower than the observed values (Fig 3a). The forest cover is reducing the brightness temperature differences in these flight lines. There is definitely a need to correct for the forest cover in retrieving SWE. Forest cover is rather dense in some part of the test areas. This has been reported recently by Hall et al. (1995). There are dense deciduous stands, coniferous stands and mixed-forest stands within the BOREAS test site, and the deciduous stands in some areas are denser than the coniferous stands.

To obtain the fractional forest coverage for the airborne microwave data, onboard video images were manually scanned to characterize the percent forest coverage for each flight line. Applying Eq (4) with the fractional forest cover derived from the video imagery, estimated SWE values corrected are plotted in Figure 3b. A linear fit of the observed versus the estimated SWE without correction gives a slope of 0.52. Because the observed SWE values are clustered around 40 to 50 mm, we chose to force the linear fit to go through the origin. With the forest cover correction, the slope improves to 0.95, and estimated SWE values are much closer to the 1:1 line, however, the standard error of estimated SWE is still rather large. This is probably due to using the averaged fractional forest cover to correct the data for the entire flight line. The correction scheme adopted for this study is highly non-linear with respect to the fractional forest cover. With 25 percent forest cover, the correction factor is 1.33, while for 75 percent forest cover, the correction factor increases to 4.0. Thus, the inhomogeneity of forest cover along a flight line may not be corrected by using the averaged fractional forest cover value of that flight line.

In order to test whether the modified algorithm can be applied to a larger area, satellite data need to be used. There are two Defense Meteorological Satellite Program (DMSP) satellites (F-10 and F-11) with SSM/I sensors onboard collecting data routinely. The overpass times for these satellites are approximately 6 a.m./p.m. for the F-11 and 10 a.m./p,m. for the F-10. Gridded pattern of flight lines were flown to simulate the satellite footprint for comparison. Three different grids,

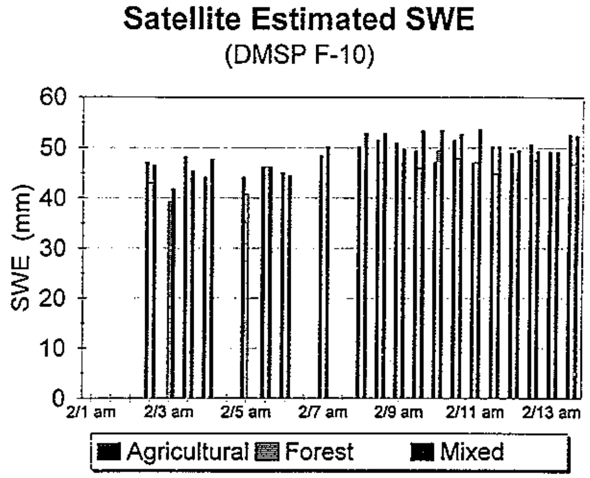


Figure 4. Estimated SWE (F-10 satellite data) for three selected grids, February 1 to 13, 1994.

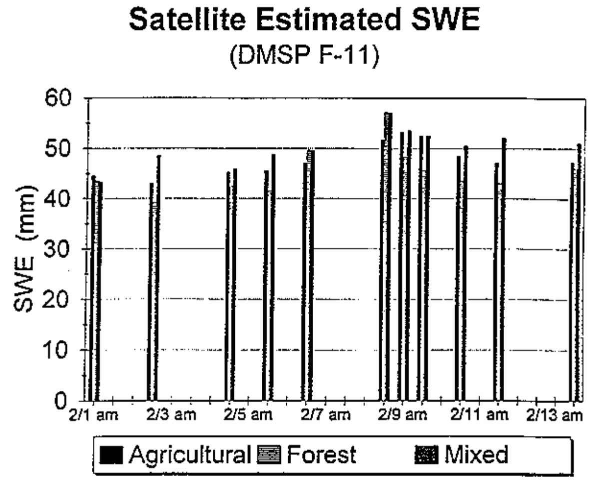


Figure 5. Estimated SWE (F-11 satellite data) for three selected grids, February 1 to 13, 1994.

Table 2. Average and standard deviations of estimated SWE (in mm) from SSM/I for selected grids.

Selected Grid	F-10 Average	STD	F-11 Average	STD	Ground Truth SWE
Agricultural	49	3	48	3	49
Mixed	47	3	50	4	40
Forested	45	2	45	5	43

agricultural, mix forested, and forested, were selected. Each grid consists of six flight lines within a 25 km by 25 km area, emulating the SSM/I 37 GHz footprint.

