Sensitivity of Passive Microwave Snow Depth Retrievals to Weather Effects and Snow Evolution

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***Abstract*—Snow fall and snow accumulation are key climate parameters due to the snow's high albedo, its thermal insulation, and its importance to the global water cycle. Satellite passive microwave radiometers currently provide the only means for the retrieval of snow depth and/or snow water equivalent (SWE) over land as well as over sea ice from space. All algorithms make use of the frequency-dependent amount of scattering of snow over a high-emissivity surface. Specifically, the difference between 37- and 19-GHz brightness temperatures is used to determine the depth of the snow or the SWE. With the availability of the Advanced Microwave Scanning Radiometer (AMSR-E) on the National Aeronautics and Space Administration's Earth Observing System Aqua satellite (launched in May 2002), a wider range of frequencies can be utilized. In this study we investigate, using model simulations, how snow depth retrievals are affected by the evolution of the physical properties of the snow (mainly grain size growth and densification), how they are affected by variations in atmospheric conditions and, finally, how the additional channels may help to reduce errors in passive microwave snow retrievals. The sensitivity of snow depth retrievals to atmospheric water vapor is confirmed through the comparison with precipitable water retrievals from the National Oceanic and Atmospheric Administration's Advanced Microwave Sounding Unit (AMSU-B). The results suggest that a combination of the 10-, 19-, 37-, and 89-GHz channels may significantly improve retrieval accuracy. Additionally, the development of a multisensor algorithm utilizing AMSR-E and AMSU-B data may help to obtain weather-corrected snow retrievals.**

***Index Terms*—Passive microwave, sea ice, snow.**

I. Introduction

PASSIVE microwave remote sensing of snow depth and/or snow water equivalent (SWE) over land has long been established (e.g., Chang *et al.* [2], Foster *et al.* [5], Künzi *et al.* [12], Pulliainen *et al.* [22], and Wilson *et al.* [28]), and more recently also over sea ice (e.g., Markus and Cavalieri [13]). All algorithms, essentially, make use of a combination of the 19- and 37-GHz channels. The reason for the use of these channels is that the 37-GHz data are more affected by scattering within the snow than the 19-GHz data; therefore the difference between these two channels is a measure of the amount of scattering within the snow, which can be used to retrieve snow information. Additionally, there are historical reasons for the use of these two frequencies since these two frequencies have been available on the Scanning Multichannel Microwave Radiometer (SMMR) (1979–1987) and the Special Sensor Microwave/Imager (SSM/I) (1987–present). With the availability of the Advanced Microwave Scanning Radiometer (AMSR-E) on National Aeronautics and Space Administration's Earth Observing System Aqua satellite (launched in May 2002), a wider range of frequencies can be utilized. AMSR-E has a frequency range from 6.9–89 GHz.

Despite the long history of passive microwave snow depth (and SWE) retrievals, algorithm accuracy still suffers from significant (and complex) error sources. These error sources can be divided into three categories: 1) errors due to variations in snow physical (and thus radiometric) properties themselves and 2) errors due to variations in the the underlying surface (such as variations in terrain) as well as 3) variations in the atmosphere. In this study we focus only on the variations in snow properties and variations in the atmosphere. Accounting for terrain variations has been investigated, for example, by Kelly *et al.* [10] and Foster *et al.* [6].

Although Armstrong *et al.* [1] found that algorithms are not as sensitive to snow grain size as was commonly assumed, the effect of grain size on the scattering is still considerable. Josberger and Mognard [9], therefore, developed an approach to account for variations in grain size using temperature fields. Wilson *et al.* [28] combined a hydrological model with SSM/I data to better account for variations in snow physical properties. Similarly, Pulliainen *et al.* [22] successfully use a simplified radiative transfer model to retrieve SWE from SSM/I data. They acknowledge that, given the vast number of degrees of freedom in the snowpack, a more complex, multilayer, snow radiative transfer model is not suited for inversion to retrieve SWE.

In this study we utilize forward model simulations of possible snow evolution scenarios using the Microwave Emission Model of Layered Snowpacks (MEMLS) [27] in order to achieve a better understanding of how snow depth and snow property changes (particularly grain size growth and densification) modulate microwave brightness temperatures, how the different AMSR-E channels are sensitive to these changes, and whether specific channel combinations can overcome potential retrieval errors. The simulations include the addition of layers for each snowfall event and also the natural densification and grain size growth with age. We exclude snow wetness in this study as wet snow dramatically changes the microwave signature of snow (e.g., Hallikainen *et al.* [8]), easily overshadowing grain size and density effects. Passive microwave algorithms for snow misinterpret wet snow areas as snow-free as a result of the blackbody behavior of a wet snow pack, and therefore approaches have been developed to identify and flag wet snow areas [24].