Figures 4 and 5 show the SWE estimates over these three grids for February 1 to 13, 1994 using all the available overpasses from F-10 and F-11 satellites. The scanning swath width of SSM/I is 1400 km. It does not provide contiguous global coverage. Therefore, there are days with no data in these figures. The estimated SWE values for the selected grids vary between 40 and 50 mm for the entire time period. The average and standard deviation of the estimated SWE values for the selected grids are tabulated in Table 2. Also listed are the averaged snow data for each grid. Satellite derived SWE values match quite well with the limited ground observations.

During February 1 to 13, there was no appreciable amounts of new snowfall for this area. SWE values retrieved from SSM/I data may give us an indication of the robustness of this method. The standard deviations of estimated SWE are less than 10 percent of the mean. SSM/I brightness temperatures can vary, from day to day, by several K due to changing air temperature, atmospheric water vapor and cloud ice contents and the position of the footprints. Ice cloud particles do not contribute much to the brightness temperature. Also microwave emission from water vapor molecules for 19 and 37 GHz are comparable; most of the variations in the estimated SWE are probably due to the sensor looking at slightly different spot from day to day.

When comparing the SWE estimates from air-borne and space-borne sensors with a forest cover correction, the estimated SWE values for the selected grids are tabulated in Table 3. The differences are about 10 mm in the agricultural and mixed grids for those data taken on February 11. This small difference may be caused by differences in the incidence angle (45° versus 53°), difference in the

Table 3. Retrieved SWE values from air-borne radiometer and SSM/I for the agricultural, mixed and forested grids.

Agricultural grid

February 11, 1994

Sensor	Time (LT)	SWE (mm)
F-10 SSM/I	10 a.m.	42
AMMR	4 p.m.	33
F-11 SSM/I	6 p.m.	47
F-10 SSM/I	10 p.m.	50

Mixed grid

February 11, 1994

Sensor	Time (LT)	SWE (mm)
F-10 SSM/I	10 a.m.	48
AMMR	3 p.m.	45
F-11 SSM/I	6 p.m.	45
F-10 SSM/I	10 p.m.	44

Forested grid

February 13, 1994

Sensor	Time (LT)	SWE (mm)
F-10 SSM/I	10 a.m.	46
AMMR	3 p.m.	12
F-11 SSM/I	6 p.m.	46
F-10 SSM/I	10 p.m.	47

time of data collection, and differences in the footprint target area.

Another factor that could affect the SWE retrieval is wet snow condition. The emissivity and scattering characteristics of a wet snowpack are significantly different from that of dry snow (Chang and Gloersen, 1975; Stiles and Ulaby, 1980). Melting results in a higher microwave brightness temperature and consequently lower estimated SWE values. Melting snow was not a factor in the early part of this experiment; the recorded air temperature in the area was substantially below 0° C. On February 13, however, the air temperature recorded at Prince Albert Airport was 1.6° C at 3 p.m. and fell to -3° C at 6 p.m. On this day we obtained a poor result when comparing the aircraft data from the forested grid with the SSM/I. The estimated SWE from the air-borne sensors was 12 mm, while the SSM/I derived value was about 46 mm. We attributed the SWE difference to the surface melting during the aircraft overflight, while the surface layer was frozen during the satellite overpasses. This assumption is also consistent with the wet snow discrimination method reported by Walker and Goodison (1993).

Summary and Conclusions

The boreal forest areas are always snow covered during the winter months, but because the canopy can obscure much of the snowpack viewed by satellite sensors, large errors may be produced when using an algorithm which was originally developed for prairie regions. However, it has been demonstrated that data collected by microwave radiometers can be used to retrieve SWE values over forested areas after adjusting coefficient B in Eqs (3) and (4). SWE retrieved from SSM/I data gave values within 20 percent of the mean during a two week period when no new snowfall was recorded. The simple correction scheme used in this study seems to give improved results. However, a more sophisticated correction scheme is needed to yield still better SWE estimates.

Snowpack melting does cause difficulty in retrieving SWE, particularly in spring when liquid water is presnet. Further study is needed to resolve the effect of snowpack melting on SWE retrieval.

Snow grain size may also contribute to large errors in retrieving SWE. In this study , aircraft data were used to calibrate coefficient B in Eqs (3) and (4). The grain size variability may be resolved by using a time dependent grain size model coupled with the retrieval algorithm. It is a challenging but necessary task to develop robust retrieval algorithms for hetergeneous areas that will give eliable SWE and allow for a quality, long-term snow data set.

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