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Furthermore, we investigate how atmospheric variability affects the retrievals using an atmospheric radiative transfer model [11] as well as retrievals of precipitable water using AMSU-B data. Studies have shown that atmospheric effects will reduce the difference between the 37- and 19-GHz channels over multiyear sea ice [15], [21]. As a deep snow cover is radiometrically very similar to multiyear ice, weather effects are consequently expected to lead to an underestimate in snow depth. Currently snow depth (or snow water equivalent) algorithms for snow on sea ice as well as on land disregard the atmospheric contribution in their retrievals. We use the MEMLS emissivities as inputs into the atmospheric radiative transfer model to quantify this and confirm our findings through a comparison of SSM/I snow depths with precipitable water retrievals from AMSU-B.

Finally, we conclude with some recommendations for improved algorithms.

V. Conclusion

The snow and atmospheric radiative transfer models used in this study created a comprehensible dataset of snow microwave signatures. Fig. 11 shows scatterplots of GR(37V19V) versus GR(19V10V) with the snow depth indicated in color. In Fig. 11(a) ratios of the emissivities, as presented in Figs. 1 and 2, are plotted. The plot clearly demonstrates the potential of a GR(37V19V)–GR(19V10V) combination for the retrieval of snow depths or snow water equivalent. Points of the same snow depth (same color in Fig. 11) lie on distinct lines in this domain. As shown in Fig. 2, the scenario with three major snowfall events would result in overestimates in snow depth because of grain size growth and thus reduction in GR. For the last 70 days the GRs decrease because of grain size growth [this is indicated by the labels A and B in Fig. 11(a)] and consequently using GR(37V19V) only would cause a retrieval of increased snow depth whereas the snow depth, actually, decreases slightly because of densification (although the SWE remains constant). Using a GR(37V19V)–GR(19V10V) combination seems to reduce this problem as the snow evolution results in GR changes along a line of constant snow depth [Fig. 11(a)].

The same relationship is apparent when an atmosphere is added to the emissivities. Different atmospheric conditions are reflected in this domain in a very similar fashion [Fig. 11(b)]. Although the sensitivity to the atmosphere varies with frequency and although we only used a discrete set of atmospheric profiles, the contribution of the atmosphere to the different frequencies is correlated so that lines of constant snow depth are discernible in the combination of GR(37V19V) and GR(19V10V), which may help to reduce errors in snow algorithms from variable atmospheric conditions without requiring actual knowledge of the atmospheric burden.

This study has shown that a combination of GR(37V19V) and GR(19V10V) (or the difference of $T_B(\text{19H})$ and $T_B(\text{37H})$ as well as the difference of $T_B(\text{10H})$ and $T_B(\text{19H})$ for snow on land retrievals) may be used for improved retrievals. While a 37–19-GHz combination is preferable for snow depths of up to about 30 cm, for snow depth greater than this a 19–10-GHz combination seems to be advantageous. The greater penetration depth at the lower frequencies would also increase the maximum retrievable snow depth of currently about 60 cm [12] with the drawback, though, of a reduced spatial resolution, which is important when looking at snow in drainage basins.

Additionally, 89-GHz data may be potentially used to detect snow fall events. Decreases in GR(37V19V) cannot, unambiguously, be attributed to either increases in snow depth or increases in grain size. The small grain size of new snow combined with the small penetration depth at 89 GHz causes increases in T_B at 89 GHz whenever we have a layer of new snow. A decrease in GR(37V19V) coincident with an increase in $T_B(\text{89V})$ may therefore be indicative of additional snow.

Furthermore, the clear coincidence of times of high atmospheric water vapor with decreased retrieved snow depth suggest the development of a multisensor approach combining AMSR-E (SSM/I) data with AMSU-B data, which could result in weather-corrected snow retrievals for both snow on sea ice as well as for snow on land. AMSU-B data could be utilized in the snow depth (SWE) retrieval directly but would also help to distinguish peaks in the 89-GHz data between new snow events and changes in atmospheric conditions. A field experiment is needed where snow properties as well as microwave measurements are carried out over a longer period to confirm the results and then to develop strategies to improve passive microwave snow retrievals.

Nevertheless, the effects of the underlying ground have not been investigated in this paper. For snow on land, these are mainly different surface and vegetation types as well as different surface slopes. There have been extensive studies on this topic (e.g., Foster *et al.* [6]). For snow on sea ice, major issues (besides variations in sea ice concentration) include variations in the emissivity of the sea ice due to sea ice type and roughness, and the effect of the adjacent ocean. Frequently, there is a salty, slushy snow layer directly above the snow–ice interface, which cannot be penetrated with microwave leading to an underestimate of snow depth. Furthermore, particularly in the marginal ice zone where the sea ice is less consolidated, ocean spray may add salt to the snow surface which could alter the microwave signal significantly.

The additional use of AMSR-E's 10-GHz channel, obviously, prevents its applicability to SSM/I data, but improved AMSR-E snow depths, using potentially 10-GHz data, could be used as a baseline to improve retrievals with SSM/I data or to develop a synergistic algorithm using AMSU-B and SSM/I data.